

APEC Workshop on Cleaner and More Efficient Operation of the Fossil Energy Industry

APEC Energy Working Group

August 2026



**Asia-Pacific
Economic Cooperation**



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1. Background and Objectives

While Asia-Pacific Economic Cooperation (APEC) member economies have been committed to increasing clean energy supply and promoting energy transitions, fossil energy will remain an important part of their energy supply for most economies for the next two to three decades due to the circumstances of resource endowment and stage of development. It would be beneficial for the fossil energy industry in the APEC region to identify and capture opportunities to improve energy efficiency and reduce fugitive emissions to reduce costs and become more sustainable.

This capacity building workshop will provide fundamental technical knowledge to policymakers and relevant officials to identify feasible solutions and provide advice by sharing current and potential future technologies and best practices that can improve energy efficiency and reduce fugitive emissions from the fossil energy industry.

The project outputs include a background research report, a capacity building workshop, and a workshop summary report. The proposed project is consistent with the goal of APEC's Energy Working Group (EWG) to maximize the energy sector's contribution to economic and social well-being while mitigating the environmental effects of energy supply and use.

2. Outcome

The APEC Workshop on Cleaner and More Efficient Operation of the Fossil Energy Industry was held on 3 and 4 December 2025 at the Shinagawa Prince Hotel in Tokyo, Japan. It was designed as an in-person workshop to facilitate knowledge sharing and policy-relevant discussions on improving energy efficiency and reducing emissions across the fossil energy value chain. The workshop featured industry experts as speakers from the coal, gas, and oil sectors, and was attended by policymakers and other relevant officials from APEC member economies, who engaged in discussions to exchange experiences, best practices, and analytical perspectives.

The methodology combined structured thematic sessions with interactive discussions. On the first day, the workshop featured keynote and scene-setting presentations followed by sector-specific sessions focusing on the coal, gas, and oil industries. Each sectoral session consisted of expert presentations highlighting industry trends, current challenges, technological options, and operational practices, followed by moderated discussions and Q&A to encourage dialogue among participants.

On the second day, discussion sessions were conducted to synthesize key messages from the coal, gas, and oil sessions. These discussions were informed by the background research report prepared by the Asia Pacific Energy Research Centre (APEREC), which was made available to participants in advance. Guided by structured discussion guidelines, the sessions aimed to confirm the completeness and relevance of the technical topics covered in the draft APEREC background research report. The discussions also sought to gather expert inputs to complement and refine the report, while reviewing sector-specific technical issues and operational characteristics and identifying potential next steps for regional cooperation.

In addition, participants visited the Idemitsu Chiba Complex as a technical site visit. It was organized to provide participants with practical insights into real-world industrial operations and energy efficiency measures. Through this combination of presentations, discussions, and site-based learning, the workshop aimed to promote actionable understanding and support capacity building within the APEC region.

A total of 37 individuals attended the workshop, including speakers and participants from 11 APEC economies: Australia; Brunei Darussalam; Canada; Chile; China; Japan; Malaysia; Papua New Guinea; the Philippines; the United States and Viet Nam.

Speakers, moderators and participants (policymakers and other relevant officials from the APEC member economies): Low Emission Technology Australia (LETA) (Australia); Department of Energy at the Prime Minister's Office (Brunei Darussalam); Petroleum Technology Alliance Canada (PTAC) (Canada); Ministry of Energy (Chile); Petro-CyberWorks Information Technology Co., Ltd. (PCICT) (China); Directorate General of Oil and Gas (Indonesia); Indonesian Coal Mining Association (APBI-ICMA) (Indonesia); INPEX Corporation (Japan); Asia Pacific Energy Research Centre (APERC) (Japan); ENEOS Explora Inc. (Japan); Komatsu Ltd. (Japan); Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI) (Japan); Institute of Applied Energy (Japan); Ministry of Energy Transition and Water Transformation (Malaysia); National Energy Authority (Papua New Guinea); Department of Energy – Energy Resource Development Bureau (The Philippines); HSB Solomon Associates LLC (The United States); Binh Son Refining and Petrochemical JSC (BSR) (Viet Nam); Department of Oil and Gas, Ministry of Industry and Trade (Viet Nam); and Ministry of Industry and Trade (Viet Nam).

3. Workshop Summary

3-1. Day 1

3-1-1. Opening session

a) Opening Remarks

Dr Kazutomo Irie, Chairman & President, Asia Pacific Energy Research Centre (APERC)

Summary

In his opening remarks, Dr Kazutomo Irie, Chairman and President of APERC, welcomed speakers and participants to Tokyo and expressed his appreciation for their participation in the APEC Workshop on Cleaner and More Efficient Operation of the Fossil Energy Industry. He emphasized that the participation, knowledge, and experience of the attendees are essential to achieving a sustainable and secure energy system in the APEC region. He also expressed gratitude to the Japanese Ministry of Economy, Trade and Industry (METI), as well as to APERC researchers, staff, and the Institute of Applied Energy for their continued support and contributions to the organization of the workshop.

Dr Irie noted that while APEC economies have been committed to expanding renewable energy supply and advancing energy transitions, fossil fuels remain a significant part of the energy mix and are expected to continue playing this role in the coming decade. According to the recently published APEC Energy Demand and Supply Outlook, this situation reflects differences in domestic energy resources, renewable energy potential, and the challenges associated with integrating variable renewable energy sources into energy supply systems.

He stressed that it is imperative for the fossil energy industry in the region to operate as sustainably as possible. Improving energy efficiency and reducing fugitive emissions were highlighted as key measures to mitigate the environmental impacts of fossil fuels while maintaining energy security. Dr Irie further pointed out that although the fossil energy industry in the APEC region has substantial potential to reduce its environmental impact and support the energy transition, gaps remain in technical knowledge regarding the most effective solutions.

He explained that the workshop aims to provide essential technical knowledge and to identify practical solutions across the coal, oil, and gas industries. The insights and experiences shared during the workshop are also expected to guide APEC in defining next steps and focus areas for capacity building needed to drive meaningful improvements in the fossil energy industry throughout the region. He concluded by reaffirming that the workshop aligns with the objectives of the APEC Energy Working Group and by encouraging continued collaboration among APEC economies toward a sustainable energy future.

b) Keynote Speech

Ms Yuna Natsumi, Deputy Director, International Affairs Division, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI), Japan

Summary

Ms Yuna Natsumi, Deputy Director, International Affairs Division, Agency for Natural Resources and Energy, METI, presented Japan's policy direction and practical approaches for decarbonizing the fossil energy sector while maintaining energy security. She introduced Japan's international cooperation framework under the Asia Zero Emission Community (AZEC), outlined the Japan's enhanced Nationally Determined Contribution (NDC), and highlighted ongoing efforts in carbon capture, utilization and storage (CCUS) as a key enabler for hard-to-abate sectors. The presentation also showcased Japanese progress in hydrogen and ammonia utilization for thermal power generation, emphasizing their roles in emissions reduction and energy security.

Ms Natsumi began her remarks by noting that while APEC economies are expanding clean energy supply and advancing energy transitions, fossil fuels are expected to remain an important part of the energy mix for the next two to three decades. This reflects differences in resource endowments and stages of economic development. In this context, she emphasized that improving energy efficiency and reducing fugitive emissions are practical measures to enhance sustainability while maintaining energy security.

She explained that the Japanese energy policy framework is based on the "S+3E" principle, with safety as the top priority, alongside energy security, economic efficiency, and environmental considerations. Ms Natsumi also outlined three key messages include in the triple-breakthrough concept guiding Japanese international energy cooperation: achieving energy security, economic growth, and emissions reduction simultaneously; pursuing a common net-zero goal through various pathways suited to respective circumstances; and contributing to global emissions reductions through the deployment of Japanese technologies.

The keynote further described the AZEC, established in 2022 under Japanese leadership, as a framework for promoting realistic and inclusive energy transitions in Asia. Ms Natsumi highlighted Japanese updated NDC, which sets targets to reduce greenhouse gas emissions by 60% in FY2035 and 73% in FY2040 compared to FY2013 levels, aligned with the global 1.5°C goal.

Turning to coal and clean coal technologies, Ms Natsumi explained that Japanese Seventh Strategic Energy Plan positions in thermal power as a transition energy source while promoting its decarbonization through hydrogen, ammonia, and CCUS. She noted that CCUS, including carbon capture and storage (CCS), is indispensable for decarbonizing hard-to-abate sectors, and that Japan is supporting advanced CCS projects to accelerate early commercialization and future business deployment.

She also presented concrete progress in hydrogen and ammonia utilization for power generation, including demonstrations of hydrogen co-firing, development of hydrogen single-fuel-firing turbines, and large-scale ammonia co-firing technologies that enable stable combustion and reduced NOx emissions. Ms Natsumi concluded that these practical demonstrations illustrate the Japanese approach to reducing emissions from thermal power while maintaining energy security, and reflect its intention to share scalable solutions with APEC economies.

c) Scene Setting

Mr Rodrigo Martinez, Researcher, APERC

Summary

The session opened with an overview of the analytical background and objectives of the workshop, presented by Mr Rodrigo Martinez, Researcher at APERC. He emphasized that enhancing energy efficiency and managing fugitive emissions across fossil fuel supply chains are important for preparing the industry to operate in an increasingly challenging environment during the energy transition.

As part of the Scene-setting Session, Mr Martinez explained the analytical context for the workshop by introducing the APEC Energy Demand and Supply Outlook (9th Edition, Volume I). The Outlook examines future energy trends in the APEC region under two scenarios. These include a Reference Scenario based on historical trends and recent developments, and a Target Scenario representing a hypothetical pathway in which each economy achieves its stated energy- and emissions-related policy targets, regardless of cost-effectiveness. Where implementation details are not specified, modelling assumptions are inferred from the targets themselves.

According to the Outlook, final energy demand in the APEC region is projected to continue growing for approximately the next 15 years in both scenarios, before stabilizing after around 2040. In the Reference Scenario, final energy demand remains relatively flat thereafter due to improvements in energy intensity and slightly slower economic growth. In contrast, in the Target Scenario, stronger energy efficiency gains—driven mainly by electrification in the transport sector—lead to a gradual decline in energy demand, with final energy demand in 2060 returning to a level similar to that of the 2022 baseline year.

Despite these differences in demand trajectories, fossil fuels are projected to remain a dominant component of the APEC energy mix over the long term. In the Reference Scenario, fossil fuels are expected to account for more than 65% of primary energy supply in 2060, while even in the lower-carbon Target Scenario they are projected to represent around 51%. Natural gas, in particular, is expected to retain an essential role in power generation, while natural gas and, to a lesser extent, coal continue to support renewable energy integration by addressing short-term supply–demand imbalances and enhancing grid stability.

In this context, the Outlook underscores that improvements in energy efficiency and reductions in fugitive emissions are increasingly important for enabling the fossil energy industry to adapt to an energy transition in which requirements for efficiency, competitiveness, and emissions management are expected to become more stringent.

Mr Martinez also outlined the structure of the workshop. A total of nine experts were invited to share their experience and respond to questions across the three main fossil fuel industries—coal, gas, and oil—covering key stages such as production, processing, and transportation. The discussions on the following day were based on a background research report prepared by APERC and provided to participants in advance. The discussion guidelines were designed to confirm the completeness and

relevance of the technical topics included in the report, while encouraging speakers and participants to share practical experiences, raise questions, and expand the scope of discussion where appropriate.

Against this background, the workshop aims to provide participants with practical knowledge on technologies and practices that enhance efficiency and reduce emissions across the production, processing, transportation, and storage of fossil fuels, while helping to bridge technology and policy perspectives.

3-1-2. Session 1: Coal Industry

Session Moderator: **Dr Atsushi Kurosawa**, Executive Research Fellow, The Institute of Applied Energy (IAE), Japan

a) Indonesia's Coal Sector in the Energy Transition Era

Mr Ignatius Wurwanto, Vice Chairman, ESG and Mining Governance, Indonesian Coal Mining Association (APBI-ICMA), Indonesia

Summary

Mr Ignatius Wurwanto discussed how the coal sector in Indonesia is addressing the challenges of the energy transition while continuing to support domestic energy needs and economic development. He emphasized the need to balance energy security, affordability, and environmental sustainability, noting that coal remains an important component of Indonesia's electricity system during the transition period. He outlined the corporate decarbonization approach of APBI-ICMA structured around three pillars—Reduction, Removal, and Green New Business—and highlighted coal mine methane (CMM) emissions as a key technical concern due to data limitations and higher emissions from underground mining. Within Indonesia's climate policy framework, he referred to Indonesia's NDC and presented four coal-sector emission reduction strategies: coal production control, improvement of CMM monitoring and reporting, further study and deployment of carbon capture and methane mitigation technologies, and facilitation of a just transition in coal-producing regions.

He began by introducing APBI-ICMA, which was established in 1989 and today represents coal mining companies and supporting industries across the Indonesian archipelago. The association acts as a key partner to the government in policy dialogue and implementation, covering a substantial share of Indonesia's coal production. Indonesia possesses large coal reserves of varying quality, which allow coal to continue underpinning electricity generation and industrial activity for several decades under current production levels.

In discussing electricity supply, Mr Wurwanto referred to the National Electricity Supply Business Plan (RUPTL) of Indonesia, under which electricity demand is expected to continue rising in line with economic growth and industrial development. Coal-fired power plants remain a central component of the generation mix, as they currently provide a cost-effective and stable source of baseload power. While the government is advancing cleaner energy options, coal is expected to retain an important role during the transition period.

Mr Wurwanto framed the energy transition challenge in Indonesia through the lens of the energy trilemma, highlighting the need to balance energy security, energy affordability, and environmental sustainability. He noted that efforts to rapidly reduce emissions without due consideration of reliability and cost could undermine economic and social outcomes. Accordingly, the approach adopted in Indonesia emphasizes gradual transition pathways supported by technological improvement and realistic investment planning.

Within this context, APBI–ICMA has articulated a corporate decarbonization approach structured around three pillars: Reduction, Removal, and Green New Business. The Reduction pillar focuses on improving operational efficiency, optimizing energy use, and replacing part of fossil fuel consumption with lower-carbon alternatives. Examples include enhanced energy management systems, logistics optimization, and the use of biofuels, with Indonesia currently implementing the B40 program and planning to advance to B50 in the coming years.

The Removal pillar centers on carbon sequestration and offset measures, particularly through mine reclamation and revegetation. Given that many coal mining operations are located in forested areas, post-mining land rehabilitation is considered a critical opportunity to improve carbon management while also restoring ecosystems and supporting local livelihoods. These activities may also provide a foundation for future participation in carbon markets.

The Green New Business pillar reflects efforts by coal companies to diversify into more environmentally friendly business areas. Mr Wurwanto noted that some companies are exploring biomass production, renewable energy projects, and other low-carbon activities on or near former mining sites. While many of these initiatives remain at the study or pilot stage, they illustrate the sector's intent to adapt its business models over time.

Mr Wurwanto further explained that several member companies are conducting feasibility studies and pilot projects involving low-carbon technologies. These include carbon capture, utilization and storage (CCUS), underground coal gasification, and renewable energy applications such as solar, hydro, and wind power. Some companies are also considering downstream diversification into sectors such as mineral processing and battery-related industries, although these initiatives are still under evaluation.

A major technical challenge highlighted in the presentation was CMM emissions. Mr Wurwanto stressed that accurate data are essential for effective emission reduction, yet current reporting does not fully reflect actual emission levels. Only a limited number of companies systematically measure and report methane emissions, and available data suggest a significant gap between estimated and reported figures.

He noted that methane emissions from underground mining operations are substantially higher than those from open-pit mines. As underground mining activities expand, the importance of improving methane measurement, reporting, and mitigation becomes increasingly critical. APBI–ICMA is therefore encouraging greater adoption of monitoring practices consistent with international guidelines, including those of the Intergovernmental Panel on Climate Change (IPCC), while recognizing that methodological differences and geological conditions remain challenges.

At the policy level in Indonesia, Mr Wurwanto referred to Indonesia's Enhanced NDC, submitted in 2022, which sets greenhouse gas emission reduction targets of 31% unconditionally and up to 43% conditionally by 2030. He emphasized that emissions from the energy sector, including fugitive emissions, are already incorporated into this framework.

He highlighted that the forestry and other land use (FOLU) sector provides the largest contribution to the overall emission reduction target in Indonesia. As a result, reforestation, afforestation, and post-mining land reclamation are regarded as especially important components of Indonesia's mitigation strategy, alongside technological measures in the energy sector.

In this context, Mr Wurwanto outlined four key strategies for reducing emissions from the coal sector. These include controlling coal production in line with long-term planning, improving CMM monitoring and data accuracy, further studying and deploying carbon capture and methane mitigation technologies, and facilitating a just transition in coal-producing regions through coordination between central and regional governments.

He concluded by emphasizing that the success of the energy transition in Indonesia will depend on close collaboration among government, industry, and international partners. By combining improved data quality, technological development, nature-based solutions, and social transition measures, the coal sector in Indonesia aims to contribute constructively to Indonesia's climate objectives while continuing to support energy security and economic development during the transition period.

b) Upstream Clean Coal Technologies

Mr Ben Rice, Head of Government Relations and Media, Low Emission Technology Australia (LETA), Australia

Summary

Mr Ben Rice, Head of Government Relations and Media at Low Emission Technology Australia (LETA), delivered a presentation focusing on what happens at the very start of the coal supply chain—where coal is mined—and how upstream clean coal technologies can be used to reduce fugitive emissions from coal mining, particularly methane. He emphasized that addressing methane emissions at the mine site is one of the fastest and most cost-effective ways to reduce the overall climate impact of coal supply chains, as emissions can be tackled before coal even leaves the pit. He highlighted the role played by LETA in working with the Australian coal industry to abate methane at mine sites, noting both the challenges involved and the opportunities created by technological innovation and supportive policy settings. At the same time, he stressed the importance of this work for Australia's trading partners in the Asia-Pacific region, as lowering emissions at the point of extraction reduces the embedded carbon footprint of exported coal.

Mr Rice introduced LETA as an industry-funded organization supported by black coal producers in Australia, whose members account for approximately 92% of Australia's coal production, most of which is exported overseas. LETA aims to help coal miners and heavy industries reduce emissions while remaining productive and competitive by investing in scalable technologies.

He also noted that Australia and its Asia-Pacific partners have built deep and long-standing energy relationships over several decades, and that as economies across the region pursue carbon neutrality, they face a shared challenge of maintaining affordable and reliable energy and materials while rapidly reducing emissions across the value chain.

A central theme of the presentation was that methane emissions from coal mining represent both a significant climate risk and a near-term opportunity. Methane is naturally present in coal seams and surrounding rock strata and is released during mining, traditionally being ventilated to the atmosphere for safety reasons. In the Australian context, methane from coal mining accounts for around 6% of Australia's total greenhouse gas emissions. Mr Rice noted that methane has a much higher warming impact than carbon dioxide—around 28 times on a 100-year basis—but a much shorter atmospheric lifetime of approximately 10 to 12 years, meaning that cutting methane emissions now can deliver rapid and noticeable climate benefits.

Mr Rice explained that upstream clean coal technologies refer to measures deployed at the mine site to reduce the emissions intensity of coal before it leaves the mine, including detecting and sealing methane leaks, pre-draining gas from coal seams, improving ventilation efficiency, and oxidizing low-concentration methane in ventilation air, and generating electricity from higher-concentration gas that would otherwise be vented.

As an investor in emissions-reduction technologies, the current focus of LETA is on ventilation air methane (VAM) abatement. Mr Rice outlined two main technological pathways, beginning with

regenerative thermal oxidizers, which divert mine ventilation air containing very low concentrations of methane through a system of ducts into a chamber with a heated ceramic bed at a temperature of around 1000 degrees Celsius. In this process, methane is oxidized into carbon dioxide and water, and the heat released is captured and reused to preheat incoming air, improving overall energy efficiency. He emphasized that deploying regenerative thermal oxidizers in Australian coal mines requires careful engineering and robust safety systems.

Recognizing the practical limits of regenerative thermal oxidizer technology, particularly in mines with very low methane concentrations, Mr Rice described catalytic oxidation systems as a complementary, next-generation solution. These systems use catalysts to trigger methane oxidation at much lower temperatures, typically around 300 to 500 degrees Celsius, which is well below the auto-ignition point of methane and most mine dusts. This lower-temperature operation reduces ignition risk, lowers energy requirements, and widens the range of mine conditions under which ventilation air methane can potentially be abated.

A major initiative supporting this work is the CATCH4 (Catalytic Oxidation of Methane) program, led by the Australian organization Mining3. Mr Rice explained that CATCH4 is a research and development initiative structured in four phases, moving from laboratory testing through to full-scale mine deployment. Phase 1 demonstrated consistent methane oxidation at temperatures below approximately 550 degrees Celsius under simulated mine conditions, while Phase 2 is now underway and involves installing a pilot catalytic oxidizer at an operating underground coal mine to treat approximately one cubic meter per second of ventilation air. He noted in his remarks that the CATCH4 program represents an industry investment on the order of around AUD 100 million, with the aim of delivering a commercially viable catalytic VAM system before 2030.

Mr Rice also highlighted the role of policy and economic drivers in enabling methane abatement. The strengthened Safeguard Mechanism in Australia places declining emissions baselines on large facilities, including coal mines, and creates financial incentives for emissions reductions through carbon credit markets. In the first compliance year, Australian coal mines collectively surrendered an estimated three to four million metric tons of carbon credits, representing costs well in excess of AUD 100 million at prevailing carbon prices. He noted that on-site methane abatement can therefore reduce future compliance costs while delivering environmental and reputational benefits.

In concluding, Mr Rice emphasized that methane from coal mining is a significant yet actionable source of greenhouse gas emissions and that upstream clean coal technologies can reduce emissions without compromising safety. He stressed that the technologies being demonstrated in Australian mines can be adapted and applied across other APEC economies to reduce the emissions intensity of existing coal supply chains while maintaining reliable energy supply.

c) Energy Efficiency in Mining Machinery

Mr Hisashi Asada, General Manager, Solution Department, Mining Business Division, Komatsu Ltd., Japan

Summary

Mr Hisashi Asada of Komatsu Ltd. presented a comprehensive overview of the company's approach to improving energy efficiency and reducing greenhouse gas (GHG) emissions in mining machinery, with particular emphasis on coal mining operations. Komatsu is a global manufacturer of construction, mining, and industrial machinery supplying equipment and integrated solutions for both surface and underground mining worldwide. Recognizing that energy efficiency is central to sustainable mining and that there is no single solution to achieving decarbonization, Komatsu has set a target of achieving

carbon neutrality by 2050 through step-by-step technological innovation. Mr Asada explained that the company's strategy integrates product development, digital solutions, automation, and human performance improvement into a unified framework. This approach aims not only to reduce emissions from mining equipment, which account for the majority of Komatsu's lifecycle emissions, but also to optimize entire mining operations. By combining smarter and greener machinery, data-driven operational optimization, and automation technologies such as autonomous haulage, Komatsu seeks to improve productivity, safety, and environmental performance simultaneously. Collaboration with mining customers plays a critical role in aligning equipment development with site infrastructure and operational requirements, ensuring that energy efficiency and GHG reduction measures are practical, scalable, and economically viable.

Mr Asada began by introducing the mining business scope of Komatsu and product offerings. Komatsu provides a wide range of mining machinery for both surface and underground operations, including haul trucks, hydraulic excavators, electric mining shovels, dozers, drills, and underground equipment. In addition to machinery, Komatsu offers mining solutions that support operational optimization, safety enhancement, and workforce development. These solutions are designed to address the increasing complexity of mining operations and to improve energy efficiency across the entire mine process.

The corporate vision of Komatsu is to be a collaborative partner committed to optimizing safe, productive, and clean workplaces. To realize this vision, the company pursues two strategic axes: enhancing the value of products by making mining equipment smarter and greener, and enhancing the value of solutions by improving efficiency across mining processes. Mr Asada explained that automation, electrification, and low-carbon power technologies such as batteries, trolley systems, and hydrogen are central to reducing emissions, while digital solutions enable visualization, optimization, and integration of mining operations on a mine-wide scale.

Addressing changes in the mining industry, including deeper mines, remote locations, and labor shortages, Mr Asada outlined three major challenges faced by mining customers: improving safety and productivity through automation, reducing GHG emissions through green machinery, and maximizing efficiency through integrated solutions. He emphasized that achieving carbon neutrality requires coordinated efforts across products and processes. The Komatsu Decarbonization Ecosystem Strategy was introduced as a framework developed through close collaboration with customers, particularly through the GHG Alliance, to align machinery development with infrastructure planning and operational needs.

A key technical focus of the presentation was the electrification of mining machinery. Mr Asada introduced the Power-Agnostic Truck concept, which is designed to operate using multiple power sources, including diesel-electric systems, trolley lines, batteries, and hydrogen fuel cells. This flexibility allows mining operations to select appropriate power configurations based on site conditions and infrastructure readiness. The concept reflects Komatsu's use of bridging technologies to transition toward zero-emission mining equipment.

Automation represents another core component of Komatsu's strategy. Mr Asada described the Autonomous Haulage System (AHS), which integrates haul trucks with fleet management systems, communication networks, and centralized control to enable fully unmanned operation. Deployed since 2008, AHS has expanded globally and is currently operating mainly in coal mines in regions such as Oceania and North America. By eliminating inefficiencies associated with manual driving, AHS enables consistent 24-hour operation, reduces fuel waste, improves safety, and contributes to lower GHG emissions.

Komatsu's digital solutions include fleet management systems, asset health monitoring, payload optimization, dispatching, and operational analytics. These technologies collect and analyze real-time data from mining equipment to improve utilization, reduce idle time, and optimize energy consumption. Mr Asada emphasized the importance of connecting individual solutions through a common digital

platform, enabling broader mine-wide optimization by linking planning, operation, and performance analysis.

In addition to equipment and digital technologies, Mr Asada highlighted the importance of human performance improvement. The group company of Komatsu, Immersive Technologies, provides simulator-based training, virtual reality, and e-learning programs to improve operator skills and reduce variability in machine operation. Case studies from coal mining operations demonstrated that simulator-based training can reduce fuel consumption by more than 6%. Regular and repeated training helps sustain these efficiency gains while maintaining safety and operational consistency.

In conclusion, Mr Asada reiterated that achieving carbon neutrality in mining requires an integrated approach that combines smart and green equipment, digital optimization solutions, automation technologies, and workforce development. By continuously refining this integrated mining value chain in collaboration with customers, Komatsu aims to improve energy efficiency, reduce greenhouse gas emissions, and support the sustainable transformation of mining operations.

d) Discussion and Q&A

Key Points of the Discussion

- In Indonesia, complex coal seam geology, brittle fault conditions, and unfavorable stripping ratios make underground coal mining technically challenging, leading policy frameworks to continue favoring open-pit operations despite increasing mining depth.
- Underground coal mining generally generates higher methane emissions than surface mining, while economically viable and widely deployable methane mitigation technologies remain limited in availability.
- Ventilation air methane abatement technologies, including regenerative thermal oxidation, are commercially available internationally, but their deployment is constrained by low methane concentrations, stringent safety requirements, long lead times, and site-specific cost structures.
- Emerging methane abatement options, such as catalytic oxidation technologies, are still under development, with broad commercial deployment expected around 2030.
- Regulatory frameworks requiring near-term emissions reductions often lead operators to rely on carbon offsets, as major mitigation projects require several years to develop and implement.
- Electrification of mining equipment is technically feasible in terms of motor performance, but battery weight, charging frequency, and payload reduction continue to limit large-scale applications in surface mining.
- Battery-electric equipment is being adopted more rapidly in underground mining, where smaller machinery and lower power and payload requirements are better aligned with current battery technology.
- No single decarbonization pathway is applicable across all mining sites, as technology choices depend on site-specific geological, operational, and emissions conditions.

Questions and Answers

QUESTION: Dr Atsushi Kurosawa to Mr Ignatius Wurwanto

Could you explain Indonesian experience in coal mining and the future outlook, particularly the potential shift from surface mining to underground mining? Given the complex geological structure of coal seams in Indonesia, what difficulties do you foresee in improving efficiency and reducing fugitive emissions under underground mining operations?

ANSWER: Mr Ignatius Wurwanto

Indonesian coal seam geology is indeed complex, particularly with respect to seam thickness and structural conditions, which makes underground mining technically challenging. This is one of the main reasons why underground coal mining is still limited in Indonesia. From a policy perspective, the government continues to favor open-pit mining because of the stripping ratio and brittle fault conditions. In addition, underground mining tends to generate higher methane emissions than surface mining. This raises concerns regarding fugitive emissions management. At present, studies are ongoing on underground coal gasification as a potential option to enhance resource recovery while addressing emissions, but the associated costs and technological readiness remain significant barriers. This session provides an opportunity to share perspectives on future technologies that could support underground mining by both optimizing resource recovery and managing fugitive emissions.

QUESTION: Dr Atsushi Kurosawa to Mr Ben Rice

You explained methane abatement measures in coal mining; however, you did not elaborate on energy efficiency measures in mining operations, transportation, and processing. What technologies are currently applied in the Australian coal industry to improve energy efficiency across the value chain?

ANSWER: Mr Ben Rice

In Australia, our efforts extend beyond methane abatement to include broader scope 1 and scope 2 technologies. We are investing in carbon capture, utilization, and storage, as well as in CO₂ liquefaction and transportation technologies across the coal value chain, including the steel and cement sectors. We are also working closely with Asia-Pacific economies on hydrogen production, including coal-to-hydrogen pathways, as an alternative for thermal power generation that still utilizes coal resources.

QUESTION: Dr Atsushi Kurosawa to Mr Hisashi Asada

You mentioned that combining hardware, software, and human capital development can improve operational efficiency. Are low-carbon certification systems, such as Japan's Green Transformation (GX) certification framework for machinery, applicable to mining machinery? Are there any international certification schemes for mining equipment efficiency?

ANSWER: Mr Hisashi Asada

At present, the main challenges lie in timing, cost and functionality. While battery-powered trucks and low-emission machinery are technically feasible, current battery systems are heavy and reduce payload capacity. Mining customers would also need to modify their operations and infrastructure to accommodate new technologies. There is no single optimal solution applicable to all customers, as operational conditions and emission-reduction priorities differ significantly across sites. We continue to engage in detailed discussions with customers to identify feasible pathways for adopting next-generation machinery.

QUESTION: Dr Atsushi Kurosawa to Mr Hisashi Asada

In the construction sector, the Japanese government has introduced a GX-certified machinery system. Could a similar or internationally harmonized standard be applied to mining machinery in order to facilitate the global diffusion of such equipment?

ANSWER: Mr Hisashi Asada

Although this point was not elaborated in detail during the presentation, battery technologies based on GX and Digital Transformation (DX) have already been introduced for construction and smaller machinery. In principle, these technologies could be extended to mining machinery as well. However, applying them to mining equipment remains challenging, as achieving an appropriate balance between new technologies and the operational requirements of mining sites is considerably more difficult.

QUESTION: Dr Atsushi Kurosawa to Mr Ben Rice

Under the safeguard mechanism in Australia, facilities must reduce emissions immediately following investment. Given that CCUS projects often require long lead times, how does the coal industry address short-term compliance challenges?

ANSWER: Mr Ben Rice

The safeguard mechanism sets declining emissions baselines for the top 200 emitters in Australia, requiring annual reductions of approximately 4.9%. Since many mitigation technologies, such as ventilation air methane abatement and carbon capture and storage, require several years to develop and deploy, companies often rely on purchasing carbon offsets in the interim to remain below their emissions baselines.

QUESTION: Mr Allan Fogwill, to Mr Ben Rice

What is the current price of offsets under the safeguard mechanism, and is it sufficient to drive emissions reductions?

ANSWER: Mr Ben Rice

Offset prices are indexed to inflation and currently stand at approximately AUD 35 per metric ton. This level is designed to balance compliance incentives with economic feasibility. Costs for methane oxidation technologies vary by site, with estimates ranging from approximately AUD 30 to around AUD 75, and in some cases approaching AUD 100 per metric ton.

QUESTION: Dr Kazutomo Irie to Mr Ben Rice

Can you provide examples of coal mines in Australia that have adopted advanced upstream methane abatement technologies?

ANSWER: Mr Ben Rice

Anglo American's steelmaking coal operations in Queensland represent one of the most advanced cases, particularly in deploying ventilation air methane abatement technologies. In addition, Kestrel Coal in Queensland has been actively developing these technologies, and several other companies are working in collaboration with the New South Wales State Government.

QUESTION: Dr Kazutomo Irie to Mr Hisashi Asada

Regarding electrification of mining machinery, opinions differ on whether electric systems can match diesel engines in power output. From your perspective, what is the general technological trend in this area? Could you clarify the technical distinctions between tethered electric, battery-electric, and diesel-electric systems?

ANSWER: Mr Hisashi Asada

From a technical standpoint, electric motors are capable of delivering sufficient power for mining applications. However, the main challenge lies not in the motor itself but in the power source and its management. Tethered electric systems, such as trolley-assisted or cable-connected solutions, are effective for equipment with limited movement, such as loading machines operating in fixed locations. Battery-electric systems, while promising, currently face constraints related to re-charging frequency, battery size, and payload reduction. Diesel-electric systems represent a transitional configuration but still rely on fossil fuels. Fuel-cell technologies, including hydrogen-based systems, are under active research and development, but battery technology for large-scale surface mining equipment has not yet reached sufficient maturity.

QUESTION: Mr Alvaine Ibarrola, the Philippines' Department of Energy, to Mr Hisashi Asada

In the Philippines, we operate several surface coal mines. If mine operators were to introduce fully battery-powered heavy equipment, how long would such equipment be able to operate compared with conventional diesel-powered machinery? In addition, do you have a comparative assessment or matrix outlining the advantages and disadvantages of battery-powered equipment relative to conventional systems, particularly for surface mining applications?

ANSWER: Mr Hisashi Asada

At present, battery-powered mining equipment is still deployed on a limited scale, although the number of applications is gradually increasing each year. Battery-electric trucks, wheel loaders, and similar

equipment are technically available; however, operational performance depends heavily on battery size and site conditions. Extending the operating range requires installing larger batteries, which in turn significantly reduces payload capacity. This trade-off makes it difficult to achieve performance equivalent to diesel-powered equipment, especially for long haul distances, uphill transportation, and continuous heavy-duty operations typical of surface mining. Balancing operating time, payload, and charging frequency remains one of the key technical challenges.

As shown in my presentation, current electrification initiatives in Japan under the GX framework have primarily focused on small-scale construction equipment, such as three-ton-class machines, which typically operate for only a few hours per charge. For larger equipment, including mining loaders and haul trucks, battery installation is still at an early experimental stage. Research and development are ongoing for fuel-cell technologies, such as hydrogen-powered systems for 20-ton-class excavators, but these technologies have not yet reached full commercial maturity. Overall, electrification is progressing incrementally, starting with smaller equipment, while large-scale mining applications require further technological advancement.

QUESTION: Mr Alvaine Ibarrola to Mr Hisashi Asada

Looking ahead, is battery-powered equipment also feasible for underground mining operations? Could such technologies be applied effectively in underground coal mines?

ANSWER: Mr Hisashi Asada

Battery-powered equipment is already being introduced more rapidly in underground mining than in surface mining. Underground operations generally use smaller machinery, such as battery-powered haulage trucks and loaders, which are better suited to current battery technology. In fact, several battery-electric machines are already in operation in underground mines. Compared to surface mining, where large-scale equipment dominates, battery technology is expected to mature faster in the underground mining context due to lower power and payload requirements.

QUESTION: Mr Phung Quoc Huy, APERC, to Mr Ignatius Wurwanto

Indonesia has traditionally relied on open-pit coal mining; however, in recent years mining activities have moved progressively deeper, with increased consideration of underground operations. Could you provide an overview of the current status of underground coal mining in Indonesia? In addition, as mining depth increases, are there plans to introduce methane mitigation or recovery measures for underground coal mines, particularly with respect to managing methane emissions from ventilation systems?

ANSWER: Mr Ignatius Wurwanto

Managing methane emissions remains a significant challenge for Indonesia, particularly given the predominance of large-scale open-pit coal mines that are now extending to greater depths. At present, suitable technologies for capturing methane from deep open-pit operations are still limited. As a result, government policy has focused on accelerating land reclamation and rehabilitation, including replanting, as a practical approach to mitigating methane-related risks. While methane emissions cannot be completely avoided, these measures aim to reduce their potential impact. With respect to underground mining, expansion remains constrained because effective and economically viable methane management technologies have not yet been fully established. This challenge is not unique to Indonesia and is shared by many coal-producing economies.

QUESTION: Mr Phung Quoc Huy to Mr Ben Rice

Ventilation air methane represents a major source of methane emissions from underground coal mines, even though methane concentrations are often below 1% due to the large volume of airflow. Regenerative thermal oxidation has been proposed as a mitigation option. Could you comment on whether this technology is already commercially available and how soon it could be deployed more widely? In addition, what is the outlook for the commercialization of catalytic oxidation technologies?

ANSWER: Mr Ben Rice

Regenerative thermal oxidation technology is already commercially available and has been deployed in several economies and other jurisdictions, including China; the United Kingdom and United States.. In Australia, however, wider deployment is constrained by typically low methane concentrations and stringent safety regulations, which require robust fail-safe mechanisms to prevent methane blowback into mine shafts in the event of an explosion. In parallel, catalytic oxidation technologies are being developed in collaboration with industry partners in Australia. Based on current development timelines, commercial deployment of catalytic oxidation systems is expected around 2030.

3-1-3. Session 2: Gas Industry

Session Moderator: **Mr Rodrigo Martinez**, Researcher, APERC

a) How Canada Reduced Upstream Oil And Gas Methane Emissions by More Than 50%

Mr Allan Fogwill, Chief Operating Officer, Petroleum Technology Alliance Canada (PTAC), Canada

Summary

Mr Fogwill provided an overview of Canada's experience in achieving substantial methane emissions reductions in upstream oil and gas operations. Canada has already achieved a reduction of more than 50% in methane emissions from this sector, demonstrating that significant emissions reductions are both technically feasible and economically manageable. This progress has been driven by clear federal and provincial policy direction, robust regulatory frameworks, collaborative research initiatives, and the rapid deployment of proven mitigation technologies. A transition from site-level estimation to equipment-level measurement has enabled more precise management of emissions from key sources, including pneumatic devices, storage tanks, compressors, and engines. Comprehensive monitoring approaches—integrating on-site sensors, vehicle-based surveys, airborne detection, and satellite verification—have supported accurate identification of fugitive emissions and super-emitters. Low-cost and in many cases cost-negative, measures such as Leak Detection and Repair (LDAR), low-bleed and no-bleed pneumatic devices, vapor recovery systems, and improvements in compressor and engine performance have played a central role, delivering both emissions reductions and energy-efficiency gains. Field demonstrations and technology consortia have further accelerated adoption by reducing operational risks. Overall, Canada's experience illustrates how coordinated policy, technological innovation, and practical field implementation can achieve large-scale methane reductions while improving operational efficiency and supporting long-term environmental objectives.

Mr Fogwill explained that Canada's efforts to reduce methane emissions from upstream oil and gas operations began in the early 2000s, when the climate impacts of methane and the relatively low cost of abatement became widely recognized. Early work focused on detailed field measurements of emissions from pneumatic controllers, compressor vents, storage tanks, and fugitive leaks. These efforts produced the first consistent datasets, enabling regulators and operators to better understand emission sources and identify practical mitigation options. The studies demonstrated that a relatively small number of equipment types accounted for a disproportionate share of emissions, providing a strong analytical foundation for subsequent policy development and technology deployment. As provinces such as Alberta, British Columbia, and Saskatchewan began developing methane-related guidance around 2006–2007, they accumulated substantial experience with monitoring methods and best practices in advance of federal regulation. This early work also highlighted the economic benefits of reducing leaks and venting through improved energy efficiency and the retention of saleable gas, reinforcing the understanding among operators that methane mitigation could be aligned with production efficiency and operational reliability.

Mr Fogwill further explained that a major policy milestone was reached in 2016, when Canada committed to reducing methane emissions from the oil and gas sector by 40–45% relative to 2014 levels. While implementation efforts slowed in some other jurisdictions, Canada proceeded with domestic action. Federal regulations under the Canadian Environmental Protection Act entered into force in 2020, establishing performance standards for venting, flaring, LDAR programs, and the operation of key equipment such as compressors and pneumatic devices. Equivalency agreements allow provinces to implement their own regulatory approaches, provided they achieve comparable emissions reductions, thereby enabling region-specific solutions while maintaining consistency at the federal level. British Columbia has committed to a 75% reduction target by 2030, while Alberta and Saskatchewan have aligned with a 45% reduction pathway. Provinces with limited oil and gas activity focus primarily on methane emissions from landfills. This multi-level regulatory framework has supported coordinated and effective implementation across diverse operating environments.

Mr Fogwill noted that Canada no longer develops standalone dry-gas fields, as gas production is now largely associated with liquids production. This characteristic allows mitigation technologies to be applied across integrated oil and gas systems. Studies have consistently identified key sources of emissions, including high-bleed pneumatic devices, reciprocating compressors and stationary engines, storage tanks without adequate vapor control, and gas releases during well completion and decommissioning. To address these sources, Canada has transitioned from site-level emission factors to equipment-level quantification, enabling more accurate reporting and more targeted mitigation strategies. A layered monitoring approach has emerged, in which on-site sensors and handheld instruments support routine LDAR activities, vehicle-mounted and airborne systems are used to survey large areas and identify super-emitters, and satellite observations provide independent verification of regional trends. While satellite data enhance transparency and public accountability, Mr Fogwill emphasized that they cannot replace high-resolution field measurements for the design and validation of mitigation solutions.

Mr Fogwill explained that mitigation technologies have evolved rapidly in response to these insights. LDAR remains the most cost-effective mitigation measure, particularly when implemented through structured maintenance programs and timely repair protocols. Several operators in western Canada have reported that gas recovered through LDAR programs and minor equipment improvements has allowed them to recover their investments within a year. Pneumatic devices have increasingly shifted from high-bleed designs to low-bleed and no-bleed alternatives, including electric actuators and systems powered by compressed air or nitrogen. New production facilities are now commonly designed around these technologies, eliminating continuous venting and improving operational reliability. Storage tanks, which historically posed challenges due to inadequate vapor handling, are being retrofitted with vapor recovery units, improved seals, and updated operating procedures, resulting in significant reductions in episodic emissions. For reciprocating compressors and stationary engines, field studies in Alberta and other provinces have quantified real-world methane slip and identified opportunities for improved tuning, maintenance, and component upgrades. Pilot projects testing high-temperature oxidation devices have demonstrated their potential to destroy unburned methane and volatile organic compounds in exhaust streams, contributing to emissions reductions and improved combustion efficiency.

Mr Fogwill also highlighted well decommissioning as a major long-term challenge, noting that more than 500,000 wells are expected to be retired in Canada. Many older wells exhibit surface casing vent flows, requiring remedial interventions to restore long-term integrity. Current research efforts focus on alternatives to carbon-intensive Class G cement, including new Portland-cement blends and innovative barrier materials that can enhance sealing performance and reduce the need for repeated remediation. International collaboration, particularly with Australia, is accelerating the testing and deployment of these solutions. Mr Fogwill emphasized the role of organizations such as Petroleum Technology Alliance Canada (PTAC) and the Canadian Emissions Reduction Innovation Consortium in reducing risks for operators by supporting field demonstrations and transparent evaluation of technologies under real operating conditions. These initiatives have documented a wide range of mitigation technologies

applicable to upstream operations, providing operators with clear guidance on technology readiness and suitability.

In concluding, Mr Fogwill emphasized that Canada's experience offers several lessons for APEC economies. Clear and stable regulatory frameworks are essential for driving sustained investment and operational change. Many effective mitigation options—such as LDAR, pneumatic device replacement, and vapor recovery—are low-cost or cost-negative when avoided gas losses are taken into account, making them well suited for large-scale deployment. Coordinated action among federal and provincial governments, regulators, and industry stakeholders helps build confidence and maintain long-term commitment. Finally, an active innovation ecosystem that integrates research, field trials, transparent measurement, and international cooperation can support continuous improvement in methane mitigation and energy efficiency across the oil and gas sector.

b) Upstream Greenhouse Gas Reduction in Malaysia (Introducing BIGST Project)

Mr Yoshihiko Enokido, Head, COO Office, Business Division 1, ENEOS Explora Inc., Japan

Summary

Mr Yoshihiko Enokido presented on the BIGST Project as well as its technical, economic, and environmental implications. The BIGST Project aims to develop five high-CO₂ gas fields offshore Peninsular Malaysia by combining upstream gas production with integrated CCS. The project responds to Malaysia's rising gas demand and declining local production, providing up to 30% of Peninsular Malaysia's supply between 2029 and 2050. Because CO₂ concentrations range from 3 to 70%, advanced separation technologies and new CCS solutions are essential to ensure both economic viability and emissions reduction. BIGST incorporates CO₂ capture at the production platform, dedicated CO₂ transport pipelines and injection at a nearby geological structure, helping minimize Scope 1 and 2 emissions. The project highlights the importance of energy-efficiency measures, including optimized gas processing and reduced flaring or venting through improved system design. It also illustrates challenges such as complex geology, high development costs and uncertainties around long-term CCS performance. As a joint initiative between PETRONAS Carigali and ENEOS Explora, the BIGST Project demonstrates a practical pathway for monetizing high-CO₂ resources while supporting Malaysia's National Energy Transition Roadmap and contributing to regional greenhouse gas reductions.

Mr Enokido began by outlining the context for upstream greenhouse gas reduction in Malaysia and the strategic importance of the BIGST Project. The five gas fields—Bujang, Inas, Guling, Sepat and Tujoh—are located approximately 180 kilometers offshore Peninsular Malaysia. These fields contain exceptionally high CO₂ concentrations, ranging from 3 to as much as 70%, presenting a major technical challenge. Historically, such fields were considered uneconomical or environmentally unacceptable due to the need to separate and dispose of large CO₂ volumes. However, advances in separation technology and the maturation of CCS options have created a feasible development pathway.

The project concept involves producing natural gas at an offshore platform, transporting the sales gas to Peninsular Malaysia, and capturing CO₂ for injection at a dedicated offshore storage site. This integrated approach enables the project to expand domestic energy supply while reducing greenhouse gas emissions. According to Mr Enokido, Malaysia's gas demand has increased steadily, while production from existing fields has declined. Without new developments, demand is projected to exceed supply, increasing reliance on imports. BIGST therefore offers a significant contribution to domestic energy security and energy efficiency, as producing local gas reduces the lifecycle emissions and energy losses associated with long-distance Liquefied Natural Gas (LNG) transport.

Mr Enokido explained that the project could supply up to 30% of Peninsular Malaysia's domestic gas supply between 2029 and 2050. The ability to monetize high-CO₂ resources also opens opportunities for other similar fields in the region. CCS plays a central role in this value proposition. By installing CO₂ capture equipment at the production platform and constructing an additional injection platform, the project can significantly reduce Scope 1 and 2 emissions. These efficiency gains align with Malaysia's National Energy Transition Roadmap, which plans an increase of gas in primary energy mix and targets a 32% reduction in Malaysia's emissions relative to 2019 levels.

Technical challenges remain substantial. Mr Enokido highlighted three main risks: geological complexity, extremely high CO₂ content and CCS performance uncertainty. The geological structure requires detailed subsurface analysis to confirm injectivity and long-term containment. High CO₂ concentrations demand advanced materials and process designs that resist corrosion and maintain compression efficiency. CCS uncertainty concerns long-term monitoring requirements, injection pressure management and regulatory approvals. Each of these factors influences the project's capital and operating costs, and engineering studies are ongoing to refine the concept.

The project partners, PETRONAS Carigali and ENEOS Explora, are also designing a optimum Measurement, Monitoring, and Verification (MMV) plan to support reliable CCS performance. Continuous pressure and temperature monitoring of the reservoir, fiber-optic sensing and periodic seismic surveys may be deployed to verify that CO₂ remains safely contained. These methods are aligned with international CCS best practices and contribute to reducing long-term uncertainty. Mr Enokido also noted that because the project is still in the study phase, specific numerical estimates cannot yet be disclosed, but engineering teams are working to refine the technical and economic models.

Mr Enokido concluded by noting that BIGST demonstrates a pathway for resource-rich economies to reduce greenhouse gas emissions while sustaining upstream development. By applying CCS, improving processing efficiency and managing fugitive emissions, high-CO₂ gas fields can become viable contributors to domestic supply. He stressed that the combination of technological progress, strong partnership between operators and supportive policy frameworks will be crucial for realizing BIGST and similar projects across the region.

c) Efforts to Reduce GHG Emissions in Ichthys LNG Project

Mr Shinya Konno, General Manager, Oceania Projects Division, Oceania Projects Unit, INPEX Corporation, Japan

Summary

Mr Konno delivered a presentation on the Ichthys LNG Project, describing INPEX integrated approach to reducing greenhouse gas emissions. The Ichthys LNG Project, operated by INPEX, is implementing a portfolio of measures to reduce greenhouse gas emissions across its offshore and onshore assets while maintaining stable LNG supply. The project's GHG profile is dominated by reservoir CO₂, fuel gas use in power generation and compression, and fugitive methane emissions. Operational initiatives include Advanced Process Control to optimize LNG train efficiency, reductions in flaring and venting, improved compressor availability and tuning of fuel gas systems to lower specific energy consumption. A structured methane-management program combines LDAR using optical gas imaging, drone-based surveys for hard-to-access areas and progressive alignment with Oil and Gas Methane Partnership 2.0 (OGMP 2.0) reporting requirements. INPEX is also assessing options to import renewable electricity from large-scale solar and battery systems to displace gas-fired power at the onshore plant. Looking further ahead, the Bonaparte CCS Project aims to provide large-scale CO₂ storage for Ichthys and other regional sources, creating a potential hub for long-term decarbonization. Together, these measures

illustrate how a large LNG project can integrate energy-efficiency improvements, methane abatement, low-carbon power and CCS into a coherent pathway for reducing GHG emissions.

Mr Konno began by introducing the Ichthys LNG Project as one of the largest resource developments operated by INPEX, linking offshore gas and condensate reserves off the northwest coast of Australia with an onshore liquefaction plant in Darwin. The value chain comprises subsea wells, a Central Processing Facility for gas treatment, a floating production, storage and offloading (FPSO) for condensate stabilization and storage, and a long subsea pipeline delivering feed gas to the onshore LNG plant. This integrated system allows Ichthys to supply LNG, LPG and condensate to global markets, but it also creates a diverse set of greenhouse gas emission sources. These include CO₂ contained in the reservoir gas, combustion-related CO₂ from turbines and other fuel gas users, and methane emissions arising from leaks, vents and equipment upsets across offshore and onshore facilities.

Against this background, INPEX has set long-term climate goals and identified Ichthys as a key platform for operational decarbonization. Mr Konno explained that the project's strategy focuses first on improving energy efficiency and reducing routine emissions before turning to larger capital-intensive projects such as CCS. Fuel gas consumption at the LNG plant and offshore facilities is a major driver of Scope 1 emissions, so the project team has introduced Advanced Process Control on critical units to keep operation as close as possible to optimal conditions. By stabilizing temperatures, pressures and flow rates, advanced process control (APC) reduces energy losses associated with process variability, improves LNG train throughput per unit of fuel and minimizes the frequency of flaring during start-up and turndown events.

Mr Konno highlighted several examples of how these control and optimization measures translate into emissions reductions. On the onshore plant, improved coordination between gas turbines, compressors and refrigeration systems has reduced the specific energy consumption per ton of LNG produced. Offshore, fine-tuning compression systems and improving off-gas recovery has lowered continuous flaring rates. In addition, reliability upgrades that increase compressor availability help avoid process upsets and unplanned shutdowns, which can otherwise lead to large flaring events when systems are restarted. Each of these steps contributes incrementally to lowering both CO₂ emissions from fuel gas and methane slip from combustion equipment.

A second major pillar of the Ichthys program is methane management. Mr Konno noted that while methane volumes are smaller than CO₂ in absolute terms, their high global warming potential means that even modest reductions can have a significant climate impact. The project has therefore rolled out a structured LDAR program across offshore platforms and the onshore plant. Trained technicians use optical gas imaging cameras to scan valves, flanges and other potential leak points on a regular schedule, logging and repairing leaks according to defined thresholds. To complement these ground-based surveys, Ichthys has also trialed drone-based methane measurements, which are particularly useful for inspecting elevated structures, confined racks and offshore topsides where access is challenging. These campaigns help identify so-called super-emitters and provide data for refining emission factors.

In parallel, INPEX is working towards alignment with the OGMP 2.0 framework, which encourages operators to replace generic emission factors with source-level measurements and transparent reporting. Mr Konno explained that this approach not only improves the accuracy of emission inventories but also supports better prioritization of mitigation actions. For example, if measurements show that a small number of components are responsible for a large share of emissions, maintenance schedules and retrofit plans can be adjusted accordingly. Over time, this data-driven method is expected to reduce both routine fugitive emissions and the risk of unexpected releases.

The project is also exploring the introduction of low-carbon power to the onshore LNG plant. Because liquefaction and associated utilities require substantial electricity, much of which is currently generated from gas turbines, INPEX is studying the feasibility of connecting large-scale solar photovoltaic facilities combined with battery storage. Mr Konno described a concept in which a dedicated

transmission line could bring renewable power to the plant, reducing the need to burn fuel gas for electricity and freeing that gas for higher-value uses. This option becomes even more important when considering future CCS deployment, since CO₂ capture and compression will increase power demand unless offset by efficiency gains or external renewable supply.

Looking further ahead, the Bonaparte CCS Project is expected to form a central component of the Ichthys decarbonization pathway. Mr Konno outlined the ongoing technical studies, including seismic surveys, appraisal wells and reservoir modelling for offshore formations located roughly 200 kilometers from Darwin. The objective is to confirm that these formations can safely and efficiently store large volumes of CO₂ over many decades, creating a storage hub that could serve Ichthys and potentially other industrial sources in northern Australia. Key issues under evaluation include injectivity, pressure management, long-term containment and monitoring plans that meet regulatory and stakeholder expectations.

Mr Konno stressed that major projects such as Ichthys LNG can only achieve sustained GHG reductions if large-scale initiatives are combined with continuous efforts in day-to-day operations. INPEX promotes a working culture in which site personnel are encouraged to propose ideas for fuel savings, process optimization and leak prevention. Such bottom-up initiatives, aligned with corporate climate targets and supported by appropriate tools and training, help ensure that energy-efficiency improvements and emission reductions are embedded in routine decision-making. He concluded that the Ichthys LNG Project provides a practical example of how an LNG value chain can integrate operational efficiency, methane abatement, renewable energy options and future CCS into a single, coherent strategy for reducing greenhouse gas emissions while maintaining secure and reliable energy supply.

d) Discussion and Q&A

Key Points of Discussion

- Clear policy targets backed by regulation, financial incentives and a cooperative ecosystem were essential for Canada's success in reducing methane emissions while maintaining a competitive oil and gas sector.
- High-CO₂ gas field development with integrated CCS in Malaysia can be economically competitive in comparison with LNG imports, but requires supportive regulation, emerging carbon pricing and careful design of multi-user storage hubs.
- Methane management in upstream operations relies on practical solutions such as LDAR, drone-based surveys, data-driven prioritization and, where possible, productive use of captured gas instead of routine flaring.
- Large LNG projects are exploring renewable power imports and, in some cases, battery storage to complement gas-fired power and future CCS operations, although economic and operational feasibility are still under active study.
- Well decommissioning, carbon dioxide-enhanced oil recovery (CO₂-EOR) economics and long-term CCS performance remain technically and financially challenging, highlighting the importance of incentives, robust monitoring and international cooperation.

Questions and Answers

QUESTION: Mr Rodrigo Martinez to Mr Allan Fogwill

Several technological solutions for methane reduction in Canada appear already applicable and cost-effective. Why has Canada succeeded in implementing these measures while other oil and gas producers seem to be lagging behind?

ANSWER: Mr Allan Fogwill

The key factor was not that Canada is inherently more capable but that it had a clear target accompanied by supporting measures. When the federal government announced methane reduction objectives, it also introduced regulations and funding mechanisms. Over about twenty years, a broader ecosystem developed combining policy, regulation, public finance and industry action. Canada moved early, but economies such as Japan or Indonesia could achieve similar results over time.

QUESTION: Mr Rodrigo Martinez to Mr Allan Fogwill

Did the Canadian oil and gas industry fully support these methane reduction policies from the beginning? A common concern in the sector is that stringent methane regulations or new taxes might undermine competitiveness and, by extension, energy security.

ANSWER: Mr Allan Fogwill

Industry prioritizes competitiveness. Canada's relatively low production costs allowed companies to allocate cash flow to emissions reduction. The government also provided tax credits, incentives and capital cost-sharing arrangements. Effective policy requires matching ambition with resources; if non-economic requirements rely solely on industry financing, the sector may suffer. Canadian royalty systems mean governments depend on a healthy oil and gas industry, so policy makers balanced environmental goals with economic viability and reliability. Recent international events had reinforced the view that oil and gas will continue to play a significant role up to 2050, and that the priority should be to make the existing industry part of the solution rather than to attempt to phase it out entirely.

QUESTION: Mr Rodrigo Martinez to Mr Yoshihiko Enokido

In high-CO₂ gas field development in Malaysia, CO₂ is typically separated and vented because it is cheapest. Without disclosing specific cost figures, is an integrated gas-plus-CCS development in Malaysia still economically competitive compared to importing LNG?

ANSWER: Mr Yoshihiko Enokido

High-CO₂ gas fields involve higher costs, but the relevant comparison is domestic development with CCS versus LNG imports. The project's assessments indicate that developing gas with CO₂ capture and storage remains cheaper than importing LNG.

QUESTION: Mr Rodrigo Martinez to Mr Yoshihiko Enokido

Is the primary driver for CO₂ capture in Malaysia regulatory requirements linked to Malaysia's climate targets?

ANSWER: Mr Yoshihiko Enokido

Malaysia has GHG reduction targets, and the project must align with those policies and regulations. The decision to capture CO₂ is aligned with Malaysian policies and regulations aimed at lowering emissions.

QUESTION: Mr Rodrigo Martinez to Mr Shinya Konno

Ichthys LNG Project's technology roadmap considers integration of renewable energy. Are there existing examples of renewable power being integrated into liquefaction, and how can variability from solar or wind be managed given the need for stable energy supply?

ANSWER: Mr Shinya Konno

Ichthys is considering importing renewable power generated outside the project area. Large-scale solar developments are being assessed, and imported renewable electricity may meet future demand including potential CCS operations. Initial imports would be limited and expanded if successful.

QUESTION: Ms Nurnadia Nabillah PG HJ Saiful Rizal to Mr Yoshihiko Enokido

Does the BIGST Project operate under a carbon pricing framework, and can the CO₂ injection platform accept CO₂ from other industries beyond the associated gas production facilities?

ANSWER: Mr Yoshihiko Enokido

Malaysia is expected to introduce carbon pricing, though it is not yet formalized. Gas producers will likely face carbon pricing in the future. BIGST currently focuses on storing CO₂ from the project itself. Malaysia is also developing a broader CCS strategy that includes the establishment of three CCS hubs. If the selected storage site proves sufficiently large, Malaysia would consider utilizing it to store CO₂ from other regions and industries. Japan and Malaysia are currently discussing CCS cooperation, and governmental dialogue on this topic is ongoing.

QUESTION: Dr Kazutomo Irie to Mr Allan Fogwill

As oil and gas are often produced together, and even within gas production there is a distinction between dry gas and wet gas with condensate. Across the spectrum from pure liquid hydrocarbons to pure gaseous hydrocarbons, are there differences in the difficulty of controlling methane emissions?

ANSWER: Mr Allan Fogwill

Natural gas production usually has gathering systems allowing use of captured methane. Many oil operations lack such infrastructure, so associated gas is often flared.

Forthcoming Canadian regulations aimed at achieving a 75% reduction in methane emissions are expected to require operators to make productive use of captured gas—for example, generating heat or producing synthetic liquid fuels—rather than simply flaring it without utilizing its energy content.

Canada no longer produces dry gas on a significant scale because it is not economically attractive. Current gas production is driven largely by the value of natural gas liquids and condensate, which are needed as diluents for transporting heavy oil from the oil sands by pipeline.

QUESTION: Dr Kazutomo Irie to Mr Allan Fogwill

Does Canada face similar challenges managing emissions from oil sands production, particularly flaring and methane control?

ANSWER: Mr Allan Fogwill

Canada has two main oil sands methods. Surface mining is capital-intensive and no new mines are expected. Steam-assisted gravity drainage, which is the dominant production method, does not necessarily generate large amounts of methane, although it does result in substantial CO₂ emissions due to the steam requirements. Both conventional oil and oil sands share issues such as surface-casing vent flows, which must be addressed during operations and at decommissioning.

QUESTION: Mr Phung Quoc Huy to Mr Yoshihiko Enokido

For CO₂-EOR projects, can additional oil revenue offset CO₂ storage costs?

ANSWER: Mr Yoshihiko Enokido

In this CO₂-EOR project, CO₂ is sourced from a nearby coal-fired power plant. Following injection, oil production increased by a factor of approximately 30–40 compared to pre-injection levels; however, overall profitability remains challenging. Incentives in the United States, such as Section 45Q, play an important role in supporting the economic viability of similar projects.

QUESTION: Mr Allan Fogwill to Mr Shinya Konno

Battery energy storage systems for managing renewable variability are expensive. What is the economic rationale for considering batteries at Ichthys?

ANSWER: Mr Shinya Konno

INPEX is evaluating multiple options to reduce GHG emissions at Ichthys. Renewable power import is in an early study stage, and battery storage is still being assessed for economic and operational feasibility.

3-1-4. Session 3: Oil Industry

Session Moderator : **Mr Nabih Matussin**, Senior Researcher, APERC

a) Refinery Production Efficiency, Challenges and Off-Gas Emissions in the APEC Region

Mr Kevin Henke, Senior Advisor, HSB Solomon Associates LLC, the United States

Summary

Mr Kevin Henke presented insights from Solomon Associates' global refinery benchmarking, which covers over 85% of global capacity. He emphasized that off-gas emissions cannot be sustainability addressed as an isolated environmental issue. Off-gas emissions controls must be integrated into the core business objectives of refineries, particularly net cash margin, return on investment, and long-term survivability. He noted that leading refineries achieve lower emissions and higher efficiency through strong asset management, reliability, and continuous benchmarking.

Reducing total energy demand, rather than pursuing efficiency in isolation, delivers the greatest impact on emissions. Benchmarking data showed that refinery age is not a key factor—older plants often outperform newer ones when maintenance and reliability are prioritized. Major inefficiencies stem from oversized steam systems, waste heat losses, and unplanned shutdowns, which elevate flaring and off-gas emissions. Amid declining margins, uncertain fuel demand, and rising costs, Mr Henke underscored the need for policies aligned with operational realities, supporting electrification, risk-based inspection, and data-driven management to ensure refineries enhance efficiency, cut emissions, and sustain competitiveness during the energy transition.

Mr Henke opened his presentation by emphasizing that refinery success is fundamentally measured by financial performance, particularly net cash margin and return on investment. Off-gas emissions, he argued, must not be treated as a standalone environmental issue. Off-gas emissions reductions need to be embedded within normal refinery operations. Leading refineries integrate emissions reduction into day-to-day decision-making rather than managing it through separate task forces.

He highlighted the importance of a strong operational foundation, including asset lifecycle management, planning, and optimization. Without high reliability as a priority, sustainable energy efficiency and emissions reduction are not achievable. Mr Henke stressed that reducing overall energy demand is more impactful than incremental efficiency gains, as demand reduction inherently lowers emissions and simplifies process operations.

Drawing on Solomon Associates' global benchmarking database, which covers over 85% of global refining capacity, he explained the company's role in identifying best-performing refineries and translating their practices into actionable insights. Solomon conducts biannual global benchmarking studies, enabling refiners to "benchmark, copy, and catch up" rather than reinventing solutions.

Addressing refinery survivability, Mr Henke presented distribution curves of break-even production costs, noting that around 90% of costs are driven by crude oil feedstock, while operating expenses account for much of the remainder. Refineries in APEC economies generally show lower break-even costs than the global average, yet significant variability remains. High-cost refineries face closure risks, and refinery rationalization is already occurring in several economies.

Reliability was identified as a decisive factor for both energy efficiency and emissions performance. Using data on crude distillation units, Mr Henke demonstrated that refinery age does not determine reliability. Some units over 100 years old operate with minimal shutdown days, while newer units may suffer frequent downtime. Unplanned shutdowns and startups increase flaring, energy losses, and safety

risks. High performers maintain reliability through disciplined maintenance, clear targets, and a continuous improvement culture.

Waste heat rejection was presented as another major inefficiency indicator. Mr Henke compared cooling tower plumes to flares, noting that both visibly represent wasted energy. Oversized steam systems were identified as a primary driver of inefficiency, accounting for roughly 50% of excess energy use. Leading refineries reduce steam system size. One technique mentioned is to directly integrate gas turbines with process heaters, and avoid unnecessary heat recovery steam generation.

He further highlighted resource inefficiency, noting that approximately 19% of crude processed in APEC refineries leaves as low-value products priced below crude input cost. Measuring and managing this loss is essential, as performance improves once waste is quantified and reduced.

Mr Henke observed that more than half of global refining capacity has not improved energy efficiency since 2018, with APEC economies performing slightly below the global average. Initiative overload, risk aversion, and narrow project justification were cited as key barriers. In contrast, leaders adopt a future-state vision and holistic economic evaluation.

He concluded by discussing policy implications, emphasizing electrification to reduce steam dependency and emissions, and warning that rigid inspection regulations may unintentionally increase flaring by forcing unnecessary shutdowns. Aligning policy frameworks with operational realities and technological progress is essential to support refinery competitiveness while advancing emissions reduction goals.

b) Intelligent Transformation in the Petrochemical Industry: Insights and Practice

Dr Jiahang Han, Director of AI Key lab, Research and Development Center, Petro-CyberWorks Information Technology Co., Ltd. (PCICT), China

Summary

Dr Jiahang Han presented on intelligent transformation at China Petroleum & Chemical Corporation (SINOPEC), emphasizing how digitalization and artificial intelligence (AI) can enhance efficiency, safety and emissions management across the petrochemical value chain. Confronting pressures from energy transition, decarbonization goals and stricter safety rules, SINOPEC treats intelligent transformation as central to high-quality growth. Its framework rests on three pillars—enterprise-wide management, end-to-end operational optimization and advanced manufacturing integrating AI, data and first-principles models. The company has evolved from rule-based systems to deep learning and generative AI, enabling real-time, data-driven decision-making. Applications include intelligent diagnostics for oil wells, predictive maintenance of compressors and furnaces, and real-time optimization of refining and polymer production. Robotics, drones, fifth-generation (5G) mobile communication systems, and Internet of Things (IoT) further strengthen safety, inspection and leak detection. These technologies have yielded measurable benefits—higher control precision, lower energy use, greater yields of high-value products and fewer process alarms. Dr Han concluded that combining AI with scientific principles builds trust in intelligent systems and ensures lasting gains in operational efficiency, emissions reduction and resilience.

Dr Han stated that the petrochemical industry is at a critical crossroads, facing increasing pressure from the global energy transition, rapid electrification, decarbonization targets, and stricter safety requirements. In response, SINOPEC has initiated a comprehensive intelligent transformation to move from traditional manufacturing toward more efficient, data-driven, and resilient operations. The

objective is not merely to increase output, but to improve operational quality, energy efficiency, safety, and emissions performance.

He introduced SINOPEC as a fully integrated energy and chemical enterprise operating across the entire value chain, from oil and gas exploration to refining, chemicals, and marketing. With operations spanning more than 70 economies and regions, SINOPEC requires holistic management and advanced optimization to sustain competitiveness. Intelligent transformation was therefore positioned as a strategic necessity for high-quality development rather than a standalone digital initiative.

Dr Han outlined three strategic pillars guiding this transformation. The first is strengthened enterprise-wide management, providing integrated visibility and risk control across diverse assets. The second is end-to-end operational optimization to narrow performance gaps with global industry leaders. The third is advanced manufacturing, driven by sustained investment in research and development and the deep integration of artificial intelligence, data, and first-principles models.

He described SINOPEC's evolution in AI application, from early expert systems to deep learning, large language models, and generative AI. This evolution is structured through the "33X AI project", integrating computing power, data, and models with supporting systems for security, standards, and operations. These capabilities are deployed across multiple business scenarios. Within five months of launch, the AI platform supported over 150,000 users and more than 60 active application modules.

At the operational level, Dr Han introduced the "petrochemical smart brain," a centralized intelligent operation platform integrating data from oil fields, and refining and chemical plants. This system has shifted operations from experience-based judgment to data-driven decision-making, from static planning to real-time scheduling, and from isolated optimization to group-wide coordination.

Specific applications were presented across the value chain. In upstream operations, intelligent diagnostic systems based on neural networks analyze surface, wellbore, and formation data to provide real-time alerts for well leaks and equipment failures. In refining and petrochemical plants, predictive maintenance systems combine first-principles models with field data to forecast equipment faults and monitor cracking furnace conditions, reducing unplanned shutdowns and emissions.

Dr Han highlighted real-time optimization technologies, including proprietary Real-Time Optimization (RTO) software, which optimize feed allocation and product yields in real time, and advanced non-linear control technologies that stabilize operations during product grade transitions. Reported outcomes included improved control precision, reduced specific energy consumption, lower alarm frequency, and increased yields of high-value products.

He also emphasized intelligent inspection and safety management through robots, drones, 5G, and Internet of Things technologies. These systems enable early detection of gas leaks, enhance personnel safety, and reduce fugitive emissions. Intelligent water management systems further support sustainability by reducing freshwater use and minimizing leakage.

Dr Han concluded that building trust in AI remains a key challenge. SINOPEC addresses this by integrating AI with first-principles models and strengthening training, ensuring that intelligent transformation delivers reliable and scalable improvements in efficiency, safety, and emissions reduction.

c) Energy Saving Improvements and Fuel Gas Flaring Reduction in Dung Quat Refinery

Mr Le Hai Tuan, General Manager, Production Division, Binh Son Refining and Petrochemical JSC (BSR), Viet Nam

Summary

Mr Le Hai Tuan outlined the long-term strategy of Binh Son Refining and Petrochemicals (BSR) to enhance energy efficiency and minimize gas flaring at the Dung Quat Refinery, Viet Nam's first refinery. Operating since 2010, the plant has maintained high reliability and over 55 million safe working hours while progressively reducing its Energy Intensity Index by 17.2% and cutting fuel oil use by two-thirds. In line with Viet Nam's 2050 net-zero goal, BSR is pursuing phased actions through 2045—short-term optimization and high-value projects, medium-term capacity and product upgrades including biofuels, and longer-term expansion into petrochemicals, hydrogen, and CCUS. Supported by the ISO 50001 (International Organization for Standardization) energy-management system, the refinery's technical initiatives—such as steam and power optimization, boiler and fuel-gas improvements, and advanced process control—have reduced flaring to 0.05% of crude intake and lowered CO₂ emissions. Mr Tuan stressed that continued innovation, disciplined energy management, and international cooperation will be crucial to achieve zero flaring by 2030 and net-zero operations by 2050.

Mr Tuan presented the experience of BSR in improving energy efficiency and reducing fuel gas flaring at the Dung Quat Refinery, Viet Nam's first oil refinery. He began by introducing the facility, which has been in continuous operation since 2010 with a design capacity of approximately 148,000 barrels per day. Since start-up, the refinery has processed more than 115 million metric tons of crude oil, successfully completed five turnarounds, and accumulated over 55 million safe working hours, demonstrating high operational reliability.

Mr Tuan explained that under increasing pressure from the global energy transition and decarbonization trends, BSR has established a comprehensive development strategy toward 2030 and a long-term vision to 2045. In the short term, the company focuses on refinery operation optimization and high-value investment projects. In the medium term, plans include capacity expansion, product upgrading, and the production of biofuels such as ethanol, sustainable aviation fuel, biodiesel, and low-carbon marine fuels. In the long term, BSR aims to expand into petrochemicals, hydrogen production, and carbon capture, utilization and storage, while strengthening related services and partnerships.

He noted that Viet Nam's commitment to achieving net zero emissions by 2050, announced at COP26, presents significant challenges for the refining sector. To address this, BSR developed a greenhouse gas reduction roadmap with multiple scenarios ranging from partial to full decarbonization. Five key measures were identified: energy efficiency improvement, deployment of renewable energy, CCUS, afforestation, and the use of carbon credits, with investment requirements varying significantly across scenarios.

Mr Tuan highlighted concrete achievements at the Dung Quat Refinery over 15 years of operation. The refinery reduced its Energy Intensity Index (EII) by 17.2% between 2014 and 2025, generating annual cost savings of approximately USD 45–60 million. Internal energy consumption was reduced, through a transition from Fuel Oil (FO) to cleaner Fuel Gas (FG) and LPG, with FO consumption declining from approximately 150,000 to 50,000 metric tons per year. Hydrocarbon flaring was also significantly reduced, with current off-gas flaring accounting for only about 0.05% of crude oil intake. Consequently, annual CO₂ emissions decreased from roughly 1.55 million metric tons to about 1.4 million metric tons, equivalent to 100% of the Refinery's design capacity.

These improvements were supported by the implementation of an ISO 50001 energy management system, overseen by a dedicated Energy Management Committee. Core principles include maximizing heat integration, optimizing steam and power networks, maintaining equipment at optimal operating conditions, applying advanced process control and digital tools, and promoting internal innovation.

Mr Tuan described several technical measures to reduce energy use and flaring. These included optimizing utility systems to shut down unnecessary compressors and pumps, converting boiler fans

from steam turbines to electric motors, and changing boiler operating modes to increase fuel gas utilization. BSR also implemented dual-firing boiler operation and improved fuel gas pressure control logic, which eliminated routine venting and further reduced flaring and sour gas emissions.

He concluded that the Dung Quat Refinery has achieved substantial improvements in energy efficiency and emissions reduction, with clear targets to achieve zero routine flaring by 2030 and net zero emissions by 2050. Mr Tuan emphasized that strong energy management systems, technical innovation, and international cooperation are essential to support deep decarbonization in the refining sector.

d) Discussion and Q&A

Key Points of Discussion

- Sustained refinery performance and low shutdown days are driven primarily by disciplined reliability management rather than equipment age.
- Clear performance targets, continuous equipment monitoring, and a strong reliability-focused culture help reduce unplanned shutdowns, energy losses, and off-gas emissions associated with frequent startups and shutdowns.
- Limited trust in data-driven AI among engineers remains a key challenge; integration with physical models and training can help address this.
- In the context of declining transportation fuel demand, market saturation is a key constraint for refineries seeking to shift toward petrochemical production.
- Competitive refineries with low operating costs and high reliability are better positioned to capture value during supply disruptions or unexpected geopolitical events.

Questions and Answers

QUESTION: Mr Allan Fogwill to Mr Le Hai Tuan

Is the boiler optimization at your refinery operated under static control settings, or does it require continuous dynamic adjustment during daily operations?

ANSWER: Mr Le Hai Tuan

The boiler optimization is operated under a single control setting during normal operations, following in-house modifications to the control logic, which involved complex adjustments and automation.

QUESTION: Mr Nabih Matussin to Mr Kevin Henke

What are the main drivers that allow crude distillation units to maintain very low shutdown days, even after many years of operation?

ANSWER: Mr Kevin Henke

The key driver is disciplined reliability management rather than equipment age. When clear performance targets are set, equipment condition is continuously monitored, and a strong reliability-focused culture is maintained, units can operate reliably for long periods. In contrast, cost-cutting approaches that undermine maintenance often lead to increased unplanned downtime, higher energy losses, and greater off-gas emissions due to frequent startups and shutdowns.

QUESTION: Mr Nabih Matussin to Dr Jiahang Han

What is the biggest challenge in implementing large-scale digital and intelligent infrastructure in refineries and petrochemical complexes?

ANSWER: Dr Jiahang Han

The biggest challenge is trust in artificial intelligence. Many engineers prefer equation-based and first-principles approaches, whereas AI applications are purely data-driven and are therefore often viewed as black boxes. We address this issue by integrating AI applications with physical and chemical models and by strengthening training and capacity building, allowing engineers to better understand and accept AI-supported decision-making.

QUESTION: Mr Rodrigo Martinez to Mr Kevin Henke

What is the main challenge for refineries in a future with declining demand for transportation fuels, particularly when shifting toward higher-value petrochemicals?

ANSWER: Mr Kevin Henke

The main challenge is market saturation. The petrochemical market is already oversupplied, so the question is not only refinery reconfiguration or capital expenditure, but where the additional products can actually be sold.

QUESTION: Mr Rodrigo Martinez to Mr Kevin Henke

Given expected refinery rationalization and declining capacity, could reduced supply increase the value of refining services and improve margins for remaining facilities, rather than leading to an overall decline of the sector?

ANSWER: Mr Kevin Henke

Competitiveness is defined by low operating expenses and low break-even costs. Reliable and competitive refineries are best positioned to benefit from market disruptions or supply shortages. Refineries able to maintain stable operations during unexpected geopolitical or supply events can capture significant economic value.

QUESTION: Mr Rodrigo Martinez to Mr Kevin Henke

Petróleos Mexicanos (PEMEX) acquired the Deer Park refinery in 2021. Although the acquisition initially raised concerns, the subsequent Russia–Ukraine crisis and elevated refined product prices enabled a rapid recovery of the investment. How do you view this case in terms of the strategic value of maintaining refinery operations?

ANSWER: Mr Kevin Henke

The Deer Park case illustrates the value of keeping refineries operational, as unexpected market disruptions can create short-term opportunities. If the refinery had been offline for maintenance, this opportunity would have been missed.

3-2. Day 2

3-2-1. Discussion

In the discussion session, the background research report prepared by APERC was used as the primary reference document, and the session framework was intended to confirm the completeness and relevance of the technical topics covered in the report.

Based on the document including the table of discussion points provided to participants, the discussion covered the relevant technologies and practices, organized by their expected impact on energy efficiency and on reducing fugitive emissions or spills, as applicable to each industry.

This session was structured as follows:

1. Coal Session (Moderator: Dr Atsushi Kurosawa, IAE)

2. Gas Session (Moderator: Mr Rodrigo Martinez, APERC)
3. Oil Session (Moderator: Mr Nabih Matussin, APERC)
4. Next Step

a) Session 1: Coal Industry

In the coal industry session, the discussion covered Mining Operations, Coal Processing and Coal Transportation, with a particular focus on energy efficiency and reducing fugitive emissions. Participants also provided feedback on whether additional topics should be included in this section of the Background Research Report.

Summary of the Background Research Report

	Energy Efficiency	Reducing Fugitive Emissions
Mining Operations	● Diesel fuel in mobile equipment accounts for ~46% of mining energy use; electricity for ventilation ~15%. ● Inefficient operator behavior can increase fuel consumption by up to 80% without productivity gains. ● Data-driven operator coaching can reduce fuel consumption by 10–20%. ● Equipment rightsizing (proper matching of trucks & shovels) reduces idle time and fuel waste. ● AI-based predictive maintenance prevents efficiency losses caused by degraded equipment. ● Underground ventilation accounts for up to 50% of electricity consumption. ● Ventilation on Demand (VoD) can reduce ventilation energy by 30–60%.	● Coal mining methane (CMM) accounts for ~40 Mt of methane globally—about one-third of fossil-fuel methane emissions. ● Ventilation Air Methane (VAM) makes up ~70% of underground mine methane emissions. ● Key mitigation options: ○ Pre-drainage of methane for power generation or pipeline injection. ○ Oxidation technologies (e.g., thermal/ catalytic oxidation) to convert dilute methane into CO₂. ○ Capture & utilization of higher-concentration methane streams. ● Methane conversion to energy provides economic incentives aligned with emissions reduction.
Coal Processing and Preparation	● Energy consumption ranges from 1.2–5 kWh/t depending on technology. ● Crushing, grinding (comminution), dense medium circulation, and dewatering are the most energy-intensive steps. ● Optimization approaches include: ○ Real-time process control for medium density and separation cut-points. ○ Upgrading aging equipment to high-efficiency alternatives. ○ Integration of process steps to minimize pumping and material handling energy. ● Producing cleaner coal reduces downstream emissions, transport costs, and improves power-plant efficiency.	● Key fugitive emissions include methane leaks and coal dust from handling. ● Reduction options: ○ Improved equipment sealing and regular maintenance. ○ Low-emission technologies for material handling. ○ Indoor or enclosed storage systems to reduce dust and emissions.
Coal Transportation	● Transport can account for up to 70% of delivered coal costs. ● Emissions / energy intensity vary by mode:	● Transport-related emissions include CO₂, CH₄, and N₂O from fuel combustion. ● Opportunities for reduction:

	○ Road: ~62 g CO₂/t-km ○ Rail: ~22 g CO₂/t-km ○ Water transport: lowest for long haul ● Modal shift from road → rail can reduce emissions by >50%. ● Optimization levers: ○ AI-based haul truck optimization ○ Next-generation conveyor systems reducing energy up to 50% ○ Efficient rail operations (longer trains, fewer empty backhauls) ● System-wide optimization can reduce fuel consumption by minimizing empty trips and idling.	○ Anti-idling policies ○ Adoption of alternative fuels (LNG, biofuels, hydrogen) ○ Electrification of haul trucks and rail systems ○ Use of autonomous haulage to ensure optimized operation and reduced fuel burn
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Key Points of Discussion

Mining Operations

- Increasing the blending ratio of biofuels can contribute to emissions reduction; however, higher biofuel use has a significant impact on operating costs, including increased maintenance expenses and potential impacts on equipment performance.
- In open-pit mining, obtaining reliable data on how to capture fugitive emissions remains a major challenge, and further research on methane recovery technologies would be valuable.
- In Australia, options such as pre-drainage in open-cut mining to capture and oxidize methane, as well as other methods to capture methane released during mining operations, are being examined in detail.
- The majority of fuel consumption occurs in haul trucks rather than in loading operations; for large trucks, efficiency improvements are achieved through diesel engines used as generators to drive electric motors, while power sources such as batteries remain a significant challenge.
- Vehicle and fleet management systems are essential for improving productivity and reducing fuel consumption and emissions in mining operations.
- Maintenance activities and data collection require highly reliable communication systems; however, wireless communication at mine sites remains technically challenging, costly, and difficult to operate and maintain.

Coal Processing

- The coal industry is placing increasing emphasis on reducing methane emissions across the entire processing and preparation chain.
- One of the key challenges in coal processing is the accurate measurement of methane emissions at a sufficiently granular level, highlighting the need for further technological development and research.
- As coal-fired power plant construction continues, managing emissions associated with coal use remains a significant and ongoing challenge.

Coal transportation

- Measures to reduce emissions from coal shipping are under consideration, including a potential transition from diesel fuel to alternative fuels such as LNG and hydrogen.
- Addressing scope 1 emissions through methane reduction at mine sites, together with reducing emissions from transportation and shipping, is critical to overall decarbonization efforts.
- The coal industry may also support the production of low-carbon and blue hydrogen, contributing to a more circular and integrated approach across the value chain.
- Distance and infrastructure choices are critical factors in Indonesian coal transportation energy efficiency improvement, due to limited availability of railway transportation systems.
- Shifting away from diesel toward more energy-efficient fuels, including e-fuels, could help reduce both transportation costs and associated emissions.

Questions and Answers

Mining Operations

QUESTION: Dr Atsushi Kurosawa to all speakers

Turning first to mining operations, energy consumption is mainly associated with diesel fuel and electricity use. Operator behavior is an important factor, as untrained operators can lead to significant fuel and energy losses in upstream mining activities. As highlighted on the first day, data-driven operator coaching can reduce fuel consumption, and proper rightsizing of mining equipment is an effective way to reduce idle time and fuel waste. In addition, AI-based predictive maintenance can prevent efficiency losses caused by equipment degradation.

In underground mining, ventilation can account for up to 50% of total electricity consumption. The application of ventilation-on-demand systems has the potential to reduce ventilation energy use by approximately 30–60%.

Based on this context, I would like to invite each speaker to comment on any additional issues or new findings that are not covered in this summary, to highlight any views that differ from the points presented, and to share practical examples and on-site experiences from their own operations.

ANSWER: Mr Ignatius Wurwanto

From the Indonesian coal mining industry perspective, the summary prepared by APEC is very interesting and broadly consistent with our experience. As mentioned previously, Indonesia is currently reducing emissions by introducing biodiesel blends. We started with B10, meaning 10% biofuel blended with fossil fuel, and this percentage has gradually increased. This year we have implemented B40, and the government plans to increase this further to B50 next year.

However, from our operational experience, higher biofuel blending has a significant impact on operating costs. Maintenance costs increase, and equipment performance is not the same as when using 100% fossil diesel. Therefore, it is important to improve equipment performance and consider how additional costs can be supported, particularly for mining machinery operations. Equipment manufacturers, such as Komatsu, have already introduced initiatives to improve equipment performance and operator behavior, but further study is needed on how biofuel use can reduce emissions without sacrificing equipment performance.

Another major concern for us is fugitive methane emissions. We still face challenges in obtaining reliable data on how to capture fugitive emissions, especially in open-pit operations, which account for around 90% of Indonesian coal mining. Unlike underground mining, where ventilation systems allow methane to be managed more easily, open-pit operations are much more difficult because everything is exposed. If future research can explore technologies to capture methane from open-pit mining, this would be very beneficial. We would very much welcome any research to be conducted in Indonesia, and we are ready to cooperate with the Indonesian Coal Mining Association to facilitate communication regarding the data and information needs related to our operations.

ANSWER: Mr Ben Rice

One issue that stands out is the future need for methane abatement in open-cut coal mining. Technically, this is much more difficult than underground methane abatement because of how ventilation air methane is managed. However, the Australian industry has begun to look closely at options such as pre-drainage in open-cut mining, where methane is captured and oxidized, as well as other methods to capture fugitive methane as it is released during mining.

These technologies are still at least a decade away from commercial availability, but they represent the next frontier for methane abatement in Australian coal mining. Most of this research is likely to take place in Queensland and New South Wales, where most black coal mining occurs, as well as in Victoria, where brown coal mining is significant. Given that coal, gas, and iron ore are Australia's three largest export products, there is strong policy interest in decarbonizing the entire resource value chain, including coal mining.

ANSWER: Mr Hisashi Asada

First, regarding mobile equipment decarbonization, we are developing battery-powered and hybrid systems for large mining trucks. Typically, customers operate one loader with ten to one hundred trucks, meaning most fuel consumption occurs on the truck side rather than the loading side. Loading machines are easier to electrify because they move over short distances. Many customers already use electric-drive loading machines, such as hydraulic excavators with electric motors connected by power cables. This is an established but very effective technology for reducing GHG emissions.

Regarding large trucks, many already use electric motors for wheel drive, powered by diesel engines acting as generators. While electric motors improve efficiency, the major challenge remains the power source, including batteries.

Second, fleet management systems are critical for both productivity and emissions reduction. Managing large fleets requires precise control of truck movements. Even small improvements, such as managing vehicle behavior at intersections to reduce stopping and idling, can significantly reduce fuel consumption. There is no single solution to eliminate emissions, so continuous incremental improvement is essential.

Third, maintenance and data collection require reliable communication systems. Mining sites face challenges in radio communication due to the large volume of data generated by equipment. While some operations use private fourth-generation (4G) or 5G networks, these systems are costly and difficult to maintain.

Finally, based on discussions on methane emissions, we believe that ventilation-on-demand systems and methane management systems in underground mines should be integrated. Even if these technologies are provided by different companies, collaboration and system integration are necessary to improve overall methane emission control.

Coal Processing

QUESTION: Dr Atsushi Kurosawa to all speakers

Do you have any feedback regarding coal processing and preparation, particularly in relation to methane emissions?

ANSWER: Mr Ben Rice

This is not an area where we are heavily investing in research, but the Australian mining industry is increasingly focused on reducing fugitive methane emissions across the entire process chain. One of the main challenges is accurately measuring methane emissions at a sufficiently granular level during coal processing. Based on current knowledge, this is an area where further technical development and research are needed.

ANSWER: Mr Ignatius Wurwanto

In Indonesia, we also face challenges related to emissions from coal-fired power plants and coal processing. The government is cooperating with international partners to study clean coal technologies, including capturing emissions from coal combustion. However, so far, the results have not met

expectations. As Indonesia continues to construct additional power plants, managing emissions from coal use remains a significant challenge, and further research is clearly needed.

Coal Transportation

QUESTION: Dr Atsushi Kurosawa to all speakers

Turning to coal transportation, transport costs can account for up to around 70% of the delivery cost, depending on transport mode and distance. Coal is transported through multiple modes, including road, rail, and waterborne transport such as seaborne and river shipping. There is scope for further optimization through improved tracking of transport trajectories, as well as through the adoption of next-generation conveyor systems, which are reportedly under development. Could you comment on coal transportation and related emissions?

ANSWER: Mr Ben Rice

In Australia, most domestically transported coal is moved by rail, while 90 to 95% of mined coal is exported by ship. The industry is currently examining ways to reduce emissions from shipping, including transitioning from diesel fuel to alternatives such as LNG or hydrogen. Although hydrogen-powered shipping is technically challenging, it is an area of active research.

If we can address scope one emissions at mine sites through methane abatement and reduce emissions from transportation and shipping, this would significantly support compatibility with the carbon neutrality targets of our trading partners. In the longer term, the coal industry may also support the production of low-carbon or blue hydrogen, closing the loop across the value chain.

ANSWER: Mr Ignatius Wurwanto

Transportation costs in Indonesia are very high, accounting for up to 70% of delivered coal costs, with fuel representing a significant share of these expenses. Most coal is transported by trucks from mines to loading points due to limited railway infrastructure and then moved by barges along rivers and to sea. As a result, distance and infrastructure choices are critical factors in Indonesia's coal transportation system and shifting away from diesel toward more energy-efficient options, including e-fuels, could help reduce both costs and emissions.

b) Session 2: Gas Industry

In the gas industry session, the discussion covered transportation, storage, and related operations, with a particular focus on energy efficiency and reducing fugitive emissions. Participants also provided feedback on whether additional topics should be included in this section of the background research report.

Summary of the Background Research Report

	Energy Efficiency	Reducing Fugitive Emissions
Exploration and Production	- Power optimization in drilling operations incorporating variable frequency drives, efficient mud pumps, and optimized lighting systems. - Improved well completion techniques that optimize stage spacing and proppant placement to maximize production rates.	- Enhanced well completion techniques that reduce venting, potentially cutting methane emissions by up to 90% compared with conventional practices. - Replacement of high-emission components, including high-bleed pneumatic devices, unpacked wet seal centrifugal compressors, and

	• Energy management systems for production facilities with comprehensive monitoring and control technologies that optimize compressor operations, glycol dehydration units, and artificial lift systems.	atmospheric storage tanks. • Transition to electric instrumentation instead of pneumatic devices to lower emissions. • Methane measurement and monitoring systems for improved detection and mitigation in the field.
Processing	• Advanced process simulation tools and real-time optimization systems that adjust operating parameters to reduce energy use. • Heat-exchange network retrofits to lower energy intensity in old facilities. • Compressor upgrades, replacing reciprocating units with rotary screw or centrifugal models, cutting energy consumption by 10–20%. • Membrane technologies for sweetening, dehydration, and nitrogen rejection, with newer polymer materials improving permeability and selectivity. • Digital twin systems that model facilities for real-time optimization, predictive maintenance, and scenario planning without operational disruption.	• Enhanced Vapor Recovery Unit systems with advanced separation technologies, membranes, and adsorption units achieving recovery efficiencies above 98%. • Lean gas flare-tip technology to destroy methane and reduce emissions from hydrocarbon flaring. • Replacement of conventional pump seals with dual mechanical seals or magnetic drive systems, reducing methane emissions by up to 95%. • Enhancement of seal and gasket technologies to minimize leaks. • Methane measurement and monitoring systems for improved detection and mitigation in processing plants.
Transportation	• Pipeline compression optimization with variable speed drives, advanced controls, and optimized ratios can reduce energy use by 15–25%. • High-efficiency compressors with advanced gas turbines, electric drives, and heat recovery can achieve thermal efficiencies above 40%. • Optimization of electrical systems supplying compressors, including power factor correction, variable frequency drives, and energy storage, improves efficiency and reduces peak demand. • Intelligent Pipeline Inspection Gauges enable maintenance that prevents efficiency losses from corrosion or deposits. • Integration of solar and wind energy with compressors can reduce emissions and supplement energy supply.	• Compressor station emission controls with dry gas seals and blowdown capture systems to reduce methane emissions and improve reliability. • Fugitive emission reduction for valves and fittings using bellows-sealed valves, welded connections, and improved isolation systems. • Smart pipeline monitoring with acoustic, infrared, and chemical sensors for comprehensive network surveillance. • Satellite-based leak detection for large-scale, continuous monitoring. • Advanced pipeline inspection technologies, including ultrasonic testing, electromagnetic acoustic transducers, and magnetic flux leakage, for detailed assessments without operational interruptions.

Storage	Geological storage optimization • Optimization of injection and withdrawal operations using advanced reservoir modeling and operational planning to maximize energy efficiency. • Use of modern compression systems with advanced control algorithms to optimize compression ratios and staging, minimizing energy consumption. • Integration of renewable energy sources such as wind and solar to power compression operations, reducing grid electricity use and emissions.	• Geological storage monitoring with continuous methane detectors, soil gas surveys, and groundwater monitoring to detect and prevent emissions from wells, surface facilities, and surrounding areas. • LNG storage efficiency improvements, including boil-off gas management, tank insulation, and regasification technologies to reduce methane emissions and energy use.
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Key Points of Discussion

Exploration and Production

- Operators address energy efficiency and fugitive methane emissions as a single integrated challenge rather than as separate issues.
- Priority measures include use of digital twins for optimizing wells and fields, strong maintenance and LDAR programs, and replacement of high-bleed pneumatics with low- or no-bleed devices.
- Methane abatement can often be cost-negative, whereas reducing CO₂ from combustion and addressing abandoned wells require capital-intensive options such as CCS and supportive regulatory and financial frameworks.

Processing

- Gas processing offers major opportunities for both energy-efficiency gains and fugitive-emissions reduction across existing and new facilities.
- Key measures include advanced process simulation and real-time optimization, retrofitting heat-exchanger networks, compressor upgrades, improved seals and gaskets, and combined use of gas and steam turbines to lift overall efficiency above 50%.
- In mature fields, retrofits and new configurations must be assessed case by case, balancing potential emission reductions against additional equipment, increased maintenance needs, and overall project economics.

Transportation

- Effective leak detection on long-distance pipelines requires monitoring close to the line using in-line tools or low-flying drones, rather than relying principally on satellite data.
- Regular inspection and maintenance of compressors and pipelines are essential to sustain efficient operation and limit methane leakage along large networks.
- Long pipelines can function as temporary gas storage, helping maintain LNG plant operations and overall security of supply when offshore disruptions occur.

Storage

- Non-emitting electricity for storage and CCS operations can come from hydro, small modular reactors and other low-carbon sources, not only wind and solar.
- Project designs need to consider the full value chain for power and storage assets, including who builds, owns, operates and maintains them on site.
- Many storage and CCS technologies remain costly, so government support, offset mechanisms and careful optimization of geological storage are important for making large-scale decarbonization projects viable.

Questions and Answers

Exploration and Production

QUESTION: Mr Rodrigo Martinez to all speakers

Do you have any feedback, or any additional topics that we should include in the exploration and production section of the background report, where we have divided the material into energy efficiency and fugitive emissions measures, such as power optimization in drilling, improved well completion and energy management systems for compressors, dehydration units and artificial lift systems?

ANSWER: Mr Allan Fogwill

I think the only thing I would add is the idea of using a digital twin approach to manage operations on the production side, which can help optimize activities across the field. More broadly, people in industry do not really separate energy efficiency from reducing fugitive emissions. They tend to look at the two issues holistically. Any approach we take has to work for both objectives, otherwise it will simply be optimized to meet the main regulatory challenge. At the moment, in most jurisdictions, that challenge is more about methane emissions than about energy efficiency, so I would treat this as an integrated topic rather than two separate ones.

ANSWER: Mr Yoshihiko Enokido

When I read the research report, I felt it was very comprehensive, and many of the points were new to me because I am not from the technical side. Even so, the measures did not seem surprising; rather, they looked feasible and effective. I was particularly encouraged by the high reduction potentials, in some cases close to 90%. If we can implement these measures, they will be very helpful for improving energy efficiency and reducing fugitive emissions. I would also add that in our discussion yesterday with EDS we confirmed that gas will continue to be very important for the world. If we can make gas industry operations more energy-efficient and cut fugitive emissions, that will have a very strong impact on reducing overall greenhouse gas emissions.

ANSWER: Mr Shinya Konno

I think the summary is very concrete and I do not have major comments to add, but I would like to emphasize the importance of maintenance for reducing emissions from existing facilities. If we do not have proper maintenance plans, unplanned shutdowns can occur. Each unplanned shutdown means additional start-ups, which usually result in higher flaring and therefore more fugitive emissions. That is why we try to minimize unplanned shutdowns through proper maintenance, and I think maintenance should be recognized as one of the key methods for reducing fugitive emissions.

ANSWER: Mr Allan Fogwill

From the Canadian experience, most of the success we have had in reducing fugitive emissions in exploration and production comes from two main areas. The first is basic maintenance, especially systematic leak detection and repair programs. The second is the transition from high-bleed pneumatic devices to low-bleed or no-bleed alternatives. If operators focus on just these two things, they can achieve substantial reductions very quickly.

These measures are often cost-saving rather than costly. By improving operations, companies can strengthen their bottom line while reducing emissions. Because of this, it is relatively easy to convince industry to adopt such measures.

Our experience is very similar. The positive results depend on having a strong baseline for asset lifecycle management. If that foundation is in place, good things tend to follow once maintenance and leak detection are systematically addressed.

QUESTION: Mr Yoshihiko Enokido to Mr Allan Fogwill

Listening to this, I feel that reducing methane can be relatively easy, because the measures are often cost-effective. I wonder whether we can apply similar thinking to carbon dioxide. In my previous role working on CCS, one of the biggest challenges was the capital cost of capture systems at refineries and plants. How far do you think we can extend energy-efficiency-type measures to CO₂ reduction?

ANSWER: Mr Allan Fogwill

In practice, industry priorities are strongly influenced by regulation. Right now methane is a significant focus, while for CO₂ we are mainly looking at CCS. In Canada we have a major CCS project that is close to a final investment decision, with a target of around 22 million metric tons of CO₂ stored per year, mostly to cut emissions from oil sands bitumen production. Energy efficiency has only a limited role in managing CO₂ from combustion, because the physics of combustion mean you cannot avoid CO₂ formation. Many companies have already implemented energy efficiency measures, and further improvements at the source become more difficult and more expensive. For deeper CO₂ reductions we need sequestration options or utilization pathways, such as producing carbon fiber.

QUESTION: Mr Rodrigo Martinez to Mr Allan Fogwill

I would also like to ask about abandoned wells. There are reports, for example from the United States, of large numbers of abandoned wells that continuously leak methane into the atmosphere. Part of the problem seems to be that regulatory frameworks do not make decommissioning a clear part of producers' economic models. How is this challenge being addressed from your perspective?

ANSWER: Mr Allan Fogwill

In general, it is not economic to close wells. The real question is how effective we can be when we do attempt to close them. A major cost driver is the high failure rate: about 70% of wells are not successfully closed on the first attempt, which means multiple interventions and much higher costs. From an emissions perspective, it does not matter very much whether a non-producing well is formally classified as abandoned or still has an owner; that is mainly an ownership issue. Most states and provinces already have regulations, but enforcement is crucial. We need coordinated action among industry, governments and regulators to move this forward. Technically, we are still in the early stages: the industry has had about a century to refine techniques for opening wells, but only around a decade of serious research on how best to close them, so we are still at an early stage in well decommissioning.

Processing**QUESTION: Mr Rodrigo Martinez to all speakers**

Turning to gas processing, many of the same technologies appear as in exploration and production, but here we tried to be more specific to gas upgrading. For energy efficiency, we included advanced process simulation and real-time optimization, retrofitting heat-exchange networks in older facilities, compressor upgrades and novel separation technologies such as membranes, as well as digital twins to model facilities in real time. For fugitive emissions, we looked at enhanced vapor recovery units, lean-gas flare tips, improved seals and gaskets, and stronger methane measurement and monitoring. Do you have any comments on this processing section, or any topics that you feel are missing?

ANSWER: Mr Allan Fogwill

I think your list is quite comprehensive. The only additional point I would make concerns the overlap between processing and transportation when we manage blowdown and purging of pipelines for maintenance. In Canada we are required to use nitrogen for purging and to capture all methane released during line purges. For large pipelines these blowdown requirements are significant, so I would suggest making this aspect more visible in the discussion.

I would like to add that we often focus on compressors, but stationary engines used for motive power are also important. Methane slip from these engines can be a significant emissions source. Improving their combustion efficiency is important, but it is probably one of the more expensive options, especially if the solution requires replacing engines with new units that can cost several million USD each. Thermal oxidation can be useful as an interim step before full replacement. We should also remember that regulators are increasingly interested in other pollutants. In Canada, for example, oil and gas producers face NOx requirements and may soon see regulatory guidelines around volatile organic compounds, not just methane.

ANSWER: Mr Yoshihiko Enokido

My comments on processing are broadly similar to what I said for exploration and production. However, I would add that gas processing could be one of the largest contributors to reducing fugitive emissions. In the past, as far as I know, operators in processing plants were not very aware of, or focused on, fugitive emissions. Today, the situation has changed, and I think we should pay much more attention to reducing emissions on the processing side.

ANSWER: Mr Shinya Konno

As discussed in the previous session, at Ichthys we have already introduced advanced processing configurations that optimize energy use across the value chain. Our facilities include gas turbine generators for power generation and steam turbine generators that use exhaust heat from the gas turbines. By combining gas turbine generators with steam turbine generators, we have improved overall energy efficiency by more than 50%. However, adding more equipment increases maintenance requirements and can affect availability. So while efficiency improves, we also face new operational challenges.

QUESTION: Mr Rodrigo Martinez to Mr Shinya Konno

Is this kind of combined configuration usually implemented only in new facilities, or can it also be retrofitted into existing plants in a cost-effective way?

ANSWER: Mr Shinya Konno

In our case this configuration was implemented in a new facility.

QUESTION: Mr Rodrigo Martinez to Mr Yoshihiko Enokido

More generally, do you think these advanced configurations can be applied cost-effectively in older plants, or are they mainly suitable for new developments?

ANSWER: Mr Yoshihiko Enokido

I think it is very case-specific. If a plant is still economically competitive, even if it is an older facility, it can justify new investments and advanced measures. In upstream projects where oil or gas fields have very low production, however, additional investment can make the project uneconomic and even force it to close. In such cases operators focus on extending field life by reducing costs, which leaves very limited funds for new technologies. So, while it is desirable to introduce new measures wherever possible, we always have to consider the economic constraints.

ANSWER: Mr Kevin Henke

I would like to mention that ENEOS carried out a decomplexing project on an ageing offshore platform and presented a paper at the Asia Pacific CCUS Conference and Exhibition in Kuala Lumpur. The paper, titled “Achieving greenhouse gas emission reduction through operations excellence program in mature offshore oil fields”, discusses related issues, data and illustrations and could be a useful reference.

Transportation

QUESTION: Mr Rodrigo Martinez to all speakers

Let us move to transportation. Gas transportation by pipeline is widely used, so we tried to cover a range of technologies. For energy efficiency, we included pipeline compression optimization, high-efficiency compressors with advanced gas turbines, electric drives and heat-recovery systems, optimization of the electrical systems that supply compressors, and intelligent pipeline inspection systems to avoid efficiency losses from corrosion or deposits. We also considered integrating renewable energy with compressors. For fugitive emissions, we looked at emission controls at compressor stations, better valves and fittings, pipeline monitoring with acoustic, infrared and chemical sensors, satellite-based leak detection for large areas, and advanced inspection tools such as ultrasonic testing, electromagnetic acoustic transducers and magnetic flux leakage. Do you have any comments on this transportation section?

ANSWER: Mr Allan Fogwill

Satellite-based leak detection is of limited practical value for maintenance. While it may be useful for headlines or identifying very large problems, it does not provide the detailed information needed to locate and repair specific leaks, and even aircraft-based monitoring can be insufficiently accurate unless the issue is significant. Effective leak detection requires monitoring closer to the pipeline, such as continuous on-site systems or low-flying drones, which are well suited to linear infrastructure. Although these options are more expensive than satellites, they generate actionable information for operators, whereas satellite data are often used mainly for communication or media purposes rather than for actual maintenance and repair.

ANSWER: Mr Yoshihiko Enokido

At first I thought satellite-based detection sounded very attractive and catchy, but after hearing Allan's explanation I understand that it is not very useful in reality for maintenance and leak repair.

ANSWER: Mr Shinya Konno

This topic is very interesting for me. At Ichthys we have a very long offshore pipeline of around 890 kilometers, so inspection is a major task. Last year we carried out a large inspection using an advanced pigging system to keep the pipeline in good condition and maintain continuous gas transportation. A long pipeline can also act as a form of storage. If something happens offshore, the gas stored in the pipeline can be used to keep the onshore LNG plant running for some time. In that sense, although a long pipeline has higher maintenance costs, it supports safe operation and energy supply security.

Storage**QUESTION: Mr Rodrigo Martinez to Mr Allan Fogwill**

Finally, let us consider storage. For energy efficiency, we included topics such as optimizing injection and withdrawal using advanced reservoir modelling, using modern compression systems with advanced control algorithms, and integrating renewable energy sources into storage operations. For fugitive emissions, we looked at geological storage monitoring using methane detectors, soil gas surveys and groundwater monitoring, as well as LNG storage efficiency measures such as boil-off gas management, insulation and regasification technologies. Do you have any comments on this storage section?

ANSWER: Mr Allan Fogwill

I think your list is comprehensive, but I want to make a couple of points. First, there is often an implicit assumption that electricity must come from wind or solar generation. In reality, the key requirement is that it should come from a non-emitting source, which could be hydro, small modular reactors or other options. For large complexes such as storage facilities, economies of scale and steady loads could make such solutions cost-effective. Other storage-related options, such as pumped hydro or compressed air energy storage, can also be relevant.

Second, when we integrate new power solutions into storage facilities we need to think about the whole value chain of installation, maintenance and operation. Many site operators do not want to manage power generation themselves; they prefer simply to receive electricity as a service. So the issue is not only the specific source of electricity but also how the whole chain of responsibilities and costs is organized.

I would also emphasize the role of cost. Some technologies work technically but are simply too expensive for many operators. In those cases, we need to consider how to manage emissions through mechanisms such as offset credits. I often use the analogy that I would love to have a luxury car, but the bank, the dealer and my family all say I cannot afford it, so that option is not really available to me. In the same way, some technology options are closed off by cost. Decarbonization pathways therefore have to be economic as well as technical solutions.

ANSWER: Mr Yoshihiko Enokido

Geological storage optimization was new and very interesting for me. I fully agree with Allan's comments on cost. If projects are not economical at this moment, government support becomes very important. In the United States, for example, there are regulatory and policy measures that support CCS projects. More broadly, I think that in each economy government support is crucial for reducing greenhouse gas emissions.

ANSWER: Mr Shinya Konno

I echo the comments made by Mr Enokido. As discussed yesterday, we are working on the Bonaparte CCS Project and are starting injection studies. Decarbonization is necessary, but at present CCS is not economically attractive. We are working to reduce costs, but to make CCS projects economically viable we need to attract more customers, including in Australia and Japan. Alongside company efforts, government support is essential, and we are discussing this with governments, including the Japanese government.

c) Session 3: Oil Industry

In the oil industry session, the discussion covered exploration and production, transportation, and refining, with a particular focus on energy efficiency, reducing fugitive emissions and oil spills. Participants also provided feedback on whether additional topics should be included in this section of the background research report.

Summary of the Background Research Report

	Energy Efficiency	Reducing Fugitive Emissions	Reducing Oil Spills
Exploration and Production	● Electronic hydraulic fracturing, automated drilling processes ● Managed pressure drilling techniques ● Advanced reservoir simulation and machine learning algorithms in Enhanced Oil Recovery (EOR)	● *Not discussed in Background Paper	● Safety Management Systems (SMS) require companies to implement thorough risk assessments, incident reporting, and continuous improvement processes. These integrated monitoring systems drastically cut spill response time from an average of 6 hours to just 45 minutes. ● The integration of AI and machine learning algorithms, as well as the use of autonomous inspection drones and underwater vehicles.

Transportation	● Sophisticated hydraulic modelling and real-time optimization algorithms to minimize pumping and compression while maintaining flow rates and pressures. ● The implementation of drag-reducing agents to reduce turbulence and friction. ● Telematics and advanced analytics in rail and truck fleet optimization.	● *Not discussed in Background Paper	● Fiber optic sensing enables real-time leak detection along thousands of kilometers of pipeline with meter-level accuracy by monitoring pressure, temperature, and acoustic signals. Combined with machine learning (>95% accuracy), it virtually eliminates false alarms and unnecessary excavations. Risk-based LDAR programs, focusing on high-risk assets, cut costs by 30–40% without compromising emission reductions.
Refining	● Oxygen enrichment within refineries ● Process unit optimization through advanced process control (APC) and real-time optimization (RTO) systems ● Utilization of cogeneration and combined heat and power systems (CHP)	● Flare gas recovery and minimization, with 95-99% capture rate ● Vapor recovery unit in storage tanks.	● *Not discussed in Background Paper

Key Points of Discussion

Exploration and Production

- Ageing infrastructure causes compressors and pumps to operate away from optimal efficiency, often resulting in increasing redundancy, highlighting the need for clearer and more systematic end-of-life replacement decision-making.
- System decomplexing—by reducing unnecessary interfaces and restoring equipment to efficient operating points—is essential to improve efficiency and emissions performance.
- Completing drilling and well completion in one continuous operation can significantly reduce energy use by avoiding interruptions, equipment changes, and rework.
- Electrification of upstream operations offers efficiency and emissions reduction potential where site conditions and low-carbon power sources allow.
- Fugitive emissions remain a concern due to legacy pneumatic devices, compressors, engines, and upstream storage tanks, underscoring the importance of lifecycle management and monitoring.
- Oil spills are primarily driven by erosion and corrosion, making risk-based inspection and mechanical integrity management critical.
- Safety Management Systems, supported by digital tools such as AI, drones, and robotic inspections, can reduce spill risks and shorten response times.

Transportation

- Energy efficiency improvements can be achieved through hydraulic modeling, real-time optimization, drag-reducing agents, and advanced analytics applied to pipelines, rail, and truck operations.

- Marine transportation efficiency is enhanced by using larger vessels such as Very Large Crude Carriers (VLCCs), upgrading single-point mooring systems and jetties, and optimizing vessel utilization.
- Fugitive emissions are influenced by the quality of truck and rail loading systems, with older systems generating significant volatile organic compound (VOC) emissions.
- Interface management in multi-product pipelines is an often underestimated source of energy waste and fugitive emissions, particularly when poor handling leads to reprocessing and additional transport.
- Guided ultrasonic wave inspection is applied to deeply buried pipelines where conventional excavation is difficult.
- Fiber-optic sensing technologies, already used in well applications, could potentially be explored for real-time pipeline monitoring, although their applicability to long-distance pipelines remains uncertain.
- Risk-based LDAR programs focusing on high-risk assets can improve spill prevention while maintaining cost effectiveness.

Refining

- Oxygen enrichment, APC, and RTO can deliver meaningful energy efficiency gains when systems are properly designed and continuously updated.
- Combined heat and power (CHP) systems represent a high-impact efficiency measure, with potential to increase overall refinery efficiency to around 80–85%.
- Crude slate optimization is critical, as both heavy sour and light crudes can increase energy consumption if not properly balanced.
- Electrification offers significant system-level decarbonization and operability benefits, but requires evaluation beyond narrow unit-level economics.
- Operational instability and frequent transients increase flaring and fugitive emissions, emphasizing the importance of reliability and simplified refinery configurations.
- Vapor recovery and flare gas recovery systems can reduce emissions, but long-term mitigation depends on addressing root causes such as excess intermediate storage and process complexity.

Questions and Answers

The Oil Session of Day 2 built upon the technical presentations delivered on the previous day and aimed to examine energy efficiency improvements, GHG emissions reduction, and oil spill prevention across the entire oil value chain. While earlier presentations focused largely on refining, the discussion deliberately expanded to include exploration and production (E&P), transportation, and the handling of crude oil and refined products.

Measures to reduce oil spills were included, recognizing their importance not only for environmental protection but also for the efficient use of resources such as crude oil.

Mr Matussin explained that although some items were not extensively covered in the background materials, they remain critical components of a comprehensive strategy for improving performance in the oil sector.

Exploration and Production

QUESTION: Mr Nabih Matussin to all speakers

In the exploration and production segment, energy efficiency measures discussed included electric hydraulic fracturing, automated drilling, managed pressure drilling, and the application of advanced reservoir simulation and machine learning for enhanced oil recovery.

While fugitive emissions were not addressed in the background paper, they were recognized as an integral issue in upstream oil and gas operations.

For oil spill reduction, the discussion highlighted the role of Safety Management Systems (SMS), which can significantly shorten spill response times through risk assessment, incident reporting, and continuous improvement. The use of digital technologies, including AI, machine learning, drones, and autonomous inspection vehicles, was also identified as a key enabler for improved spill prevention and response.

From an upstream perspective, what are the key structural challenges affecting energy efficiency in exploration and production activities?

ANSWER: Mr Kevin Henke

A major structural challenge in exploration and production is ageing infrastructure. Much like refining assets, E&P facilities are typically designed for peak operational conditions. As production declines over time, equipment such as compressors and pumps gradually moves away from its optimal efficiency curve.

Over time, equipment such as compressors may operate far from their optimal efficiency, often alongside other units running at low utilization. This underscores the need for clearer and more systematic decision-making on end-of-life management. Pneumatic devices are not intended to operate indefinitely, and continued use requires deliberate strategies for maintenance, upgrading, or replacement. Rather than simply replacing ageing equipment with identical units or maintaining multiple underutilized systems, greater emphasis should be placed on decomplexing asset configurations by reducing unnecessary interfaces and restoring equipment to more efficient operating points.

Over time, compressors and other equipment can become very inefficient and increasingly redundant. This highlights the need to bring forward more information to support decision-making on end-of-life replacement. Rather than maintaining multiple low-utilization units, decomplexing by simplifying systems and restoring equipment to efficient operating points is essential.

ANSWER: Dr Jiahang Han

From an energy efficiency perspective, substantial savings can be achieved if drilling and well completion can be finished in one continuous operation. Completing the well in a single continuous operation avoids unnecessary interruptions, equipment changes, and rework after initial completion. Ultimately, this depends on robust well design and sound field engineering.

ANSWER: Mr Le Hai Tuan

Oil spills most commonly originate from erosion and corrosion in piping and equipment. To address this, we apply risk-based inspection (RBI) systems that allow us to predict degradation, plan timely maintenance, and prevent failures. For example, erosion issues in slurry pipelines at RFCC unit were resolved through targeted inspection and replacement based on RBI findings. Additional measures include systematic flange inspections, high-point camera monitoring, and the increasing use of robotic and remote inspection technologies. Together, these practices have proven effective in reducing spill incidents and improving operational integrity.

Transportation

QUESTION: Mr Nabih Matussin to all speakers

In the transportation segment, several measures were identified to improve energy efficiency. These include the use of sophisticated hydraulic modeling and real-time optimization to minimize pumping and compression requirements while maintaining required flow rates and pressures. The application of

drag-reducing agents was also highlighted as an effective means of reducing turbulence and friction in pipelines, thereby lowering overall pumping energy demand. In addition, telematics and advanced analytics can be applied to optimize rail and truck fleets transporting crude oil and oil products.

While fugitive emissions in transportation were not addressed in detail in the background paper and are often considered relatively limited, the discussion noted that this assumption may warrant further examination.

To reduce oil spills, fiber-optic sensing technologies enable real-time leak detection along thousands of kilometers of pipeline with meter-level accuracy by monitoring pressure, temperature, and acoustic signals. When combined with machine learning systems, these technologies can significantly reduce false alarms and unnecessary excavations. In parallel, risk-based LDAR programs focusing on high-risk assets can reduce costs by 30–40% without compromising emissions reduction performance.

Do you have any additional views or comments on this?

ANSWER: Mr Kevin Henke

Two additional aspects merit attention. First, the loading of rail cars and trucks plays a critical role in overall emissions performance. The type of loading systems in use varies widely: while advanced, emissions-free loading technologies are available, some facilities still rely on relatively simple systems that generate significant VOC emissions.

Second, within the broader transportation process, interface management—particularly on the product side—represents an often-overlooked source of energy inefficiency and fugitive emissions. In multi-product pipeline systems, managing interfaces between different products is critical. Poorly managed interfaces can result in product off-specification, requiring transfer to trucks, shipment to other facilities, or temporary processing to adjust specifications. In some cases, products are returned to refineries for reprocessing, creating additional energy consumption, operational costs, and emissions. This recycling loop generates substantial waste that is frequently underestimated, despite its practical significance.

Addressing these issues represents a clear opportunity for improvement, as advanced technologies and management practices are already available.

ANSWER: Dr Jiahang Han

Regular pipeline inspection is fundamental to safe and efficient transportation. Guided ultrasonic wave inspection is applied to deeply buried pipelines, where conventional excavation is challenging and alternative inspection approaches are required.

In addition, fiber-optic sensing technologies, which are already used in well applications, could potentially be explored for real-time monitoring of pressure, temperature, and acoustic signals along pipelines, although their applicability to long-distance pipelines is not yet clear.

ANSWER: Mr Le Hai Tuan

In the transportation segment, energy, fuel consumption, and costs can be reduced by utilizing larger vessels and tankers. For example, upgrading single-point mooring (SPM) systems to enable the loading of crude oil from offshore facilities onto VLCCs allows for economies of scale in marine transport. This approach not only reduces transportation costs but also contributes to lower emissions per unit of cargo. Similarly, upgrading jetty to accommodate larger vessels, even for importing additional feedstocks and fuel blending components can further enhance transport efficiency.

In addition, transportation efficiency can be improved by optimizing vessel utilization. One option is to use the same vessel for both import and export operations — for example, importing naphtha and subsequently using the same ship to export refined products or importing VGO and exporting SFMO/MFO. Such measures reduce empty return voyages and improve overall logistics efficiency.

ANSWER: Mr Allan Fogwill

I would like to add a brief clarification regarding the exploration and production segment. Most of the points I presented apply to both gas and oil operations, including leak detection and repair, pneumatic devices, and storage tanks. It is important to note, however, that upstream storage tanks differ fundamentally from refinery storage tanks. They tend to be more vulnerable and present distinct operational and emissions-related challenges.

In addition, engines and compressors used in exploration and production are key areas where efficiency improvements and emissions management are particularly important.

Refining

QUESTION: Mr Nabih Matussin to all speakers

In the refining stage, several measures can improve energy efficiency. Oxygen enrichment in refinery burners increases combustion efficiency by enhancing effective airflow, thereby reducing fuel consumption. Energy use can also be lowered through process unit optimization using APC and RTO systems. In addition, CHP systems enable the simultaneous production of electricity and heat, improving overall efficiency.

To reduce fugitive emissions, key measures include minimizing and recovering flare gas, with capture rates of 95–99%, and implementing vapor recovery systems in storage tanks.

With that, I will start with the first measure.

ANSWER: Mr Le Hai Tuan

Regarding oxygen enrichment in the refinery, I know that many refineries already apply this solution. In our case, the air flow for combustion in the FCC regenerator is currently constrained and close to its operational limit. By applying oxygen enrichment, we can address this situation. By increasing the oxygen content of the combustion air, rather than relying on air largely composed of nitrogen, we can improve the combustion reaction and reduce overall energy consumption.

APC and real-time optimization systems need to be updated continuously to reflect actual operating conditions. In reality, operating conditions change over time, including changes in feedstock supply and feedstock properties, and the models therefore need to be updated to optimize the process.

Cogeneration systems can significantly improve energy efficiency in refineries. In our refinery, boilers and FCC systems are currently used to produce steam and electricity, with an overall energy efficiency of around 35–40%. With cogeneration, where steam and electricity are produced at the same time, energy efficiency can be increased to around 80–85% and the energy intensity of the refinery can be reduced. We are now studying the gradual replacement of our existing boilers and FCC-based generation with cogeneration systems.

Regarding flare gas recovery systems, to achieve zero flaring we would need to install gas recovery units, possibly at the outlet of the flare piping, to recover gas that would otherwise be flared. This would be good for the environment, but it is costly and not always economically viable, as it depends on the type and value of the hydrocarbons recovered. If such systems are required by government regulations, we would consider adopting more advanced recovery systems.

ANSWER: Dr Jiahang Han

I would like to share one example from SINOPEC. At present, SINOPEC is using solar power to produce hydrogen-based products, where the process relies on electricity rather than conventional fossil

fuels. In this approach, the required power is supplied by solar energy, including captive solar power systems dedicated to refinery operations.

In the western part of China, additional solar panels have been installed together with battery storage systems. With this configuration, electricity generated from solar power can be used directly for process operations, such as the production of chemicals, instead of relying on gasoline or other fossil-fuel-based energy sources. In this case, equipment and processes are increasingly electrified, with power supplied from renewable electricity rather than liquid fuels.

ANSWER: Mr Kevin Henke

Electrification represents a major opportunity, but many operating companies struggle to justify investment because they focus on narrow economic benefits rather than system-level impacts. Electrification can significantly simplify systems, reduce maintenance costs, and improve overall operability, and these broader benefits should be considered.

However, unintended consequences must be recognized. Technologies such as gas turbines or heat recovery steam generators, often assumed to improve efficiency, have in some cases degraded overall refinery efficiency due to operational factors. Similarly, APC, RTO, and AI systems are effective only when plants operate stably; without reliable operations, such systems are often turned off. Operational instability and frequent transients increase flaring and emissions, highlighting the need to minimize process complexity and eliminate unnecessary equipment—an area where electrification can be highly leveraged.

Regarding storage tanks, vapor recovery systems are costly and often treat symptoms rather than root causes. From a continuous improvement perspective, intermediate storage represents waste and is frequently used to buffer underlying operational issues. With stable and reliable operations, many storage tanks could be eliminated, thereby reducing associated emissions.

QUESTION: Mr Nabih Matussin to Mr Le Hai Tuan

Do higher crude slate percentages lead to increased energy consumption in refineries, and how does crude slate composition affect refinery energy use?

ANSWER: Mr Le Hai Tuan

Crude slate selection plays a very important role in refinery energy consumption. Processing heavier and more sour crude generally requires higher energy use for treatment, while lighter crude can also increase fuel consumption due to additional heating and vaporization requirements. Therefore, it is necessary to optimize the crude oil slate by selecting appropriate crude properties and balancing these variations to manage overall energy consumption in the refinery.

QUESTION: Mr Nabih Matussin to Mr Le Hai Tuan

From a broader policy and regional perspective, what principles should guide oil sector improvements?

ANSWER: Mr Le Hai Tuan

Across the oil value chain, reliability must be recognized as the foundation of both energy efficiency and emissions reduction. Electrification, CHP, and digital technologies are critical enablers, but their success depends on disciplined operations, simplified system design, and robust inspection regimes. These principles are universally applicable and provide a strong basis for regional cooperation within APEC, particularly in the sharing of best practices and the alignment of technical approaches.

d) Next Step

Summary

Moderators of each fuel sector sequentially presented brief summaries of the discussions from the Day 1 sessions, and provided an overall recap of the topics covered during the workshop.

Session 1 Coal Industry [Dr Atsushi Kurosawa]

Coal is a very attractive resource in terms of reserves and resources in place. However, coal is not a uniform resource in terms of coal rank, mining depth, and technological choices. In this sense, coal resource categories are diverse, and they cannot be treated as equal or homogeneous resources.

Coal can also be upgraded into gases or liquids that are easier to use, and the necessary technologies already exist. However, there is a problem of potential CO₂ emissions. These emissions can be reduced by CCUS technologies. CCS is technically ready to use; however, cost issues remain a major challenge.

While there are many challenges, there are also available technologies. In addition, appropriate institutions are required. It is necessary to consider both the readiness of technology and the readiness of institutions when making future strategic choices for the coal industry.

Session 2 Gas Industry [Mr Rodrigo Martinez]

Regarding the topics included in the gas industry section, the general consensus was that they are comprehensive; however, there are areas that require further focus, as well as additional topics to be included, particularly in exploration and production.

Regarding exploration and production, it was highlighted that maintenance and replacement of high-bleed devices, especially pneumatic equipment, would already deliver significant improvements in energy efficiency and reductions in fugitive emissions. The importance of digital twins for the optimization of operations was also emphasized. Well completion was identified as an area still under development, where cost-effective improvements are expected, although it remains at an early stage. Across these topics, the importance of cost was repeatedly highlighted, as solutions must be cost-effective to gain support from both industry and government.

In processing, maintenance and replacement of high-bleed devices were again emphasized, along with additional challenges related to stationary engines and compressors. A key issue raised was the complexity of processing plants. Certain energy efficiency and fugitive emissions solutions may increase complexity, and the general philosophy is therefore to move toward less complexity in order to improve energy efficiency and reduce emissions. The implementation of technologies and practices will need to be considered on a case-by-case basis, as the economic and financial conditions of asset operations will determine which solutions are viable.

Regarding transportation, the importance of pipeline inspection tools (PIGs) was highlighted. It was also noted that satellite data alone are not sufficient for implementing ground-level solutions, as higher-resolution methane emissions data is required. However, this raises cost and implementation challenges. For storage, maintenance was again identified as a key focus area. With respect to integrating renewable energy into gas storage injection and regasification operations, it was clarified that the use of low-carbon power sources already represents an improvement. Direct integration of wind or solar generation is not necessary, given the technical and business expertise challenges, and there is no need to suggest that the industry move into different business areas.

Overall, cost remains the overarching consideration. In describing achievable solutions and practices, cost-effectiveness must always be addressed.

Session 3 Oil Industry [Mr Muhammad Nabih Matussin]

In exploration and production, the discussion focused on the use of advanced technologies such as electric hydraulic fracturing and automated drilling processes to enhance energy efficiency. The use of advanced reservoir simulation and machine learning algorithms was also discussed. In terms of reducing oil spills, the application of AI and automation can further enhance response times, enable better resource management, and improve spill mitigation.

For transportation, the use of sophisticated hydraulic modeling and optimization was highlighted as a way to minimize pumping and compression energy requirements while maintaining required flow rates and pressures. As mentioned by Mr Henke, efficient loading of crude oil and other products, as well as improved interface management during the transportation of oil products between different locations, can also contribute to efficiency improvements. In addition, to reduce oil spills, the enhanced use of fiber optic sensing was discussed, as it can enable real-time leak detection along thousands of kilometers of pipelines.

In refining, there is potential to replace existing equipment with more efficient alternatives. Examples discussed include increased oxygen enrichment within refineries and further optimization through advanced process control and real-time optimization systems. The use of more efficient power systems to generate electricity from lower-carbon power sources was also highlighted. In addition, flare gas recovery and minimization were discussed as measures that could further reduce fugitive emissions. The potential use of vapor recovery units on storage tanks was also noted; while these solutions are costly, their broader deployment would require stronger support from both industry players and governments.

3-2-2. Closing remarks

Dr Kazutomo Irie, Chairman & President, APERC

Summary

In his closing remarks, Dr Kazutomo Irie, Chairman and President of APERC, expressed appreciation to the speakers and participants for their active contributions to the workshop on cleaner and more efficient operations in the fossil energy industry. He noted that, due to time constraints, not all questions and comments could be addressed during the sessions, but the feedback received is valuable and will be considered in future activities.

Dr Irie highlighted that the workshop featured a wide range of informative presentations and active discussions over one-and-a-half days, making it difficult to comprehensively summarize all outcomes. Nevertheless, he underscored that the workshop served as an important starting point for strengthening cooperation among APEC economies to enhance energy efficiency and reduce emissions in the fossil energy sector.

He further stated that, based on the outcomes of the workshop, APEC intends to continue efforts toward cleaner and more efficient fossil energy operations in the region. Subject to approval by the APEC Energy Working Group, a series of capacity-building workshops focusing on coal, oil, and natural gas, with in-depth discussion of each fossil energy sector, were proposed. Dr Irie concluded by indicating APERC's intention to seek continued cooperation from participating economies and formally adjourned the workshop.

3-2-3. Site Visit

Site Visit Summary

The site visit involved a guided briefing and on-site tour of **the Idemitsu Chiba Complex**, an integrated refinery and petrochemical complex in Chiba, Japan. Participants first received an overview of the complex, including its history, overall layout, and integrated operating structure linking refining, petrochemical production, and logistics. The explanation also covered the role of the complex as a key domestic supply base, as well as the centralized monitoring and control systems that support continuous 24-hour operations.

During the briefing, explanations were provided on crude oil reception and refining processes, including offshore crude oil unloading at the sea berth, atmospheric distillation, and downstream upgrading and desulfurization units that enable the production of low-sulfur fuels and petrochemical feedstocks.

In addition, specific technical initiatives related to energy efficiency were introduced. The participants were informed about the modification of a residual fluid catalytic cracking (RFCC) unit that utilizes surplus oxygen supplied from within the surrounding industrial complex. This project was presented as an example of industrial cooperation that enables energy savings while maintaining strict safety management through detailed risk assessments. It was also noted that manufacturing technologies for sustainable aviation fuel (SAF) have been developed and established in recent years, and that some of these technologies and operational knowledge can potentially be applied to the manufacturing processes of the company's petroleum and petrochemical businesses. Following the briefing, participants took part in a site tour that allowed them to observe key facilities across both the refinery and petrochemical areas. These included crude oil and product storage tanks, major processing units, marine and land-based logistics infrastructure such as jetties, inner harbors, pipelines, and truck loading facilities, as well as lubricant manufacturing units and automated filling operations. Explanations were also provided on how integrated pipelines and shared utilities support efficient material and energy flows within the complex.

Throughout the visit, safety, reliability, and environmental management were highlighted as core operational priorities. Participants were briefed on emergency response and fire-fighting arrangements, seismic reinforcement measures, spill prevention systems, and quality control and environmental monitoring practices, including VOC recovery and the real-time monitoring of air and wastewater emissions.

Overall, the site visit enabled participants to gain a practical understanding of how integrated operations, industrial symbiosis, and robust safety and environmental management are applied in practice at a large-scale refinery and petrochemical complex, providing relevant insights for APEC economies.

4. Appendix

4-1. Agenda

MC: Mr Yoshiaki Imaizumi, Deputy General Manager, APERC

Day 1: (3 December 2025)	
8:30-9:00	Registration (Emerald Room, 28th Floor)
9:00-9:10	Opening Remarks Dr Kazutomo Irie, Chairman & President, Asia Pacific Energy Research Centre (APERC)
9:10-9:25	Keynote Speech Ms Yuna Natsumi, Deputy Director, International Affairs Division, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry (METI), Japan
9:25-9:40	Scene Setting- Mr Rodrigo Martinez, Researcher, APERC
Session 1: Coal Industry	
	Session Moderator Dr Atsushi Kurosawa, Executive Research Fellow, The Institute of Applied Energy (IAE), Japan
9:40-10:00	Indonesia's Coal Sector in the Energy Transition Era Mr Ignatius Wurwanto, Vice Chairman, ESG and Mining Governance, Indonesian Coal Mining Association (APBI-ICMA), Indonesia
10:00-10:20	Upstream Clean Coal Technologies Mr Ben Rice, Head of Government Relations and Media, Low Emission Technology Australia (LETA), Australia
10:20-10:40	Energy Efficiency in Mining Machinery Mr Hisashi Asada, General Manager, Solution Department, Mining Business Division, Komatsu Ltd., Japan
10:40-11:00	Discussion and Q&A
11:00-11:15	Coffee Break
Session 2: Gas Industry	
	Session Moderator Mr Rodrigo Martinez, Researcher, APERC
11:15-11:35	How Canada Reduced Upstream Oil And Gas Methane Emissions By More Than 50% Mr Allan Fogwill, Chief Operating Officer, Petroleum Technology Alliance Canada (PTAC), Canada
11:35-11:55	Upstream Greenhouse Gas Reduction in Malaysia (Introducing BIGST Project) Mr Yoshihiko Enokido, Head, COO Office, Business Division 1, ENEOS Explora Inc., Japan

11:55-12:15	Efforts to Reduce GHG Emissions in Ichthys LNG Project Mr Shinya Konno, General Manager, Oceania Projects Division, Oceania Projects Unit, INPEX Corporation, Japan
12:15-12:35	Discussion and Q&A
12:35-14:00	Lunch (Pearl Room, 26th Floor)
Session 3: Oil Industry	
	Session Moderator Mr Nabih Matussin, Senior Researcher, APERC
14:00-14:20	Refinery production efficiency, challenges and off-gas emissions in the APEC region Mr Kevin Henke, Senior Advisor, HSB Solomon Associates LLC, USA
14:20-14:40	Intelligent Transformation in the Petrochemical Industry: Insights and Practice Dr Jiahang Han, Director of AI Key lab, Research and Development Center, Petro-CyberWorks Information Technology Co., Ltd. (PCICT), China
14:40-15:00	Energy saving improvements and Fuel Gas flaring reduction in Dung Quat Refinery Mr Le Hai Tuan, General Manager, Production Division, Binh Son Refining and Petrochemical JSC (BSR), Viet Nam
15:00-15:20	Discussion and Q&A
15:20-15:30	Group Photo
17:00–19:00	Dinner Reception (Pearl Room, 26th Floor)

Day 2: (4 December 2025)

Discussion Session (Emerald Room, 28th Floor)	
9:00-11:10	1. Coal Session (Moderator: Dr Atsushi Kurosawa, IAE) 2. Gas Session (Moderator: Mr Rodrigo Martinez, APERC) 3. Oil Session (Moderator: Mr Nabih Matussin, APERC) 4. Next Step
11:10-11:15	Closing Remarks Dr Kazutomo Irie, Chairman & President, APERC
11:15-12:15	Lunch (Pearl Room, 26th Floor)
12:35-17:00	Site Visit Idemitsu Chiba Complex

4-2. List of Acronyms

4G – Fourth-generation mobile communication system
5G – Fifth-generation mobile communication system
AI – Artificial Intelligence
APC – Advanced Process Control
APEC – Asia-Pacific Economic Cooperation
APEREC – Asia Pacific Energy Research Centre
APBI-ICMA – Indonesian Coal Mining Association (Asosiasi Pertambangan Batubara Indonesia)
AHS – Autonomous Haulage System
AUD – Australian Dollar
AZEC – Asia Zero Emission Community
BSR – Binh Son Refining and Petrochemical Joint Stock Company
CCS – Carbon Capture and Storage
CCUS – Carbon Capture, Utilization and Storage
CHP – Combined Heat and Power
CMM – Coal Mine Methane
CO₂ – Carbon dioxide
DX – Digital Transformation
EII – Energy Intensity Index
EOR – Enhanced Oil Recovery
FPSO – Floating Production, Storage and Offloading
FOLU – Forestry and Other Land Use
GHG – Greenhouse Gas
GX – Green Transformation
IAE – Institute of Applied Energy
IoT – Internet of Things
IPCC – Intergovernmental Panel on Climate Change
ISO – International Organization for Standardization
LDAR – Leak Detection and Repair
LETA – Low Emission Technology Australia
LNG – Liquefied Natural Gas
METI – Ministry of Economy, Trade and Industry (Japan)
NDC – Nationally Determined Contribution
OGMP 2.0 – Oil and Gas Methane Partnership 2.0
PCICT – Petro-CyberWorks Information Technology Co., Ltd.

PETRONAS – Petroliaam Nasional Berhad
PTAC – Petroleum Technology Alliance Canada
RFCC – Residual Fluid Catalytic Cracking
RBI – Risk-Based Inspection
RTO – Real-time optimization
RUPTL – Indonesia’s National Electricity Supply Business Plan
SAF – Sustainable Aviation Fuel
SINOPEC – China Petroleum & Chemical Corporation
SMS – Safety Management System
SPM – Single-Point Mooring
VLCC – Very Large Crude Carrier
VOC – Volatile Organic Compounds
VAM – Ventilation Air Methane

4-3. Presentation Materials

1. Scene setting: APEC Workshop on Cleaner and More Efficient Operation of the Fossil Energy Industry

2. Indonesia's Coal Sector in the Energy Transition Era

3. Upstream Clean Coal Technologies

4. Energy Efficiency in Mining Machinery

5. How Canada Reduced Upstream Oil And Gas Methane Emissions By More Than 50%

6. Refinery production efficiency, challenges and off-gas emissions in the APEC region

7. Energy saving improvements and Fuel Gas flaring reduction in Dung Quat Refinery

1. Scene setting: APEC Workshop on Cleaner and More Efficient Operation of the Fossil Energy Industry



Context: future of energy demand in APEC

APEC Energy Demand and Supply Outlook 9th Edition

The Reference scenario (REF)

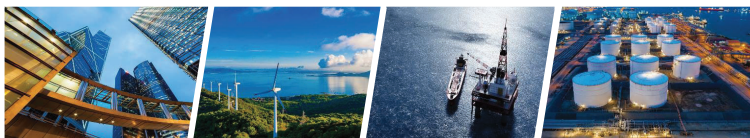
Economy-specific pathways based on **historical trends**, recent developments, and APERC's assumptions about the evolution of the energy system within each APEC economy. REF offers a **baseline to compare with TGT projections**.

The Target scenario (TGT)

A **hypothetical pathway** where each economy **achieves its energy-related policy targets** regardless of cost-effectiveness. When implementation details are lacking, assumptions are inferred from the targets themselves or emissions-related goals.

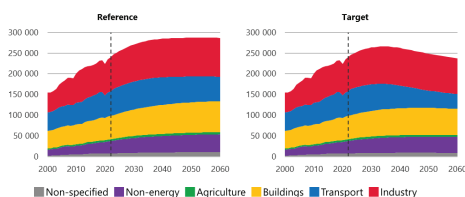


2



Future of energy demand in APEC

APEC total final energy demand per sector in REF & TGT (PJ)



- In REF, total final demand grows from 2022 to 2060 by 19%. Buildings account for the most significant increase in energy use.
- In TGT, total final energy demand peaks in the 2030s and declines 9% from that peak (-1.3% from 2022). The electrification of the transport sector is the primary driver of the decrease in final energy demand.

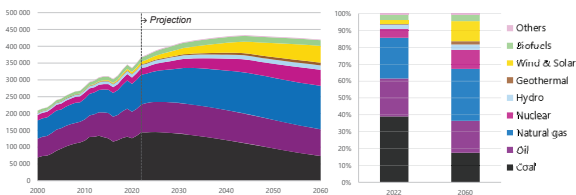


Source: APEC Energy Demand and Supply Outlook, 9th edition.

3

In REF, fossil fuels continue to dominate energy supply

APEC primary energy supply by fuel in REF (PJ)



- Primary energy supply grows by 12% by 2060.
- Fossil fuels' share of primary supply decreases from 86% (2022) to 67% (2060).
- Coal phase-down is uneven; still significant in some economies.
- Renewable energy reaches 21% of primary supply in 2060.

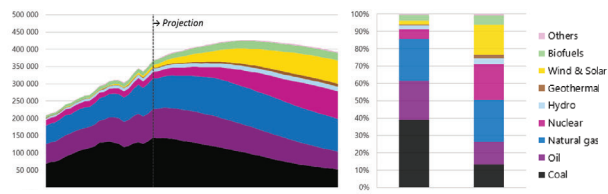


Source: APEC Energy Demand and Supply Outlook, 9th edition.

4

In TGT, renewables rise significantly, but fossil fuels remain essential

APEC primary energy supply by fuel in TGT (PJ)



- Primary energy supply grows by 9% by 2060 in TGT.
- Fossil fuels' share of primary energy supply decreases from 86% (2022) to 51% (2060).
- Renewables' share of primary energy supply rises to nearly 30% in 2060.
- Nuclear increases to 20%, providing low-carbon, dispatchable power.



Source: APEC Energy Demand and Supply Outlook, 9th edition.

5

This workshop responds to the projected long-lasting role of fossil energy in the APEC region

- Fossil energy is projected to remain a significant part of APEC's overall energy mix despite progress in clean energy.
- Improving energy efficiency and reducing fugitive emissions can offer cost and sustainability gains for the fossil energy industry.
- This workshop aims to equip policymakers and officials with practical knowledge on technologies and practices that strengthen efficiency and lower emissions in the fossil energy industry.



6

Focus of today's section: technologies and practices to improve energy efficiency and reduce fugitive emissions

3rd of December

Session 1: Coal Industry

- Indonesia's Coal Sector in the Energy Transition Era
- Upstream Clean Coal Technologies
- Energy Efficiency in Mining Machinery

Session 2: Gas Industry

- How Canada Reduced Upstream Oil And Gas Methane Emissions By More Than 50%
- Upstream Greenhouse Gas Reduction in Malaysia (Introducing BIGST Project)
- Efforts to Reduce GHG Emissions in Ichthys LNG Project



7

Focus of today's section: technologies to improve energy efficiency and reduce fugitive emissions

3rd of December

Session 3: Oil Industry

- Refinery production efficiency, challenges and off-gas emissions in the APEC region
- Exploration and Practice of Intelligent Transformation and Upgrading in the Petrochemical Industry
- Energy saving improvements and Fuel Gas flaring reduction in Dung Quat Refinery



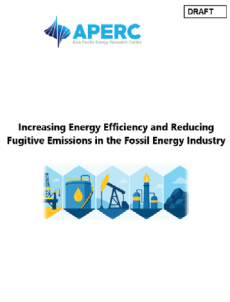
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Focus of tomorrow's section: discussion of the most impactful solutions for the improvement of the fossil energy industry

Discussion guidelines:

- Do you have any issues or new findings that are not listed in the summary of the background research report?
- Do you have any opinions that differ from the background research report?
- Do you have any real examples and on-site situations?

Note: speakers and participants received a copy of the background research report, along with a summary in table format.



9

Tomorrow's discussion will follow the structure of the background research report

Session 1: Coal Industry (35 min)		
	Energy efficiency	Reducing fugitive emissions
Mining Operations		
Processing and Preparation		
Transportation		
Session 2: Gas Industry (35 min)		
	Energy efficiency	Reducing fugitive emissions
Exploration and Production Processing		
Transportation		
Storage		



10

Next steps

- By the end of this workshop, participants will have a stronger understanding of the technologies and practices that improve energy efficiency and reduce fugitive emissions in their domestic fossil energy industry.
- Insights from today's discussions will guide our next steps as we develop the most useful resources for the APEC region, through future capacity building workshops and concise and actionable guidance for policymakers in the upcoming years.



11



Thank you.
<https://aperc.or.jp>



2. Indonesia's Coal Sector in the Energy Transition Era





APBI-ICMA
ASosiasi Pertambangan Batubara Indonesia
INDONESIAN COAL MINING ASSOCIATION

Indonesia's Coal Sector in the Energy Transition Era

Ignatius Wurwanto
Vice Chairman for ESG and Mining Governance APBI-ICMA
APEC 2025 – 3 and 4 December 2025

Visit our website
www.apbi-icma.org

ABOUT APBI-ICMA

36 Thirty Six Years of Dedication
Founded on 20 September 1989 in response to the challenges of member economies coal mining industry

66.5% Members of association contribute of total production in 2024

Primary Members Based on the Business License

Category	Count
CCOW	96
UP OP	26
UP OP	44

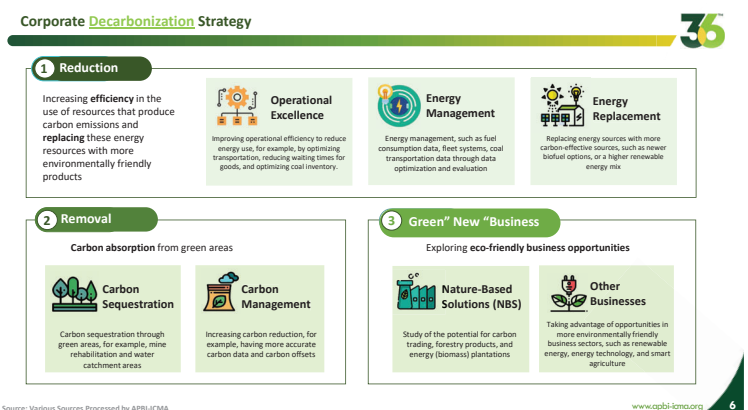
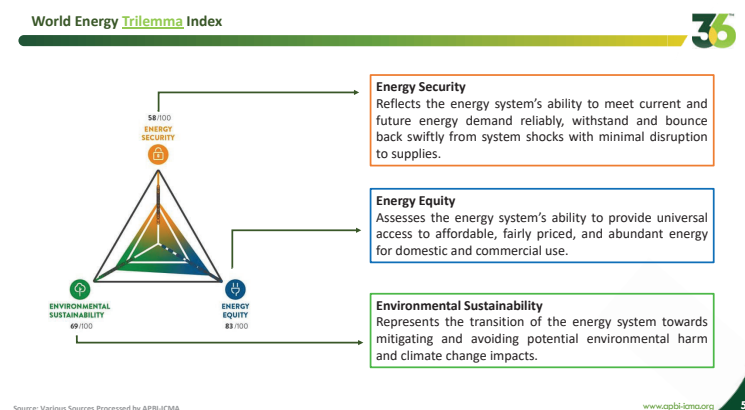
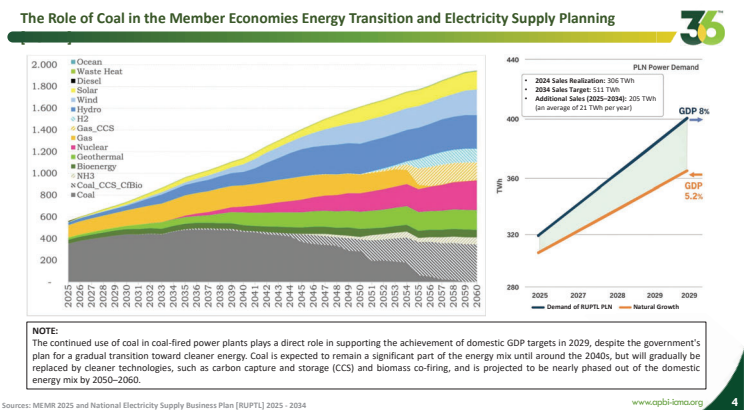
Associate Members Based on the Business License

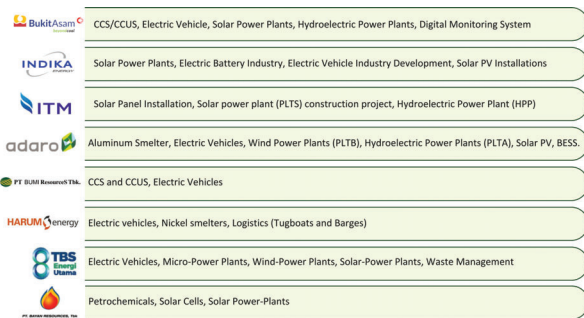
Category	Count
TRADER	61
CONSUMPT	16
INDUSTRI	8
CONTRACTOR	15
OTHERS	9

Some of APBI-ICMA Members









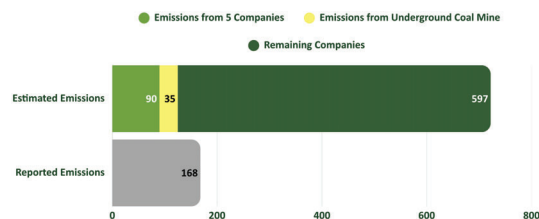
Source: Various Sources Processed by APBI-ICMA

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7

Five companies alone account for half of reported emissions, revealing major underreporting.

Coal Mine Methane Emissions in 2024 (kt CH₄)

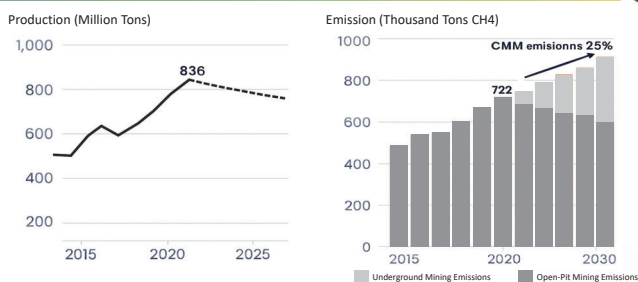


NOTE: The five companies reporting CMM emissions are Bukit Asam Tbk., Golden Energy Mines Tbk., Indo Tambora Raya Megah Tbk., Kideco Jaya Agung, and TBS Energi Utama Tbk. All of them are APBI-ICMA members.

Source: Ember Analysis, Handbook of Energy and Economic Statistics of Indonesia

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8



NOTE: This position is justifiable. Given the higher emissions associated with underground mining, coal downstreaming is being encouraged as a mitigation strategy. However, the associated costs are still relatively high at this stage.

Source: Ember Analysis

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9

Sector	GHG Emission Level 2010* (MTon CO ₂ -eq)	GHG Emission Level 2030 (MTon CO ₂ -eq)				GHG Emission Reduction (MTon CO ₂ -eq) Annual Average Growth BAU (2010-2030)				Annual Average Growth BAU (2010-2030)	Average Growth 2000-2012
		BAU	CM1	CM2	CM1	CM2	CM1	CM2	CM1		
1. Energy*	453.2	1,669	1,31	1,22	358	446	12.5%	15.5%		6.7%	4.5%
2. Waste	88	296	256	253	40	43	1.4%	1.5%		6.3%	4%
3. IPPU	36.9	66.9	63	61	7	9	0.3%	0.3%		3.4%	0.10%
4. Agriculture	110.5	119.66	110	108	10	12	0.3%	0.4%		0.4%	1.3%
5. Forestry and Other Land Uses (FOLU)**	647	714	214	-15	500	729	17.4%	25.4%		0.5%	2.7%
TOTAL	1,334	2,869	1,95	1,63	915	1,240	31.89%	43.20%		3.9%	3.2%

CM1 : Counter Measure 1 (Unconditional Mitigation Scenario)
CM2 : Counter Measure 2 (Conditional Mitigation Scenario)
*) Including Fugitive
**) Including Emission from Estate and Timber Plantation

~60%

The forestry sector has the LARGEST share in the domestic greenhouse gas emission reduction target.

NOTE: In accordance with Decision 1/CMA.3 (Glasgow Climate Pact), it has been requested to revisit and strengthen their 2030 NDC targets. Indonesia responded by submitting its Enhanced NDC on 23 September 2022, raising its emission reduction targets to 31.89% (unconditional) and 43.20% (conditional). The Enhanced NDC serves as a transition toward Indonesia's Second NDC.

Source: Various Sources Processed by APBI-ICMA

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1. Coal Production Control

- Imposition of a moratorium on new coal mining permits.
- Establishment of long-term production limits aligned with energy needs and climate objectives.
- Adjustment of annual production plan approvals (RKAB) in accordance with long-term production limits.

3. Implementation of CMM Capture and Utilization

- Prioritizing methane drainage in underground mines with high emission levels
- Initiating feasibility studies and pilot projects for other mitigation technologies, such as ventilation air methane (VAM) oxidation and pre-mining drainage in surface mines

2. Improvement of CMM Monitoring, Reporting, and Verification Mechanisms

- Development of Indonesia's CMM emission factors by incorporating coal basin characteristics, mining depth, and coal calorific value.
- Requiring direct measurements for underground coal mines to reduce uncertainty and enhance safety.
- Mandating facility-level emission reporting as part of the annual production plan (RKAB) approval process.

4. Facilitating a Just Transition in Coal-Producing Regions

- Establishing a coordination framework between central and regional governments on just transition initiatives
- Developing roadmaps and just transition programs at the regional level
- Mobilizing financing to support the implementation of just transition programs

THANK YOU

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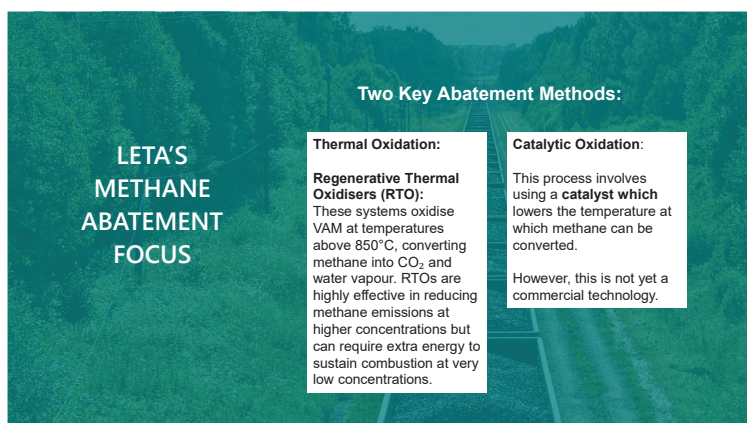
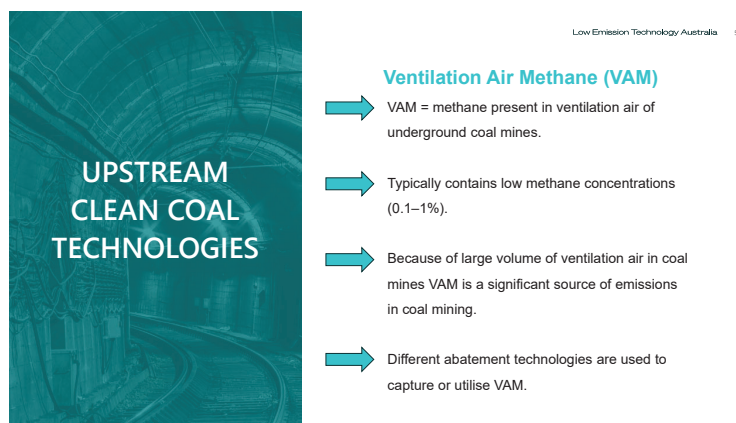
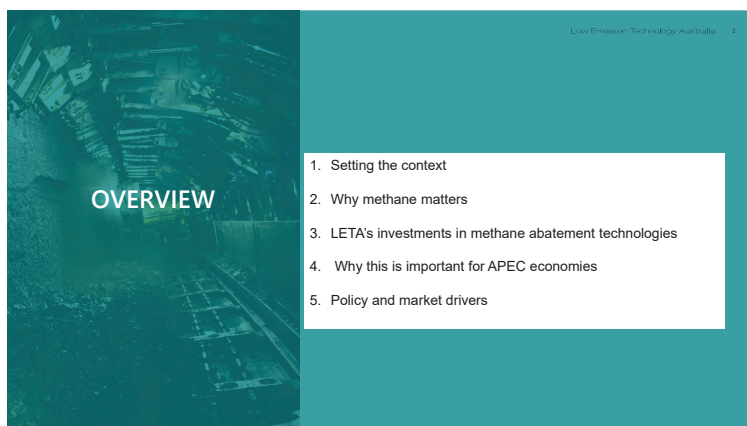


Source: Ember Analysis

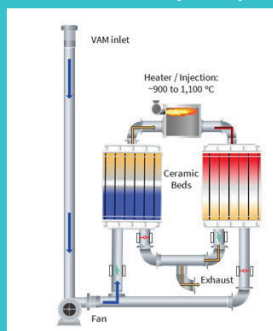
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3. Upstream Clean Coal Technologies



REGENERATIVE THERMAL OXIDISERS (RTOs)



- Regenerative Thermal Oxidisers utilise a ceramic bed to oxidize VAM.
- Capable of operating on methane concentrations down to 0.4%.
- LETA is working with Anglo American on deploying an RTO at a Queensland mine site.
- Project goals:
 - Equip the industry with a technology to safely and effectively reduce methane emissions from gaseous coal mines in line with the safeguard mechanism.
 - Provide a project implementation methodology for other mines to follow when developing their own VAM abatement projects.

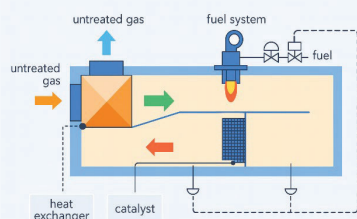
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RTO: TECHNICAL AND SAFETY CHALLENGES

- Methane concentration:**
RTOs require methane concentrations in the ventilation air to fall within a certain operating window to sustain efficient and stable combustion.
- Low methane levels:**
If methane concentrations are too low, as is often the case in Australia, where some mines have less than 0.3–0.4% methane in VAM, the RTO may require supplementary fuel to maintain the temperatures needed for oxidation.
- High methane levels:**
If methane levels are unexpectedly high, the system must safely divert or dilute the gas to prevent overheating.
- Fluctuating gas levels:**
Coal mines experience fluctuating gas levels over time due to changing geology, production rates and operating conditions.

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CATALYTIC VAM ABATEMENT

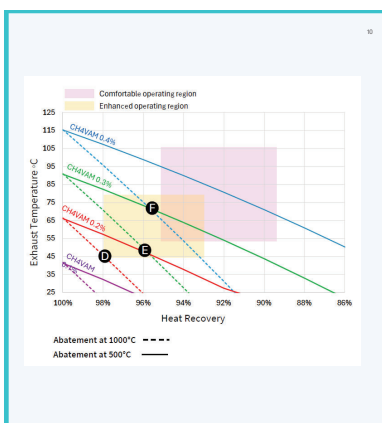


- Catalytic technology for VAM abatement operates in a similar manner to RTOs but employs catalysts to trigger the conversion reaction.
- This enables the system to operate at lower temperatures and lower methane concentrations.
- The catalysts are placed with the heat exchange media in the bed increasing the total column of material.
- Catalytic reactors operate at lower temperatures, ranging between 300°C to 500°C, below the auto ignition point of methane.
- Working with Mining3, LETA is assessing the suitability of the technology for safe deployment at scale in Australia.

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CATALYTIC VAM ABATEMENT

- This chart illustrates why catalytic abatement technologies will play an important role.
- The purple box represents the practical operating range of current RTO technology.
- RTOs would need greater than 98 per cent heat recovery efficiency to operate at 0.2 per cent methane concentration levels.
- This level of heat recover would be extraordinarily hard (if not impossible to achieve).



10

CATCH4 PROGRAM



- LETA and industry partners have invested in a multi-phase program called **CATCH4 (Catalytic Oxidation of Methane)** led by the Australian company Mining3.
- The goal is to develop, test, and commercialise a catalytic oxidiser specifically designed for mine ventilation air methane.
- The program is structured in four phases, moving from laboratory research through to full-scale mine deployment.
- Phase 1, which has now been completed, involved:
 - Laboratory testing of multiple catalyst formulations under VAM like conditions.
 - Identification of catalyst materials that can consistently oxidise methane at temperatures below about 550°C.
 - Development of an initial pilot unit design and preparation of capital and operating cost estimates.

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- Phase 2 of CATCH4 is now underway and is focused on field testing catalytic oxidisers at an operating underground coal mine.
- A pilot unit is being installed to treat around one cubic metre per second of ventilation air drawn from a mine duct or shaft.
- The trial will examine how the catalyst performs with real mine air that contains dust, humidity, and fluctuations in methane concentration and airflow.
- Data will be collected on methane destruction efficiency, pressure drop, maintenance requirements, and operating costs.
- If the results are positive, Phase 3 and Phase 4 will scale up to larger demonstration units capable of treating the airflow from a typical ventilation shaft.



METHANE'S CLIMATE IMPACT AND NEAR-TERM OPPORTUNITY

- Methane (CH_4) is a potent greenhouse gas with a much higher warming effect than carbon dioxide (CO_2) on a tonne-for-tonne basis.
- Over a 100-year time horizon, one tonne of methane has a warming impact roughly 28 times that of one tonne of CO_2 .
- Methane has a relatively short atmospheric lifetime of around 10 to 12 years, compared with CO_2 , which persists for centuries.
- This combination of high short-term potency and short lifetime means that cutting methane now can have a rapid and noticeable effect on global temperature trends.

BENEFITS FOR AUSTRALIAN TRADING PARTNERS

- Upstream methane abatement reduces the emissions associated with coal exported from Australia.
- Power generators and steelmakers in China; Japan; and Korea can report lower scope 3 emissions when they purchase coal with a reduced upstream footprint.
- This supports their own national climate commitments and corporate net zero strategies.
- It demonstrates that traditional energy and industrial supply chains can be made cleaner through technology rather than being shut down.

POLICY AND MARKET DRIVERS IN AUSTRALIA

- Australia has strengthened its Safeguard Mechanism, which now sets declining emissions baselines for large industrial facilities, including coal mines.
- Facilities that emit less than their baseline can generate Australian carbon credit units, while those that exceed their baseline must purchase credits.
- This embeds a cost for unabated methane emissions and a value for emissions reductions achieved on site.
- Federal and state governments are also providing targeted funding and grants for innovation in methane abatement from coal mining.
- Policy signals are therefore aligned with LETA's work by encouraging investment in VAM abatement technologies and projects.

ECONOMIC INCENTIVES

- In the first compliance year of the revised Safeguard Mechanism, Australian coal mines collectively needed to surrender an estimated 3 to 4 million tonnes of carbon credits.
- At a carbon price of roughly 30 to 35 Australian dollars per tonne of CO_2 equivalent, this represents a cost well in excess of 100 million dollars.
- On site methane abatement reduces the number of credits that mines need to buy in future years.
- Each tonne of methane destroyed on site reduces both compliance costs and emissions liabilities.
- Over time, investment in abatement infrastructure can therefore pay for itself through avoided carbon credit purchases, alongside the climate and reputational benefits.

KEY MESSAGES

- Methane from coal mines is a significant but also an actionable source of greenhouse gas emissions.
- Upstream clean coal technologies, such as RTOs and catalytic oxidisers, can reduce fugitive methane emissions without compromising on safety.
- RTOs are ready for deployment in mines with suitable methane concentrations, and catalytic systems are being developed to cover low methane conditions.
- Policy frameworks and carbon markets in Australia are sending clear signals that methane emissions carry a cost and that abatement has value.
- Technologies being proven in Australian mines can be adapted and applied in other APEC economies to clean up existing coal supply chains.

CONCLUSION

- Reducing fugitive methane from coal mining is a critical and achievable step toward cleaner fossil energy operations.
- Through organisations like LETA and with support from government and industry, Australia is piloting and proving technologies that can be shared globally.
- Ventilation air methane abatement cuts emissions and strengthens the long-term sustainability of coal supply chains.
- APEC economies have an opportunity to lead on methane mitigation by collaborating on technology, standards and finance.
- Thank you for your attention. I look forward to discussing these ideas further and exploring potential partnerships.

Arigatou gozaimasu!



4. Energy Efficiency in Mining Machinery



Energy Efficiency in Mining Machinery

APEC Workshop, 2025/12/3-4

Cleaner and More Efficient Operation of Fossil Energy Industry

Hisashi Asada
General manager, Mining Business Division
Komatsu Ltd.

Komatsu Mining Product Offerings



KOMATSU

APEC Workshop 2

Komatsu Mining Offerings – Products & Processes

	Surface Mining	Hard Rock (UGHR)	Soft Rock (UGSR)
Products	Haul trucks Hydraulic shovels and excavators Dozers Motor graders Electric mining shovels Draglines Electric and Mechanical drive wheel loaders Rotary blasthole drills Track loadhaul drills CPAs	Trucks Loaders Rock drills & bolters Load haul dumps Hydraulic cutters Mechanical cutter Tunnel boring machine (TBM)	Logistical systems Room and pillar systems Entry development systems Crushing
Process	MODULAR platform & solutions Payload optimization Autonomous haulage Operator training simulator & solutions	Operator training simulator & solutions Operational optimization platform for underground mining	MST

KOMATSU

APEC Workshop 3

Roadmap to Komatsu's vision :the future mining

- Products: Improve efficiency (incl. on-machine automation), reduce CO2 emissions
- Processes: Improve efficiency throughout all workplace processes



KOMATSU

APEC Workshop 4

Mining machinery business and Carbon Neutrality

Carbon neutrality is a major challenge for the mining machinery business, and it cannot be solved by one solution, but aims to solve it from multiple aspects.

	Risk (Challenges)	Action Plan
Voice of customer International Council on Mining and Metals (ICMM)	• by 2040: Greenhouse gas emission-free at surface mining. • by 2025: Minimize the operational impact of diesel exhaust at underground mining. • by 2025: Make collision avoidance technology available to mining companies. • Common focus of major mining companies: "safety and productivity improvement by automation" & "greenhouse gas reduction".	• Machine efficiency improvement through operational optimization • Electrification, zero-emissions • Automation and traffic control technologies • Two-pronged approach of improvements, in "Products" and "Processes". Create highly productive workplaces of the future.
Changes in social situation	• Due to the difficulty of obtaining licenses for new mine development, it will be necessary to mine further away from residential areas than before. • Due to the higher cost of surface mining for deeper deposits, mining at deeper depth will be necessary. • Mining contractors will face difficulties to secure work forces due to more severe operating site environment.	• Remote operation (remote control) • Automation, optimization and solution • Correspond to change in customer's requirement. "Further remote places" "Further deep in underground"

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APEC Workshop 5

Initiatives for GHG Reduction – Electrification of Mining Machinery

Komatsu is collaborating with major mining companies to reduce GHG emissions by electrifying mining machinery.

Komatsu GHG Alliance

12 Major mining companies



- GHG alliance member event (May 2023)
 - Invited GHG Alliance members to Arizona proving ground.
 - Introduced battery charging technology using trolley system.



To provide know-how of mining operation including mine design, plan, methodology, infrastructure etc.

- No of trucks, Haul road
- Infrastructure
- Payload, cycle time
- Maintenance

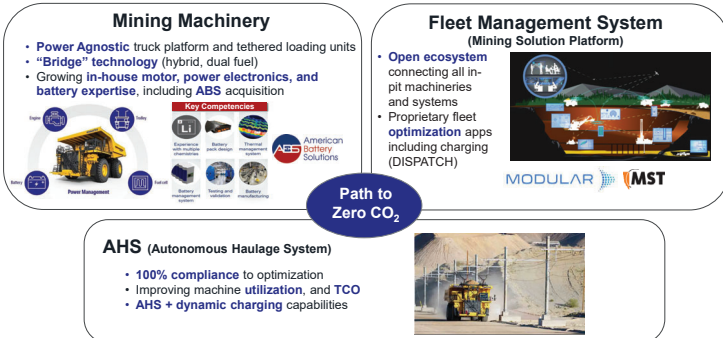
To provide information of product planning, development, test, development of Power Agnostic Dump Trucks*

*Power Agnostic Dump Trucks : Concept for a mining haulage vehicle that can run on a variety of power sources including diesel electric, electric, trolley (wired), battery power and even hydrogen fuel cells to support customers achieve reduction of zero emission of GHG.

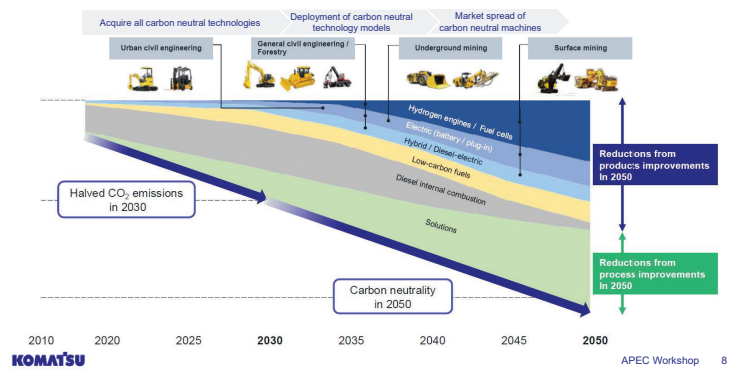
KOMATSU

APEC Workshop 6

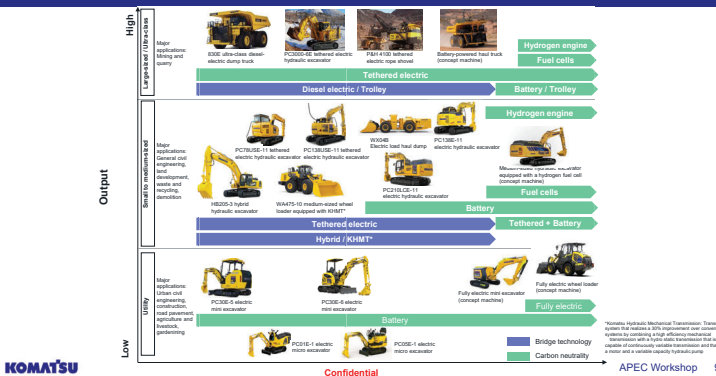
Komatsu Decarbonization Ecosystem Strategy



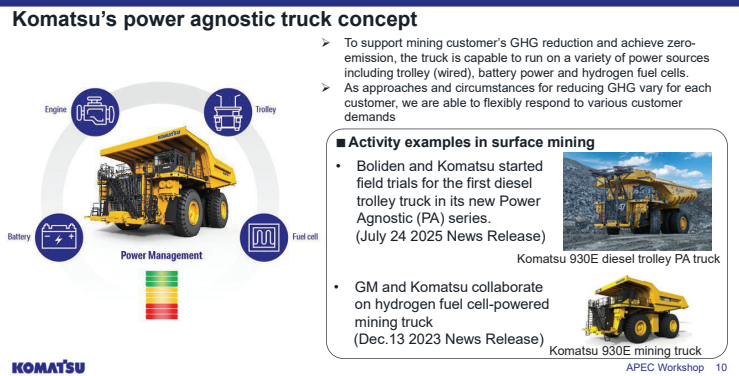
Roadmap for achieving carbon neutrality



Development roadmap for carbon neutrality by products



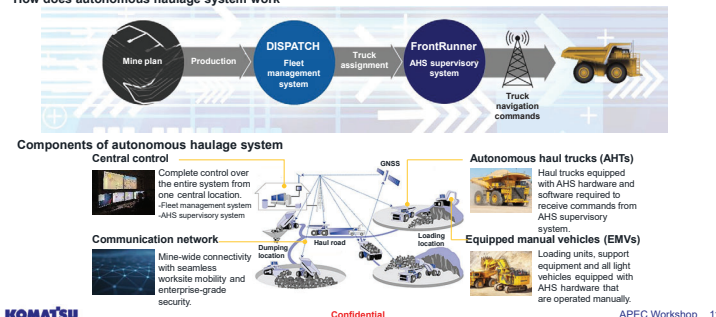
Initiatives for GHG Reduction – Power Management for Mining Machinery



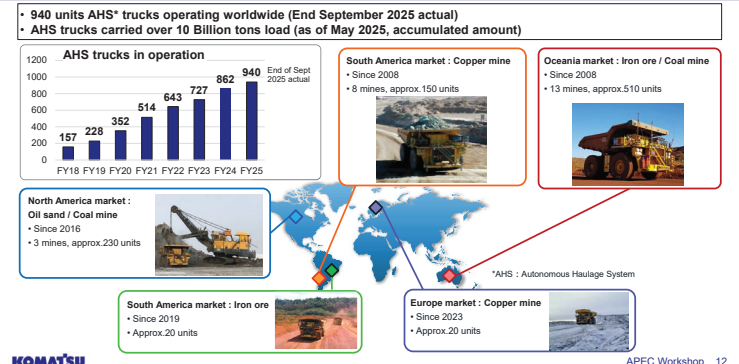
Efforts for Automation : Autonomous haulage system (AHS)

Komatsu's AHS contributes to safe and continuous operation, GHG reduction, and improved productivity.

How does autonomous haulage system work

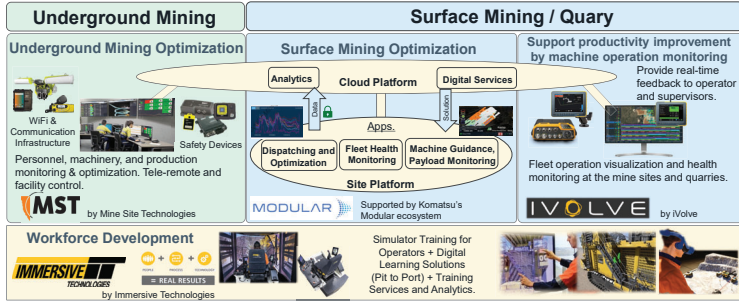


Mining Automation – Promoting GHG reduction by the deployment of AHS



Solution business for mining and quarry customers

Komatsu through its group companies offer multiple all-makes solutions contributing for **haul mine process optimization**, **customer workforce development** for surface/underground mines and quarries to achieve **GHG reduction**.
all makes providing service to non-Komatsu machinery as well

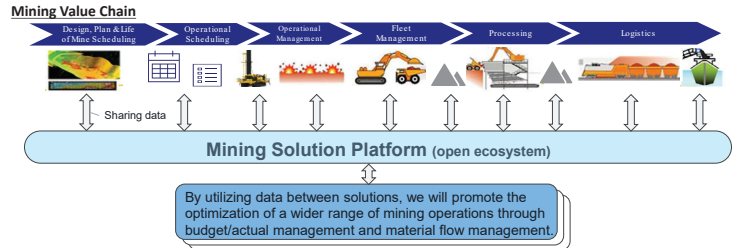


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Whole of Mine Optimization by Solution Platform

Until now, optimization solutions within each mining operation have progressed. Each solution needs to share data on a common platform to optimize a wider range of mining operations.

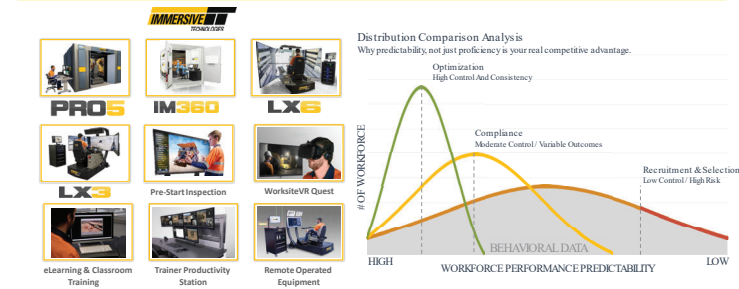


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Further improve GHG emissions by maintaining the highest level of human performance

With the aim of improving human operations of mining machinery, Komatsu provide a training UX by mining machinery simulators and new technology.



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Contribution to GHG reduction by operator trainings (example)

The case of Oceania Coal mining customer

The customer's problem

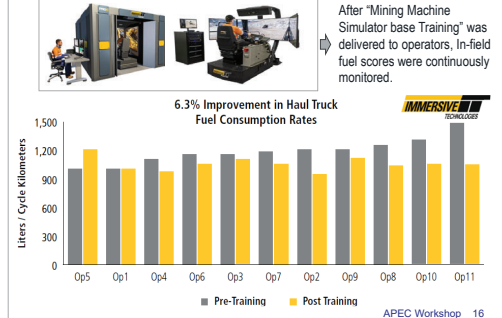
The company had an initiative to address rising fuel costs and greenhouse gas emissions.

Solution

Historical fuel consumption rates were benchmarked, and operators were randomly assigned to either a training or control group. The training group received **simulator based sessions** targeting several common operating errors including aggressive throttle application, aggressive braking and speed control. The control group received no instruction.

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Results



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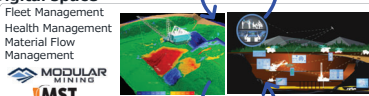
Contribution to Energy Efficiency by Realizing the Value Chain of Mining Machinery and Solutions

Real Space



KOMATSU provide **smarter and greener mining machinery** for actual operations, optimize actual operations with **digital solution apps**, and provide **offline training** for personnel who operate them to maintain continuous and advanced on-site operations and further improve efficiency.

Digital space



Operator Skills Management



Solutions for Mining Machinery

- Remote support for operations from a bird's eye view.
- Data-driven guidance for optimal operations.
- Data-driven guidance for optimal maintenance.

Solutions for Operators

- Optimal training is conducted in a simulator based on actual machine data. Strengthen your skills with repeated offline training.
- Emergency Training that is difficult to perform with the actual machine can also be carried out.
- Extracted from the simulator's training data
- Feedback points to the real world.

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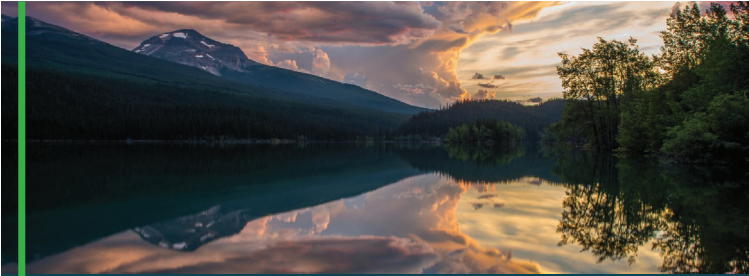
KOMATSU

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Thank you

5. How Canada Reduced Upstream Oil And Gas Methane Emissions By More Than 50%



HOW CANADA REDUCED UPSTREAM OIL AND GAS METHANE EMISSIONS BY MORE THAN 50%

November 2025





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Agenda



History and Policy Evolution

Methane Emissions Reduction Ecosystem

- What it is
- Key Canadian Organizations, including PTAC

Innovation as a key solutions pathway

- What we have achieved
- Case studies

Where we go from here



Fieldwork Conducted for the Methane Slip Project

Early Awareness and Research Initiatives



Recognition of Methane Impact

- Early 2000s saw growing awareness of methane's environmental effects in the oil and gas sector.

Initial Emission Studies

- Studies focused on inventorying emissions and identifying major methane sources like pneumatic devices, venting, and fugitive emissions.
- Industry-Government Collaboration: Pilot projects and best practices developed through joint efforts.
- Ongoing Evolution: Continuous updates to regulations and best practices.

Foundation for Future Initiatives

- These efforts laid the groundwork for structured and large-scale methane mitigation initiatives.

Canadian Government Policy Milestones



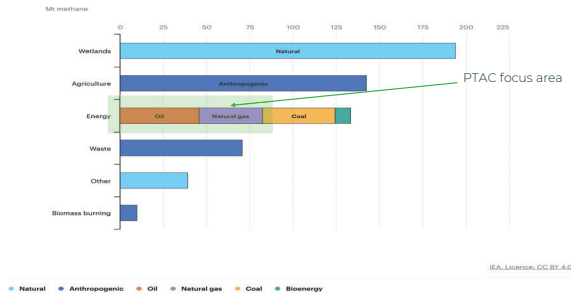
YEAR	EVENT
2000–2015	Limited federal action on methane; focus on CO ₂
2016	Canada pledges 40–45% methane reduction compared to 2014 by 2025
2018	Federal CEPA regulations published
2020	Regulations come into force
2021	Canada joins Global Methane Pledge
2022	Canada's Methane Strategy launched
2023–2025	Draft amendments released; satellite data confirms reductions

Provincial methane policy highlights



PROVINCE	REDUCTION TARGET	KEY REGULATIONS	EQUIVALENCY STATUS	MONITORING APPROACH
Alberta	45% by 2025	Directive 060, 017, MERR	Yes (2020–2030)	Satellite + Alt-FEMP
British Columbia	45% by 2025, 75% by 2030	CleanBC Methane Regs	Yes (2025)	Aerial + Continuous
Saskatchewan	45% by 2025	OGEMR, MAP	Yes (2025)	LDAR + Pneumatics
Ontario & Quebec	50% by 2030 (landfills)	Federal landfill regs, Quebec offset credits	N/A	Surface + Point-source

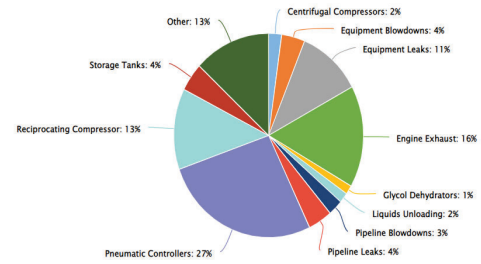
Sources of Methane



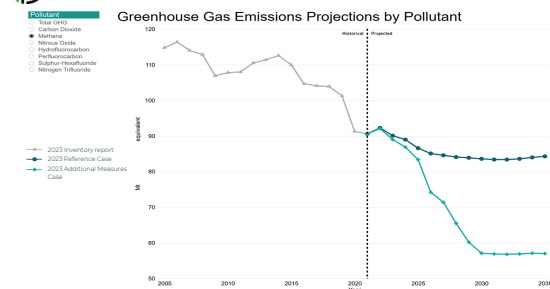
Oil and Gas Industry Sources of Methane



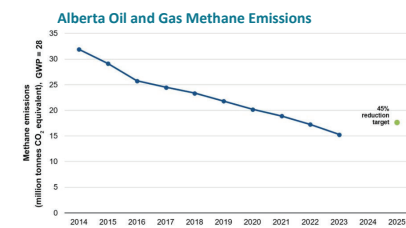
Percent of Total Oil and Gas Methane Emissions by Emission Source (Year 2021)



CANADIAN METHANE EMISSIONS



PROVINCIAL PERFORMANCE



- British Columbia: in 2023, achieved a **51%** reduction from 2014.
- Alberta: in 2023, achieved a **52%** reduction from 2014.
- Saskatchewan: in 2024, achieved a **71%** from 2015.

Technology Innovation is a Key Solutions Pathway



Development of Methane Sensors

- On-site: is useful for the mitigation of emissions from specific pieces of equipment
- Vehicle-mounted: is used for the mitigation of emissions for a specific site
- Drones and Aircraft: are useful for the identification of emission sources in a localized area, limited usefulness for the assessment of mitigation solutions
- Satellites: are useful for regional and global emissions identification, have limited usefulness for quantification, not useful for assessment of mitigation solutions



Development of Methane Mitigation Solutions

- Leak Detection and Repair: the cheapest and easiest solutions – basic maintenance
- Pneumatics: low-cost solutions – low bleed or no bleed
- Storage Tanks: limited solutions due to poor operational characteristics
- Engines and Compressors: complex solutions requiring expensive replacements and retrofits

PTAC Methane Programs



Research & Innovation

- To develop technologies, processes and databases to improve methane mitigation

Technology Development

- To derisk methane emissions and reduction technologies through field trials, thereby accelerating adoption

Commercial Implementation

- To deploy methane emissions reduction technologies at well sites

International Collaborations

- To expand access and options for methane reduction technologies globally



Development of Best Mitigation Practices



Methane Emission Protocols

- Protocols target key methane sources including well cement integrity and leak detection methods. These protocols improve emission monitoring accuracy.

Operational Compliance Steps

- BMPs provide practical steps for operators to enhance compliance and operational efficiency in managing emissions.

Emission Reduction Impact

- Adopting BMPs has led to measurable methane emission reductions and improved environmental outcomes sector-wide.

13

Project Highlights



Management Practices for Methane Emissions in Stationary Engines

- Project assessed 110 stationary engines (mainly Caterpillar and Waukesha) for their emissions parameters in field conditions. Best management practices and design changes were developed, as well as adjustments to a Canadian equipment database used by Environment and Climate Change Canada (ECCC).



New Technology to Reduce Methane Emissions from Stationary Engines

- Successfully tested an Oxiperator technology designed to eliminate uncombusted methane emissions in stationary engines.



Alberta Methane Field Challenge

- Collaborative field trials to assess real-world performance of new methane sensing technologies to speed up adoption by the regulator.

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Additional Project Highlights



Decommissioning Barrier Materials

- Testing six barrier materials for well plugging and decommissioning, showing a need for better tools and procedures to reduce the number of interventions required to stop surface casing vent flows



Replacement of Class G Cement

- Testing alternative Portland cement mixes to replace Class G cement in Canadian oil and gas wells, following its discontinuation by a major supplier due to its higher emissions during manufacturing



Decommissioning Strategies for Oil & Gas Wells

- Will evaluate sealing cement methods to eliminate surface casing vent flows and guide producers on effective treatment options

15



Technology Development

Canadian Emission Reduction Innovation Consortium (CanERIC)

Funding
Leverage
Ratio

2:1

PURPOSE

- To de-risk methane emissions detection and reduction technologies through field trials

CanERIC 1.0

- Addressing real-life technology issues related to costs, installation, and maintenance
- 3 years, 31 subprojects, 53 sites from 27 participants

CanERIC 2024

- Focusing on tanks and lower cost pneumatics solutions
- One-year installment, 5 producers, 7 technologies, deployed at 22 sites

OUTCOMES AND LEARNINGS

- Acceleration of technology adoption by producers
- Helping vendors make improvements to better meet end-users' needs
- Contributed to the ~52% methane emissions reduction achieved by industry

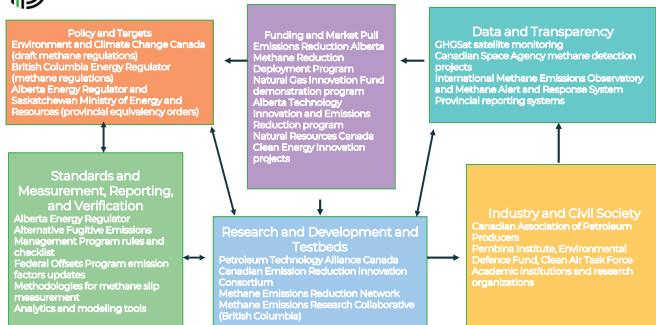
Committee Participants



16



Canada's Methane Emissions Reduction Technology Development Ecosystem Map



17

Lessons Learned (so far)



Regulations:

- Federal requirements + provincial equivalency agreements drove early success; 40–45% reduction exceeded ahead of 2025 targets.

Technology:

- Leak Detection and Repair (LDAR), pneumatic device replacements, and vapour recovery units widely adopted; cost-effective and production-friendly.

Economic Opportunity:

- Over 130 Canadian firms in the methane tech sector; job creation and global leadership potential.

Collaboration:

- Federal-provincial agreements and engagement with industry are essential for continuous reductions.

18

Collaboration with like-minded organizations



Industry Challenges and Opportunities for Methane Reduction

- Sharing PTAC's learnings of the key focus areas for oil and gas producers and how methane emissions reduction technology solutions and business process improvements are considered.

Technologies Available

- Sharing PTAC's assessments of various technologies for deployment in oil and gas upstream operations
- <https://ptac.org/wp-content/uploads/2024/04/Advancing-to-Net-zero-Report.pdf>

Industry Connections

- Assisting APERC with connections in the upstream oil and gas sector to facilitate information gathering, policy and regulatory understanding, and changes in the sector

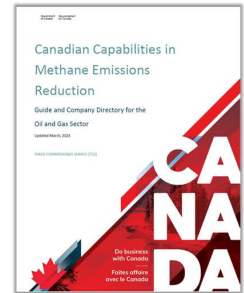
19



METHANE MONITORING, QUANTIFICATION, and ABATEMENT

- Featuring 60 Canadian energy cleantech companies.

- Full PDF available here:



20



PTAC
THANK YOU!

PETROLEUM
TECHNOLOGY
ALLIANCE
CANADA

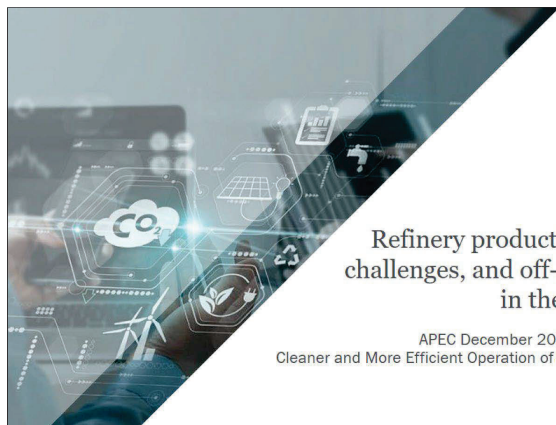
Canada's success demonstrates scalable methane reduction strategies for the oil and gas sectors globally.

Proven technologies (LDAR, pneumatics, vapour recovery) offer cost-effective solutions for international adoption.

Collaborative frameworks between government and industry can accelerate global methane mitigation efforts.



6. Refinery production efficiency, challenges and off-gas emissions in the APEC region



Refinery production efficiency, challenges, and off-gas emissions in the APEC region

APEC December 2025 Workshop in Tokyo
Cleaner and More Efficient Operation of Fossil Energy Industry

SOLOMON

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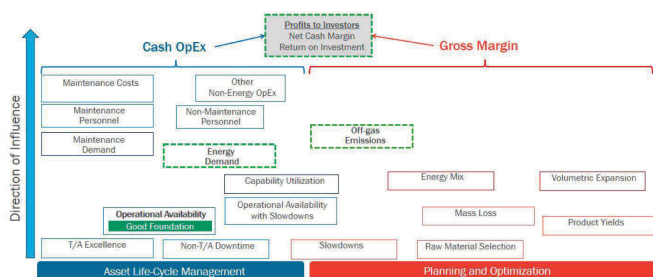
Global Energy Performance Information
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Solomon Refining and Petrochemical KPIs

Actionable Insights into Resilience, Resource Utilization, and Reliability



KPI = Key Performance Indicator, T/A = turnaround, OpEx = operating expense

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Solomon Associates

Trusted advisor to the global energy industry

Global leader in benchmarking the energy value chain – upstream to downstream – since the early 1980's

Largest, historical, proprietary database in the industry, covering over 85% of the world's refining capacity

Created standardized performance measurements and metrics for the industry, including custom emissions reduction metrics, like CWB

Created a language of continuous improvement to support our clients' success



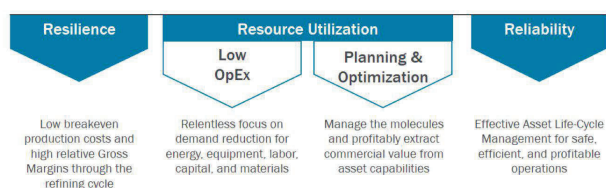
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What it Takes to Survive and Thrive in Petroleum Refining

Resilience, Resource Utilization, and Reliability (RRR)



Frequent performance benchmarking against better performing peers is essential to drive continuous improvement in each of these areas

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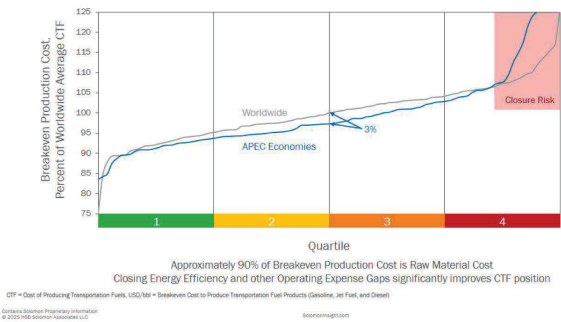
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Resilience

Competitiveness and Survivability

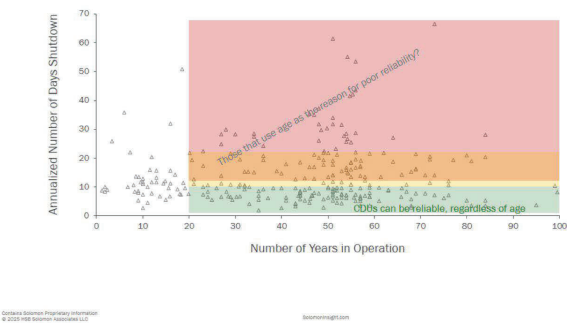
Break-even Production Cost (Transportation Fuel Products)



Reliability

Aging Atmospheric Crude Distillation Units (CDUs)

2024 Study (APEC Economies)



Unreliability, Waste, and Inefficiency

Importance of Refinery Reliability in production efficiency and reducing off-gas emissions

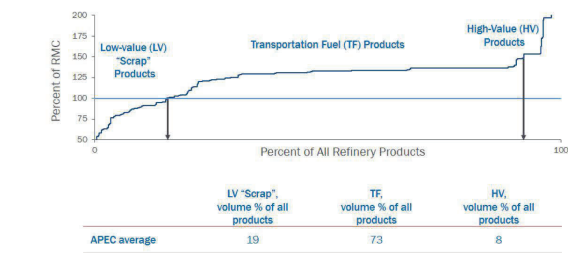


Flaring and cooling tower plumes are indicators in underlying reliability and efficiency performance gaps. All energy consumption above the minimum energy required becomes waste heat rejected to air, directly or via cooling water.

Resource Utilization

Effective Use of Raw Material

Upgrading of Crude Oil and Other Raw Materials



2024 Study



ExcerptInsight.com



Achieved a Step-Change Improvement in Energy Efficiency in two biennial Solomon Study Cycles



Reduced Steam System Size

Scanned with CamScanner



The Whole is Greater than the Sum of its Parts

-

Incremental economics can be misleading

Improve economic thinking skills, including total life-cycle cost analysis

<https://www.solomoninsight.com/blog/overcoming-obstacles-to-improve-energy-efficiency-in-refining>

Contains Solomon Proprietary Information

References



APEC Average compared to World's Best Refineries Average

*For reference only
Structural constraints may limit gap closure

© 2000 Blackwell Science Ltd, *Journal of Internal Medicine* 247: 395–400

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www.scribd.com

Refinery production efficiency, challenges, and off-gas emissions

Refining Margins fall from 2022 highs

Availability and capacity utilization

Energy Costs (both high and low)

Alignment with governmental climate

Uncertainty of refined product demand

Non-Energy OpEx at increasing high level

Investor pressure to cut Non-Energy OpEx

investor pressure to cut Non-Energy OpEx

Workshops and publications on electrification

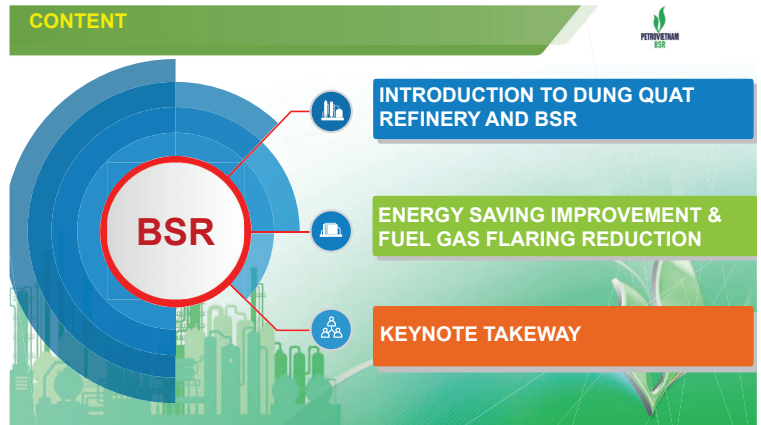
- Contains Scientific Proprietary Information

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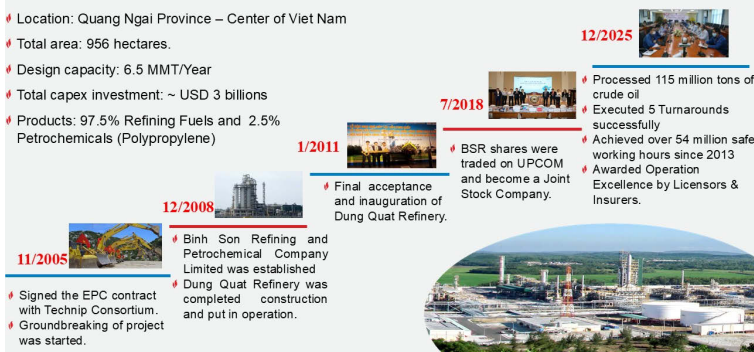
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Action from Insight®

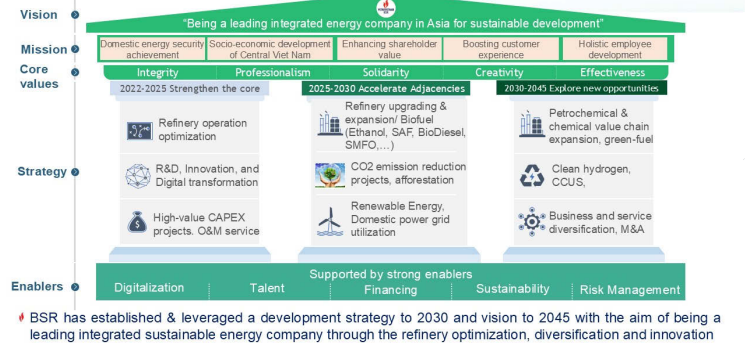
7. Energy saving improvements and Fuel Gas flaring reduction in Dung Quat Refinery



I. INTRODUCTION TO DUNG QUAT REFINERY AND BSR



I. INTRODUCTION TO DUNG QUAT REFINERY AND BSR



I. INTRODUCTION TO DUNG QUAT REFINERY AND BSR

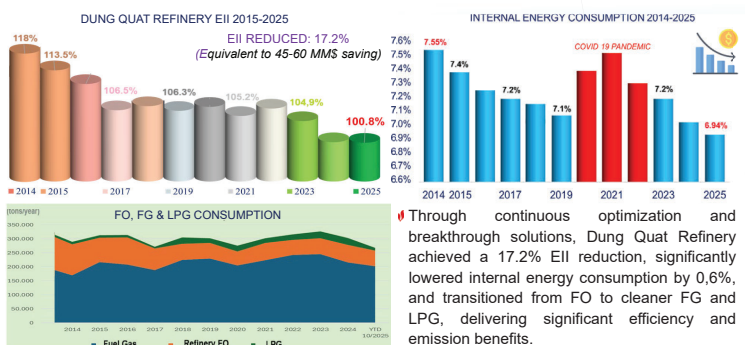
Roadmap For Green House Gas Emission Reduction Of Dung Quat Refinery

Contents	Emission reduction plan (*)			
	Case 1	Case 2	Case 3	Case 4
GHG reduction target by 2050	90%	100%	35-40%	10-12%
Investment costs (million \$)	~ 1,800	~2,100	~700	~170
Solutions				
1. Energy saving, %	7.70	7.70	7.70	7.70
2. Renewable energy, %	2.02	2.02	2.02	2.02
3. CCUS, %	77.40	77.40	22.45	0
4. Afforestation, %	2.33	6.53	2.33	1.14
5. Buy carbon credits, %	2.33	6.53	2.33	1.14
Total of GHG reduction, %	91.6	100	36.6	12.00

(*) Plan may be changed depending on government regulations, policies and carbon credit market conditions.

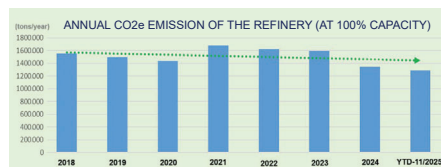
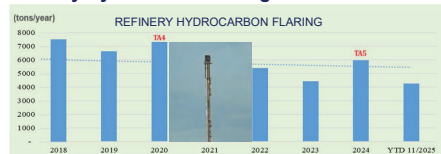
BSR has outlined 4 scenarios for decarbonization roadmap by 2050 combines energy efficiency, renewable energy, CCUS, afforestation, and carbon credits to achieve 10%-100% GHG reduction depending on the strategic investment and budget control.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

Refinery Hydrocarbon Flaring and CO2 Emission From 2018 To 2025

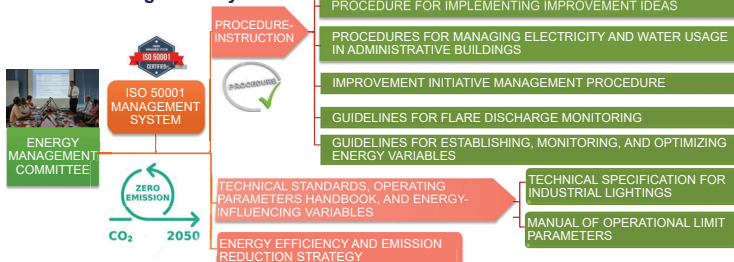


Dung Quat Refinery has significantly reduced hydrocarbon flaring over the years, with clear downward trends to ~ 4500 tons/year (0.05%) despite turnaround periods, reflecting strong operational performance and effective implementation of flare-reduction initiatives. Its target is to achieve "zero flaring" by 2030.

Total CO₂e emissions have steadily declined from 2018 to 2025 thanks to continuous energy optimization, fuel switching, and advanced emission-reduction measures across the refinery.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

BSR Integrated Energy & Emission Management System

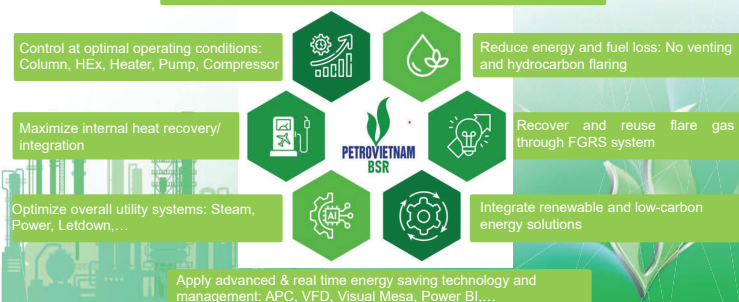


By implementing a comprehensive ISO 50001 energy management system with clear policy, strategy, procedures, guidelines, and technical standards, It has strengthened operational excellence, enabling significant reductions in EII, internal energv consumption, and CO₂ emission.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

Principles of Energy Optimization and Gas Flaring Emission Reduction

Maintain effectively ISO 50001 Energy Management System
Encourage internal innovation, energy-saving & gas emission reduction



II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

Operational Optimization & Energy Efficiency Improvement Solutions

No	Unit	Improvement solutions	Objectives	Investment	Year	Benefits	Payback
1	Utility	Stopped 1 Air Compressor	Power saving	Optimization	2018	2,300 tons FO/year 0.4% EII - USD 1,100,000/year	
3	NHT	Optimed capacity of 2 Make-up Gas Compressor (90/90 to 50/50)	Power saving	Optimization	2019	1,500 tons FO/year 0.26% EII - USD 825,000/year	
4	Sea Water Intake	Stopped 1 Seawater Pump	Power saving	Optimization	2021	3,050 tons FO/year 0.6% EII - USD 1,600,000/year	
5	CDU	Installed additional Heat Exchanger E-1135	Heat recovery	Optimization	2024	550 tons FO/year 0.1% EII - USD 200,000/year	
6	RFCC	Optimized E-1525 inlet BFW temperature	Reducing MP Steam consumption	Optimization	2024	1,000 tons FO/year 0.2% EII - USD 515,000/year	
7	RFCC	Switched COB FDF from Turbine to Motor	Addressing LP steam venting Energy saving	Optimization	2025	2,200 tons FO/year 1% EII - USD 3,000,000/year	

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

Ongoing & Upcoming Key Energy Improvement Projects

No	Unit	Improvement solutions	Objectives	Investment (USD)	Year	Benefits	Payback
1	Utility	Installing inverter for Electric Motor	Power saving	700,000	2029	1,500 tons FO/year 0.3% EII - USD 772,000/year	01 years
2	CDU	Air Preheater Installation for Charge Heater H-1101	Heat Recovery Save Fuel Gas	5,000,000	2025-2030	5,000 tons FO/year 0.7% EII - USD 1,900,000/year	< 4 years
3	Power Plant	Installation 01 gas turbine instead of steam turbine	Energy efficiency improvement	35,000,000	2025-2030	10,800 tons FO/year 2% EII - USD 5,500,000/year	< 2 years
4	Power Substation	Import power from domestic grid (EVN)	Cheap and Cleaner Energy	15,000,000	2025-2029	8,500 tons FO/year 1.5% EII - USD 4,000,000/year	< 5 years
5	Under study	Wind Power Plant with 50 MW	Green Energy CO ₂ reduction	Under study	2027-2030	Under study	Under study

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION

Fuel Gas Flaring Reduction Solutions And Ongoing Projects

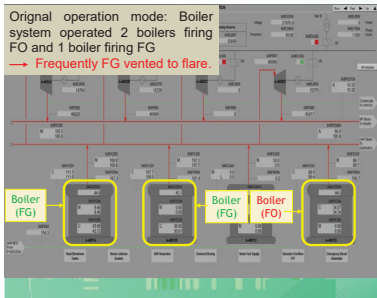
No	Unit	Improvement solutions	Objectives	Investment (USD)	Year	Benefits	Payback
1	CDU	Install 2" pipeline to sending excessive Off-Gas to RFCC	Recover Off-Gas venting to Flare	538,000	2015	1080 tons FO/year 0.2% EII - USD 410,000/year	< 1.5 years
2	PP Plant	Install 2" pipeline to sending Off-Gas from PP Plant to RFCC	Recover Off-Gas venting to Flare	80,000	2024	3400 tons FO/year 0.6% EII - USD 1,300,000/year	< 1 year
3	Process units	Using N2 as sweeping gas (FG) at process units for flare system	Minimize FG purging to Flare Emission reduction	150,000	2025	3,369 tons FO/year 0.6% EII - USD 1,280,000/year	< 1 year
4	Fuel Gas System	Replace FO with LNG	Energy saving Emission reduction	2,000,000	2026	~1-2% EII ~USD 2,000,000/year 40 – 100 ktons CO₂/year	< 2 years
5	Refinery Flare	Install a FGRS at Main Flare	Recover valuable FG for reuse Emission reduction	5,000,000	2030	4828 tons FO/year - USD 1,500,000/year 6,165 tCO₂/year	< 5 years

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



Changing operation mode of boiler system: Switched two boiler firing FO and one boiler firing FG into 2 FG boilers and 1 FO boiler

Implementation steps



Calculated and evaluated the Fuel Gas and Fuel Oil network balance of the Refinery.

Conducted the risk assessment and implement a MOC.

Issued steam load shedding guidelines and other related procedures for abnormal situations of the refinery fuel gas network. Carried out training program and operational drills for operators.

Changed the boiler operation mode into 2 FG Boilers and 1 FG boiler in 2014 to maximize FG consumption.

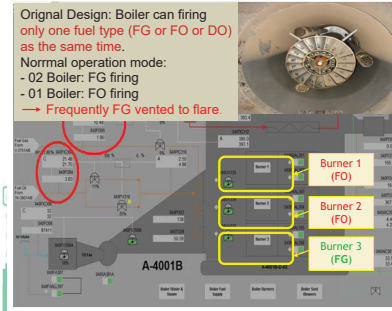
Saved approximately 3 – 4 tons of Fuel Gas per hour, equivalent to 27,000 – 36,000 tons per year.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



Dual-firing Boiler Solution: Operated two burners firing FO and one burner firing FG.

Implementation steps



Conducted trial test the boiler operating with two burners using FO firing and one burner fuel gas (FG) firing, adjust the optimal fuel-to-air ratio.

Collected data and developed a new operating curve for dual-fuel combustion, with two burners firing fuel oil and one burner firing gas fuel.

Designed a new control logic to enable stable and safe dual-fuel operation

Developed procedures, operating guidelines, and abnormal handling instructions for this application.

Selected an appropriate boiler operating mode since 2017 to prevent excessive FG being flared.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



Benefits of Dual-firing of Boilers



Save/reduce approximately 6.128 tons of Fuel Oil consumption per year.



Develop an operating procedure for boilers in dual-fuel mode firing and handle abnormalities in case of incidents.



No investment cost, the benefits amount to approximately USD 3.7 million per year.

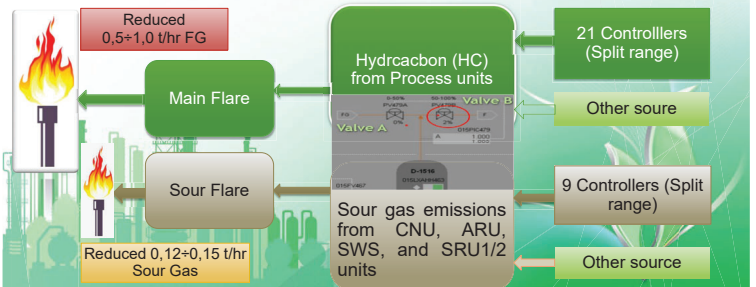


Reduce CO₂ emissions at Dung Quat Refinery by approximately 19,082 tons per year.

II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



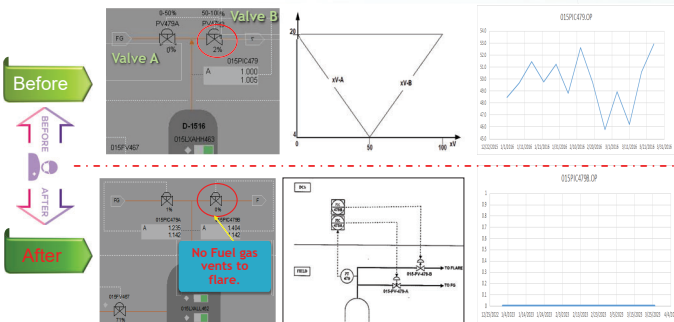
Change of control principle: Switch from split range controller to independent dual control (couple controller) and adjust the pressure setpoint values of valve A&B controllers to minimize the amount of hydrocarbon gas and sour gas flared.



II. ENERGY SAVING IMPROVEMENT & FUEL GAS FLARING REDUCTION



Results of the solution



III. KEYNOTE TAKEAWAY



Creativity and Innovation

Dung Quat Refinery has delivered remarkable energy performance improvements and substantial hydrocarbon flaring & CO₂ emission reduction. Targeting to EII < 95%, zero flaring by 2030 and Net-Zero in 2050.

BSR's integrated energy & emission management system with clear policies, strategies, procedures and KPI's ensure successfully disciplined governance and continuous improvement across all operation.

Strong technical innovation enable BSR to successful energy transition and deeper decarbonization. In addition, strengthening cooperation with ASIA energy companies (ENEOS, COSMO, SK, PETRONAS...), licensors, vendors, and consultants to aim sustainable development.

BSR is committed to a long-term low carbon transition aligned with global energy trends. Its 2050 roadmap integrates energy efficiency, renewable & clean energy, CCUS, afforestation and carbon credits.



4-4. Background Research Report



Increasing Energy Efficiency and Reducing Fugitive Emissions in the Fossil Energy Industry

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I. Introduction

While APEC member economies have been committed to increasing clean energy supply and promoting energy transitions, fossil energy is still an important part of their energy supply due to the circumstances of resource endowment and stage of development, and is expected to continue for some time.

The APEC project (EWG_202_2024A) consists of a capacity building workshop that will provide the fundamental technical knowledge needed to improve the fossil energy industry in terms of energy efficiency and the associated emissions savings for policymakers and other relevant officials. The project outputs include a background research report, a capacity building workshop, and a workshop summary report.

This background research report provides a comprehensive analysis of energy efficiency enhancement and fugitive emission reduction strategies across three critical fossil energy industries. The report examines three stages of the oil industry: upstream exploration and production, midstream transportation, and downstream refining operations. It analyzes the natural gas industry from exploration and production through processing, transportation, and storage. Finally, it investigates the coal industry encompassing mining operations, processing and preparation, and transportation systems.

The report serves as a technical foundation for capacity building workshop aimed at accelerating the deployment of efficiency and emission reduction technologies across APEC member economies' fossil energy sectors. By providing policymakers and industry professionals with detailed technical knowledge and proven implementation strategies, this analysis supports informed decision-making and effective policy development to achieve sustainability goals while maintaining energy security.

II. Oil Industry

1. Overview

This section examines the current state of energy efficiency and pollution reduction technologies and practices in the oil industry, spanning from upstream exploration and production through midstream transportation to downstream refining operations.

It analyzes specific opportunities and challenges in exploration and production, transportation, and refining operations, while highlighting emerging technologies that promise to transform industry practices (Fig. II.1). Successful case studies and best practices from around the world also will be discussed.



Figure II.1. Stages of the oil industry operation

2. Exploration and Production

2.1 Energy Efficiency

The exploration and production (E&P) stage in the oil industry presents numerous opportunities for energy efficiency improvements, as it typically accounts for the largest share of energy consumption and emissions in oil operations. Optimizing drilling operations represents a fundamental approach to reducing energy intensity in upstream activities. Modern drilling technologies, including automated drilling systems and real-time optimization software, can reduce drilling time by 20-30% while improving wellbore quality and reducing energy consumption per foot drilled¹. The implementation of managed pressure drilling techniques has demonstrated energy savings of up to 15% compared to conventional drilling methods, while simultaneously improving safety and reducing non-productive time².

Enhanced Oil Recovery (EOR) operations, while essential for maximizing resource recovery, are traditionally energy-intensive processes. However, recent advances in EOR efficiency have shown promising results. The integration of advanced reservoir simulation and machine learning algorithms enables operators to optimize injection strategies, reducing the energy required per barrel of incremental oil recovered (Fig. II.2). Carbon dioxide EOR projects, when integrated with carbon capture and storage facilities, can achieve negative emissions while improving recovery factors, as demonstrated by projects in the Permian Basin and Saudi Arabia's Uthmaniyah field³.

¹ Society of Petroleum Engineers. (2023). Advances in Automated Drilling Systems. SPE Journal, 28(4), 234-251

² International Association of Drilling Contractors. (2023). Managed Pressure Drilling: Best Practices and Case Studies. Houston: IADC

³ Carbon Capture Journal. (2023). CO2 EOR Projects: Global Status and Opportunities. Issue 92, 12-18.

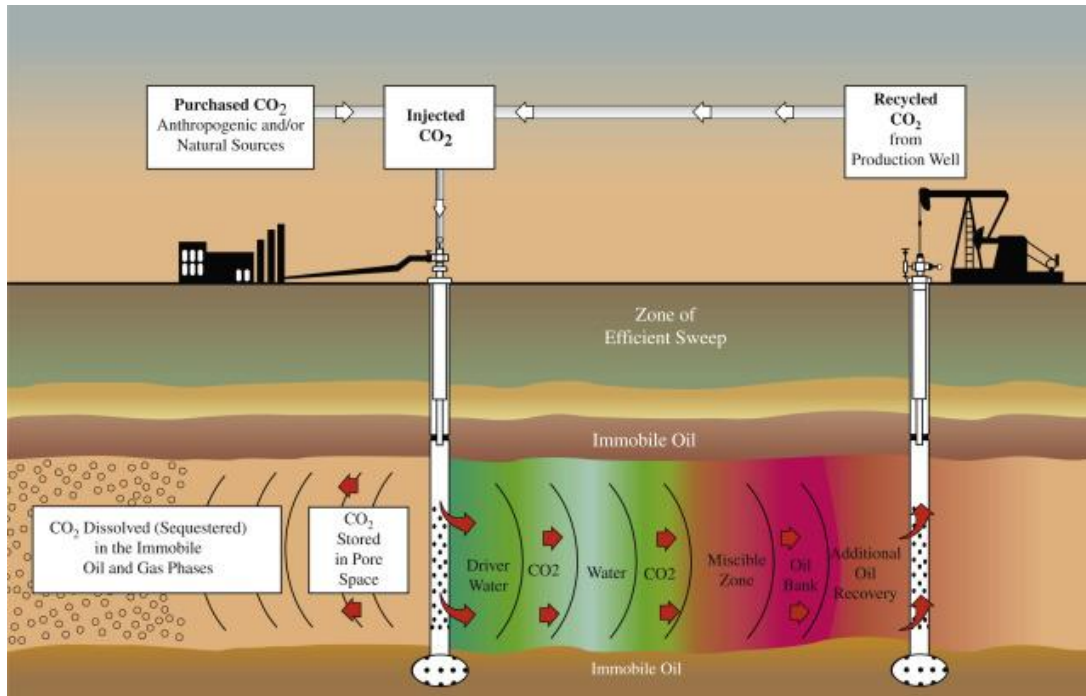


Figure II.2. Diagram of CO₂ Enhanced Oil Recovery

(Source: Larry W. Lake et al. , 2019)⁴

Power generation and electrification of upstream operations represent a significant change in how the oil industry approaches energy consumption. Norway has emerged as a global leader in this area, with over 50% of its offshore production expected to come from fully or partially electrified platforms by 2025.

The Norwegian Continental Shelf demonstrates that electrified assets can reduce emissions by 86% (Fig. II.3)⁵. This dramatic reduction is achieved by replacing gas turbines with power from shore, using Norway's abundant renewable hydroelectric resources. The economic viability of electrification projects depends on factors including distance from shore, field lifetime, and electricity prices, but technological advances in high-voltage direct current transmission are expanding the feasible range for such projects.

⁴ Larry W. Lake et al.. CO₂ Enhanced Oil Recovery Experience and its Messages for CO₂ Storage. <https://doi.org/10.1016/B978-0-12-812752-0.00002-2>

⁵ Rystad Energy. (2024). Upstream Electrification Could Wipe Out More Than 80% of Oil and Gas Production Emissions. Oslo: Rystad Energy.

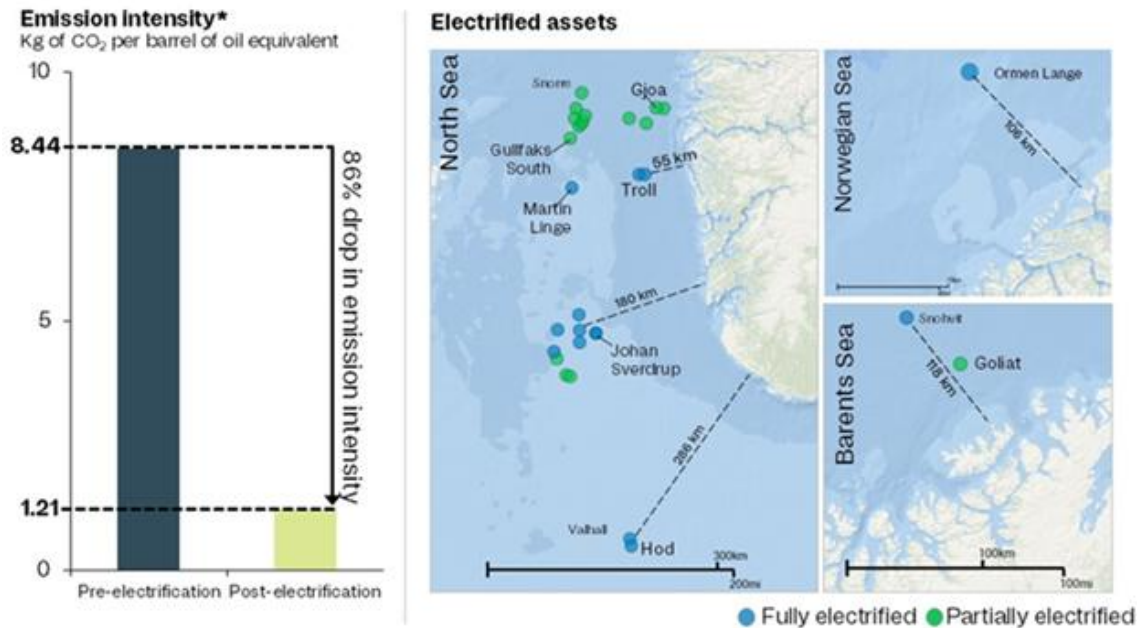


Figure II.3. Electrified Norwegian offshore upstream assets

(Source: Rystad Energy, 2024)⁶

2.2 Reducing Oil Spills⁷

Human error remains a leading cause of oil spills, making comprehensive safety training and operational protocols essential components of oil spill prevention strategies. The oil industry has adopted a culture of safety excellence that emphasizes continuous education, regular certification updates, and strict adherence to international maritime and pipeline safety standards. Crew fatigue management programs ensure that personnel operating critical systems maintain optimal alertness levels, while standardized communication protocols reduce miscommunication during vessel transfers and loading operations. Regular safety drills and emergency response simulations prepare teams to handle potential oil spill scenarios effectively. The implementation of behavior-based safety programs has proven particularly effective in identifying and correcting unsafe practices before they lead to incidents, with companies reporting a 30% reduction in near-miss events.⁸

Proactive environmental monitoring serves as a crucial early warning system for potential oil spill incidents and enables rapid response when incidents occur. Advanced satellite imagery and aerial surveillance technologies can detect surface oil sheens within hours of a spill, allowing response

⁶ Rystad Energy. <https://www.rystadenergy.com/news/upstream-electrification-emissions-oil-gas-norway>

⁷ Methane emissions for oil and gas operations are all in the natural gas section

⁸ Safety Management International. (2024). Behavior-based safety programs: Implementation strategies and performance outcomes. *Occupational Safety Review*, 29(1), 78-95.

teams to mobilize quickly and implement containment measures (Fig. II.4). Underwater monitoring systems use acoustic sensors and pressure gauges to detect pipeline leaks in real-time, triggering automatic shutdown procedures when abnormal conditions are detected. Weather forecasting integration helps operators postpone high-risk operations during adverse conditions, while oceanographic modeling systems predict spill trajectories to optimize response strategies. These monitoring networks create a comprehensive surveillance web that significantly reduces the time between oil spill occurrence and initial response.

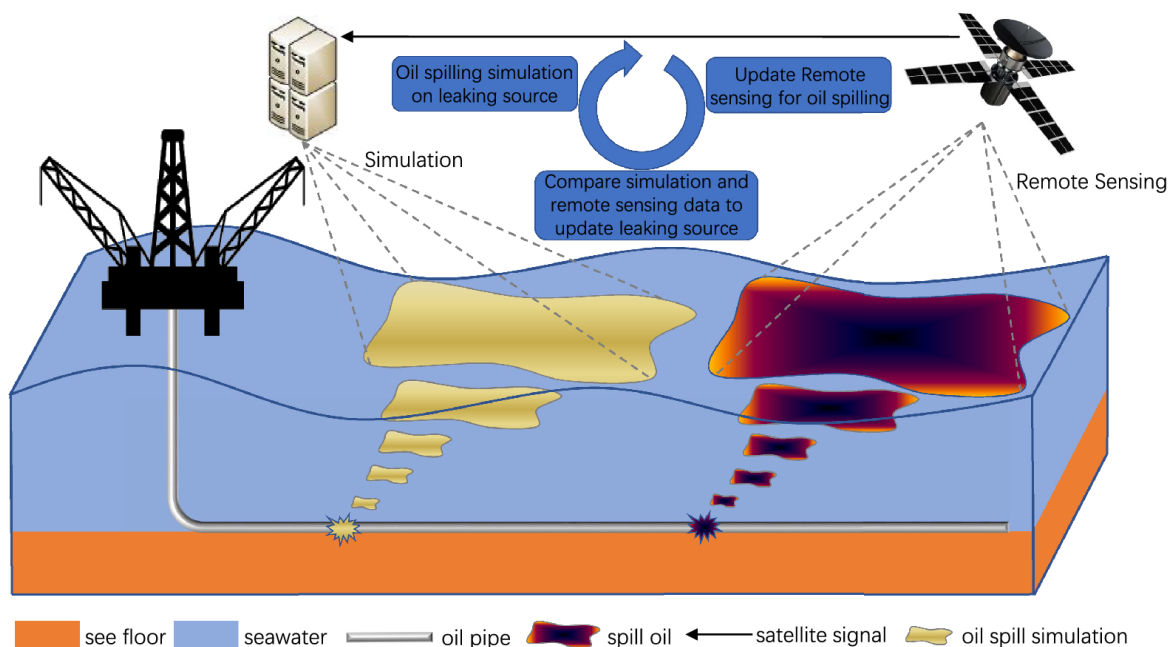


Figure II.4. Offshore oil spill monitoring and detection system

(Source: Yuewei Wang et al., 2023)⁹

Stringent regulatory frameworks have driven substantial improvements in oil spill prevention across the oil industry, with international organizations establishing increasingly robust safety standards. The International Maritime Organization's MARPOL Convention sets strict guidelines for vessel construction, operational procedures, and crew qualifications, while regional regulations often impose even more demanding requirements. Oil companies must demonstrate compliance through regular inspections, detailed documentation, and third-party audits that verify adherence to established protocols. The implementation of Safety Management Systems (SMS) requires companies to maintain comprehensive risk assessment procedures, incident reporting mechanisms, and continuous improvement programs. These monitoring networks create a comprehensive surveillance web that significantly reduces the time between spill occurrence and

⁹ Yuewei Wang et al.,.. Cyber-physical oil spill monitoring and detection for offshore petroleum risk management service. *Scientific Reports* volume 13, Article number: 4586 (2023).

initial response from an average of 6 hours to 45 minutes.¹⁰

The oil industry continues to develop innovative technologies that promise even greater oil spill prevention capabilities in the coming decades. Artificial intelligence and machine learning algorithms are being integrated into monitoring systems to predict equipment failures before they occur, while blockchain technology enhances supply chain transparency and accountability. Autonomous inspection drones and underwater vehicles provide continuous monitoring capabilities without exposing human personnel to hazardous conditions. Advanced materials science has produced stronger, more corrosion-resistant pipeline coatings and tank linings that extend infrastructure lifespan by 40% and reduce failure rates¹¹. The integration of Internet of Things (IoT) sensors throughout oil infrastructure creates visibility into system performance, enabling predictive maintenance strategies that prevent equipment failures before they result in spills.

2.3 New Technology

Cloud computing provides oil companies with enhanced data control, better analytic insights, more efficient production, and safer drilling capabilities. The technology enables companies to scale at speed, accelerate innovation, streamline operations, and become more agile in responding to market changes.

Edge computing enables real-time analysis of data at remote exploration sites, drilling locations, and distribution pipelines, allowing for faster data processing and more profitable business decisions. This distributed computing approach is particularly valuable for operations in remote locations where immediate data processing and decision-making are critical for safety and efficiency.

The integration of cloud and edge computing creates a hybrid infrastructure that maximizes the benefits of both centralized processing power and distributed real-time analysis, enabling oil companies to optimize their operations.

Advanced analytics and big data enable companies to extract valuable insights from enormous volumes of data generated from exploration, drilling, refining, and logistics. BP's AI-powered predictive maintenance on offshore rigs reduced unplanned downtime by 30% and saved USD 50 million annually by forecasting pump failures two weeks in advance¹².

Big data analytics can predict oil price fluctuations by aggregating global economic, political, and

¹⁰ Global Marine Environmental Consortium. (2023). Effectiveness of integrated monitoring systems in spill response time reduction. *Marine Environmental Protection*, 31(7), 423-439.

¹¹ Materials Science & Engineering Review. (2023). Advanced coatings for corrosion prevention in marine petroleum infrastructure. *Materials Engineering Quarterly*, 37(2), 189-206.

¹² <https://research.aimultiple.com/automation-in-the-oil-and-gas-industry/>

market conditions, while optimizing well placement, drilling parameters, and production rates through seismic and drilling data analysis. Predictive analytics enables scenario-based simulations and future maintenance requirement predictions through variable analysis and condition-based monitoring.

Some research indicates that predictive maintenance can decrease machine downtime, translating into significant productivity gains. Machine learning algorithms analyze seismic data to optimize reservoir modeling and drilling strategies, while AI-driven chatbots and virtual assistants streamline service requests, ensuring faster response times and improved operational efficiency.

3. Transportation

3.1 Energy Efficiency

Pipeline optimization and pressure management represent fundamental approaches to improving energy efficiency in oil transportation. Modern pipeline operations utilize sophisticated hydraulic modeling and real-time optimization algorithms to minimize pumping and compression energy requirements while maintaining required flow rates and pressures. The implementation of drag-reducing agents can decrease pumping energy requirements by 20-40% in liquid pipelines, with particularly significant benefits in long-distance crude oil pipelines (Fig. II.5)¹³. Variable frequency drives on pumps and compressors enable precise speed control, reducing energy consumption by 10-30% compared to traditional throttling control methods. Advanced pipeline batching strategies, optimized using machine learning algorithms, can reduce interface mixing and pumping energy requirements while maximizing pipeline utilization.

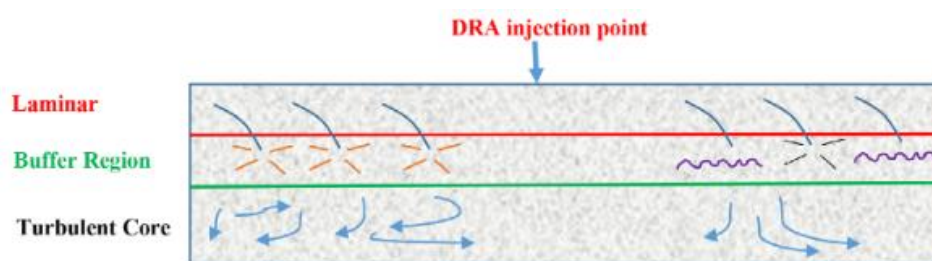


Figure II.5. Various layers of fluid flowing through a pipeline in a turbulent flow¹⁴

(Source: Sayeed Rushd et al., 2023)¹⁵

¹³ Pipeline & Gas Journal. (2023). Drag Reducing Agents: 50 Years of Flow Improvement. 250(7), 44-49.

¹⁴ The injection of drag reducers weakens the pulsation and inhibits the formation and development of vortices.

¹⁵ Sayeed Rushd et al., Applications of drag reducers for the pipeline transportation of heavy crude oils: A critical review and future research direction. The Canadian Journal of Chemical Engineering

Pump and compressor station efficiency improvements offer substantial energy savings opportunities throughout transportation networks. The replacement of aging compressor units with modern, high-efficiency designs can improve station efficiency by 15-25%. Heat recovery systems on compressor stations can capture waste heat for use in fuel gas conditioning, building heating, or power generation through organic Rankine cycle systems. Regular performance monitoring and optimization of compressor operations, including optimal unit selection and load sharing, can reduce fuel consumption by 5-10% without capital investment¹⁶.

Marine transport fuel efficiency has become increasingly important as international shipping faces pressure to reduce emissions. The International Maritime Organization's Energy Efficiency Design Index has driven adoption of technologies including hull optimization, air lubrication systems, and waste heat recovery that can reduce fuel consumption by 20-30% in new tankers¹⁷. Slow steaming practices, while extending voyage times, can reduce fuel consumption by up to 60% on long-distance routes. Advanced weather routing systems using satellite data and machine learning can optimize vessel routes to minimize fuel consumption while maintaining schedule reliability, achieving fuel savings on typical voyages.

Rail and truck fleet optimization leverages telematics and advanced analytics to improve fuel efficiency in overland transportation. Driver behavior monitoring and coaching programs can reduce fuel consumption by 5-15% through optimized acceleration, braking, and speed management. Route optimization algorithms considering real-time traffic, weather, and delivery constraints can reduce total miles driven by 10-20% while improving delivery reliability. The adoption of alternative fuels, including compressed natural gas and hydrogen fuel cells for short-haul trucking, offers pathways to reduce both emissions and operating costs in regions with supportive infrastructure.

3.2 Reducing Oil Spills

Pipeline leak detection and repair (LDAR) programs have evolved from periodic surveys to continuous monitoring systems capable of detecting small leaks in real-time. Fiber optic sensing technology can detect pressure changes, temperature anomalies, and acoustic signatures associated with leaks along thousands of kilometers of pipeline, with location accuracy within meters. Machine learning algorithms analyzing data from multiple sensor types can distinguish between actual leaks and false alarms with accuracy rates exceeding 95%, reducing unnecessary excavations and service interruptions. The implementation of risk-based LDAR programs,

¹⁶ Gas Compression Magazine. (2024). Optimizing Compressor Station Operations Through Advanced Control. 19(1), 34-41.

¹⁷ International Maritime Organization. (2024). Fourth IMO GHG Study 2023. London: IMO.

prioritizing high-consequence areas and equipment with higher leak probabilities, can reduce program costs by 30-40% while maintaining or improving emission reduction effectiveness¹⁸.

Tank storage emission controls address both working losses (from filling and emptying) and standing losses (from temperature and pressure changes). Internal floating roof tanks can reduce emissions compared to fixed roof tanks, while geodesic dome roofs on external floating roof tanks eliminate wind-induced losses. Advanced seal designs incorporating multiple sealing surfaces and low-permeation materials can reduce rim seal emissions by 80% compared to older designs. Pressure-vacuum relief valves with tight sealing and narrow operating ranges minimize breathing losses, while vapor balancing systems between tanks can eliminate emissions during tank transfers.

Compressor station emission reduction focuses on eliminating leaks from seals, valves, and connections while minimizing operational venting. Dry seal systems on centrifugal compressors can reduce seal leakage by 90-95% compared to wet seal systems, with the added benefit of eliminating seal oil contamination of the gas stream¹⁹. Electric motor drives eliminate combustion emissions and can be powered by renewable electricity, though their application is limited by power availability and reliability requirements. Advanced station automation enables remote operation and monitoring, reducing the need for on-site venting during maintenance operations and improving response times to abnormal conditions.

3.3 New Technology

Smart pipeline monitoring systems represent the convergence of multiple technologies to create intelligent, self-monitoring transportation networks. Digital twins of pipeline systems integrate real-time sensor data, hydraulic models, and historical performance data to predict and prevent failures before they occur. These systems can identify developing threats such as corrosion, ground movement, or third-party interference weeks or months before they would result in leaks.

Alternative fuels for transport vessels are rapidly developing as the maritime industry seeks to meet ambitious decarbonization targets. Ammonia-fueled vessels, while still in early development, offer the potential for zero-carbon shipping, with major engine manufacturers developing ammonia-compatible designs. Hydrogen fuel cells provide zero-emission power for smaller vessels and auxiliary power on larger ships, with several demonstration projects proving technical feasibility. Methanol, produced from captured CO₂ and renewable hydrogen, offers a lower-carbon alternative that can utilize existing infrastructure with minor modifications. Battery-electric propulsion, while limited to short-distance applications, is being adopted for harbor tugs and

¹⁸ Environmental Science & Technology. (2024). Risk-Based LDAR Programs: Optimizing Cost and Environmental Performance. 58(5), 2341-2350.

¹⁹ Sealing Technology. (2023). Dry Gas Seals: Technology Evolution and Performance. 2023(4), 8-12.

coastal ferries, eliminating local emissions in port areas.

Advanced materials for pipeline integrity promise to extend asset life while reducing maintenance requirements and emissions. Nanocomposite coatings with self-healing properties can automatically repair minor damage, preventing corrosion initiation and extending coating life (Fig. II.6). High-strength steel alloys enable higher operating pressures with thinner wall thicknesses, reducing material requirements and installation costs. Smart materials incorporating sensors directly into pipe walls or coatings enable continuous monitoring of stress, temperature, and corrosion, providing early warning of developing problems. These advanced materials, while currently more expensive than traditional options, offer lifecycle cost advantages through reduced maintenance and extended service life.

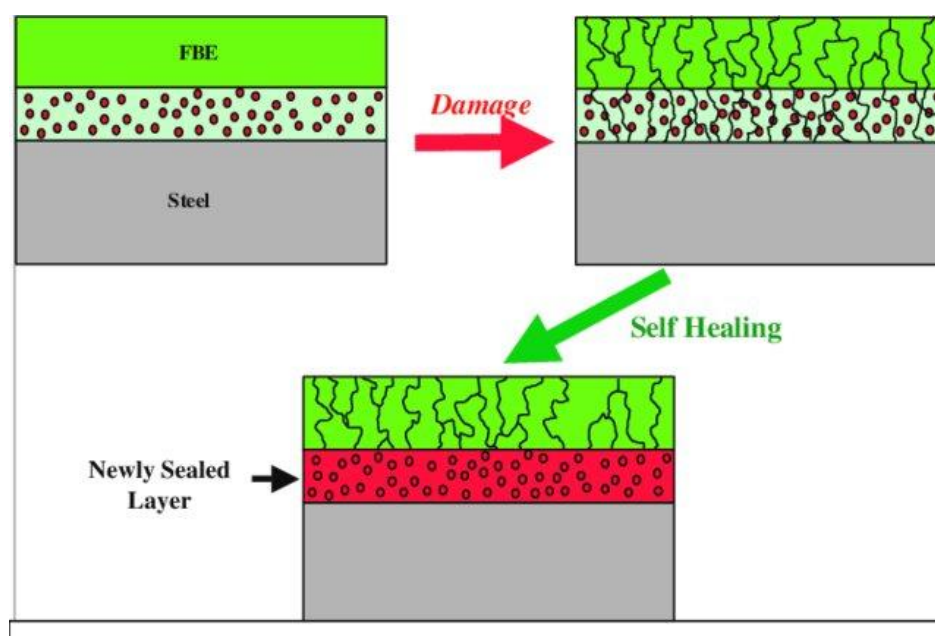


Figure II.6. Structure of pipeline with self-healing properties²⁰

(Source: J. Alan Kehr and David G. Enos, 2016)²¹

4. Refining

4.1 Energy Efficiency

Furnace and boiler efficiency improvements represent significant opportunities for energy savings, as these units typically account for 40-60% of refinery fuel consumption. Ultra-low NO_x burners with advanced combustion control can achieve thermal efficiencies while meeting stringent

²⁰ FBE stands for fusion-bonded epoxy.

²¹ J. Alan Kehr and David G. Enos. FBE, a Foundation for Pipeline Corrosion Coatings

emission standards. Air preheating systems using advanced materials can operate at temperatures exceeding 1000°C, recovering 20-30% more heat than conventional designs. Oxygen enrichment of combustion air can reduce fuel consumption by 10-15% while enabling processing of lower-quality fuel gases. Advanced combustion control systems using laser-based sensors and model predictive control maintain optimal excess air levels, improving efficiency by 2-5% compared to traditional control methods.

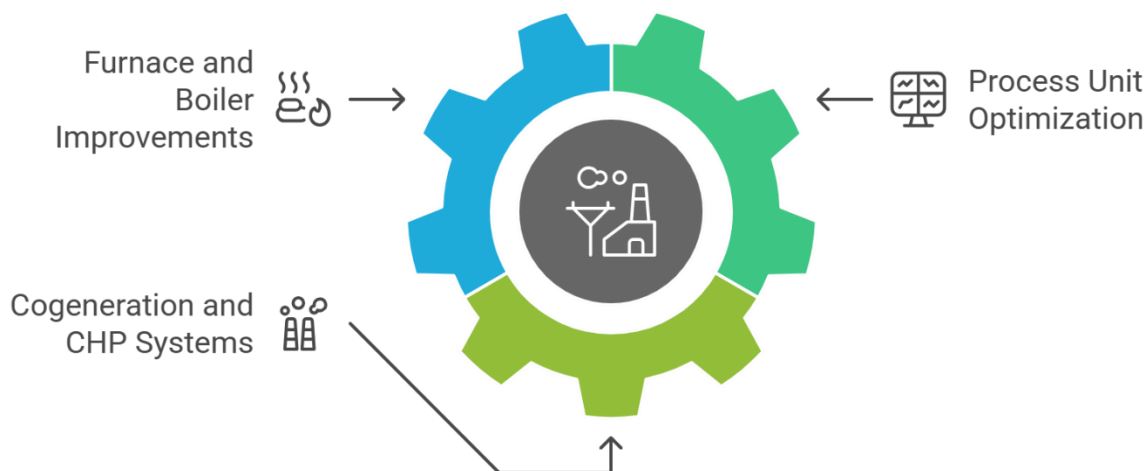


Figure II.7. Enhancing Refinery Efficiency

Process unit optimization through advanced process control (APC) and real-time optimization (RTO) systems has become standard practice in world-class refineries. Modern APC systems can reduce energy consumption while improving product yields and quality consistency. The integration of machine learning with traditional process models enables prediction and optimization of complex unit interactions, identifying optimization opportunities that traditional methods miss. Digital twins of process units enable testing of operational changes and debottlenecking strategies without disrupting actual operations, accelerating the pace of efficiency improvements.

Cogeneration and combined heat and power (CHP) systems provide highly efficient solutions for meeting refinery steam and power requirements. Modern gas turbine-based CHP systems can achieve total efficiencies exceeding 85%, compared to 35-40% for separate heat and power generation²². The integration of steam turbine generators with process unit pressure letdown requirements enables power generation from pressure energy that would otherwise be wasted.

²² Combined Heat and Power Association. (2024). CHP in Refineries: Global Best Practices. London: CHPA.

Emerging solid oxide fuel cell systems promise even higher efficiencies, potentially exceeding 90% when integrated with refinery fuel gas systems, though current costs limit widespread adoption.

4.2 Reducing Fugitive Emissions

Refinery LDAR programs have evolved to incorporate risk-based approaches and advanced detection technologies that improve effectiveness while reducing costs. Optical gas imaging cameras enable rapid screening of entire units, identifying leaks 5-10 times faster than traditional methods²³. Fixed continuous monitoring systems in high-risk areas provide real-time leak detection and enable immediate response, reducing emission duration from days to hours.

Storage tank emission controls in refineries must address the diverse range of products and operating conditions present in refining operations. Vapor recovery systems connected to the refinery fuel gas system can recover 95-99% of vapors from gasoline and light product tanks, with recovered vapors contributing 1-2% of total refinery fuel gas. Nitrogen blanketing systems on tanks containing heavy products prevent oxidation while minimizing emissions, though careful design is required to prevent over-pressurization. Advanced floating roof designs incorporating full-contact honeycomb decks can reduce emissions by 90% compared to traditional pontoon designs, while geodesic domes eliminate wind effects and precipitation intrusion.

Flare gas recovery and minimization represents one of the most visible opportunities for emission reduction in refineries. Modern flare gas recovery systems can capture 95-99% of gases previously sent to flare during normal operations, with recovered gas valued at USD 2-5 million annually for a typical refinery²⁴.

4.3 New Technology

Advanced process control and digital twins are transforming refinery operations by enabling optimization and predictive capabilities. Digital twins incorporating molecular-level process models can predict product properties and optimize operations across entire refineries, reducing energy consumption by 5-10% while improving product yields. Machine learning algorithms trained on years of operational data can identify optimal operating conditions that human operators might never discover, pushing units to their theoretical efficiency limits. Real-time optimization systems can respond to changing market conditions and feedstock qualities within minutes, maximizing profitability while minimizing emissions.

Electrolytic hydrogen production powered by renewable electricity offers a pathway to zero-carbon hydrogen, though current costs limit application to niche uses. Advanced hydrogen

²³ Environmental Protection Agency. (2023). Method 21 - Determination of Volatile Organic Compound Leaks. 40 CFR Part 60, Appendix A-7.

²⁴ Refining & Petrochemicals Middle East. (2023). Flare Gas Recovery Systems: ROI Analysis. September Issue, 42-46.

network optimization, incorporating multiple purity levels and pressure cascades, can reduce total hydrogen production requirements by 10-20% while meeting all process requirements.

Electrification of refinery processes represents a frontier technology with potential to dramatically reduce direct emissions. Electromagnetic heating technologies show promise for specific applications such as visbreaking and delayed coking, potentially eliminating fired heaters for these processes. While widespread electrification faces challenges related to electricity availability and reliability, targeted applications in conjunction with on-site renewable generation offer near-term opportunities.

Bio-refining and renewable integration are reshaping the refining landscape as facilities adapt to process renewable feedstocks alongside traditional crude oil. Co-processing of bio-oils in fluid catalytic crackers and hydrotreaters can incorporate 10-30% renewable content with minimal modifications. Stand-alone renewable diesel and sustainable aviation fuel units using hydroprocessing technology can achieve greenhouse gas reductions of 50-80% compared to petroleum fuels. Advanced catalysts and process designs enable processing of increasingly diverse feedstocks, including waste oils, agricultural residues, and algae oils, expanding the potential for renewable integration while managing food-versus-fuel concerns.

5. Case Studies

5.1 Midstream Innovation: Trans-Alaska Pipeline System Efficiency Upgrades

The Trans-Alaska Pipeline System (TAPS), operating for over 45 years in one of the world's most challenging environments, has undergone continuous efficiency improvements that demonstrate the potential for enhancing aging infrastructure. Facing declining throughput that threatened operational viability, TAPS operators implemented a comprehensive efficiency program that has reduced energy consumption per barrel transported by 35% since 2000. These improvements have extended the pipeline's economic life while significantly reducing its environmental footprint.

The implementation of strategic pig runs using advanced cleaning and inspection tools has reduced friction losses by maintaining internal pipe cleanliness, improving flow efficiency. Variable frequency drives installed on pump stations enable precise matching of pumping power to flow requirements, reducing electricity consumption by 25% compared to the original constant-speed configurations. Advanced supervisory control and data acquisition (SCADA) systems using machine learning algorithms optimize pumping schedules and heat management, minimizing energy use while preventing wax deposition and maintaining oil temperature above pour point (Fig. II.8).

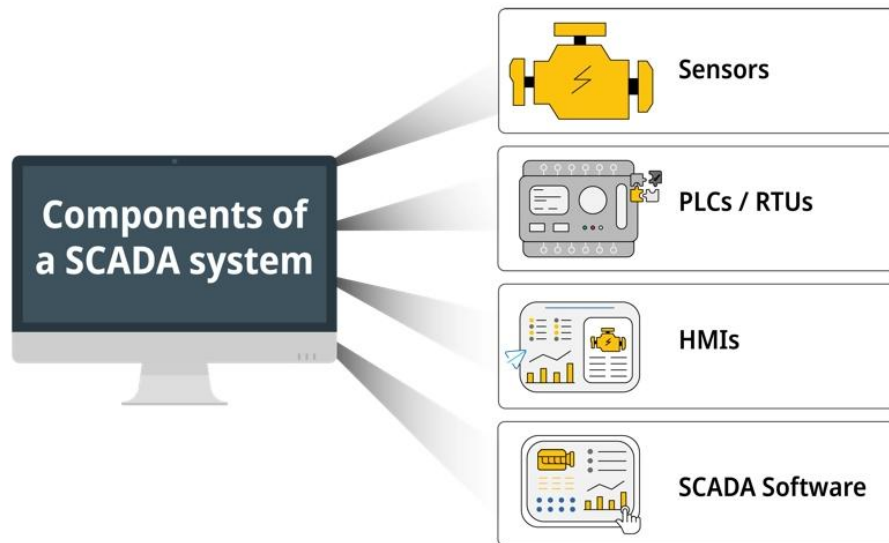


Figure II.8. Components of a SCADA System
(Source: Fluke)

The integration of waste heat recovery systems at pump stations has been particularly successful, capturing heat from turbine exhausts and pump motor cooling systems for use in facility heating and oil temperature maintenance. This has reduced the need for supplemental heating by 60%, saving millions of dollars annually in fuel costs. The use of drag-reducing agents, carefully optimized for Alaska North Slope crude characteristics, has enabled throughput increases of 15-20% without additional pumping power, improving the economics of marginal fields and extending field life.

5.2 Downstream Excellence: Singapore Refinery Emission Reduction Program

Singapore's refining sector, representing one of the world's largest refining hubs, has achieved remarkable emission reductions through a combination of regulatory requirements, economic incentives, and industry collaboration. The implementation of comprehensive emission reduction programs across Singapore's refineries has reduced greenhouse gas emissions intensity by 40% over the past decade while maintaining competitiveness in global markets. This success demonstrates how stringent environmental standards can drive innovation and efficiency improvements without compromising economic viability.

The Jurong Island integrated chemical complex showcases the benefits of industrial symbiosis, with extensive heat integration between refineries and petrochemical plants reducing total energy consumption by 20% compared to standalone facilities²⁵. Shared utilities including steam,

²⁵ Journal of Cleaner Production. (2023). Industrial Symbiosis in Singapore's Jurong Island. 378, 134-145.

hydrogen, and industrial gases optimize production efficiency while minimizing emissions. The implementation of advanced process control across all major units, combined with real-time optimization systems, has improved energy efficiency by 5-8% while enhancing operational flexibility to respond to market conditions.

Refineries have responded by implementing comprehensive LDAR programs using optical gas imaging and continuous monitoring, reducing fugitive emissions by 70% from 2015 levels.

III. Natural Gas Industry

1. Overview

The natural gas industry represents a significant component of the global energy landscape, accounting for approximately 24% of global primary energy consumption and serving as a bridging fuel during the transition to lower-carbon energy systems²⁶. Global natural gas demand rose by 2.8% in 2024 and is expected to grow in the coming decades. However, this growth trajectory is accompanied by significant environmental challenges that demand urgent attention through enhanced energy efficiency and fugitive emissions control.

Fugitive emissions, referring to the unintentional release of greenhouse gases throughout the natural gas industry. According to the International Energy Agency, approximately 80 million tonnes of methane were emitted from the global oil and gas industry in 2023 (Fig. III.1), representing about 25% of global methane emissions²⁷.

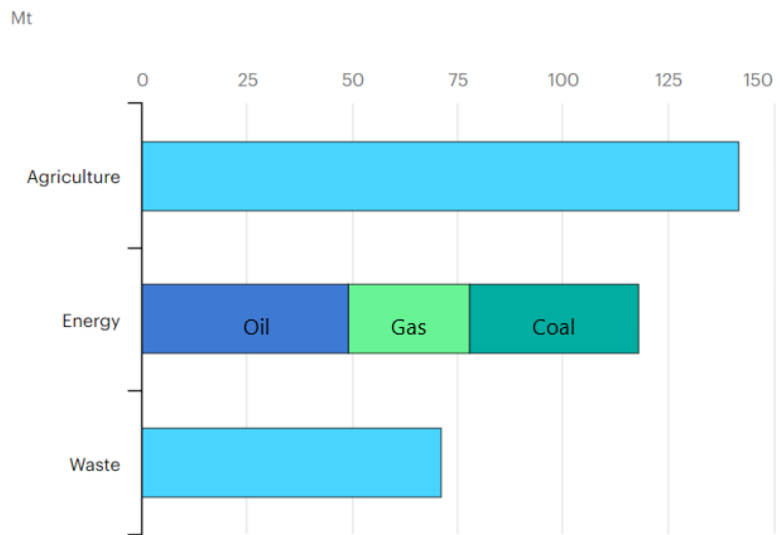


Figure III.1. Global methane emissions and sources of emissions, 2023
(Source: IEA, 2024)

²⁶ International Energy Agency. (2025). Global Energy Review 2025. Paris: IEA Publications.
²⁷ International Energy Agency. (2024). Global Methane Tracker 2024. Paris: IEA Publications.

This section examines energy efficiency enhancement and fugitive emission reduction strategies across the natural gas industry, except the end-use stage, including exploration and production, processing, transportation, and storage (Fig. III.2).

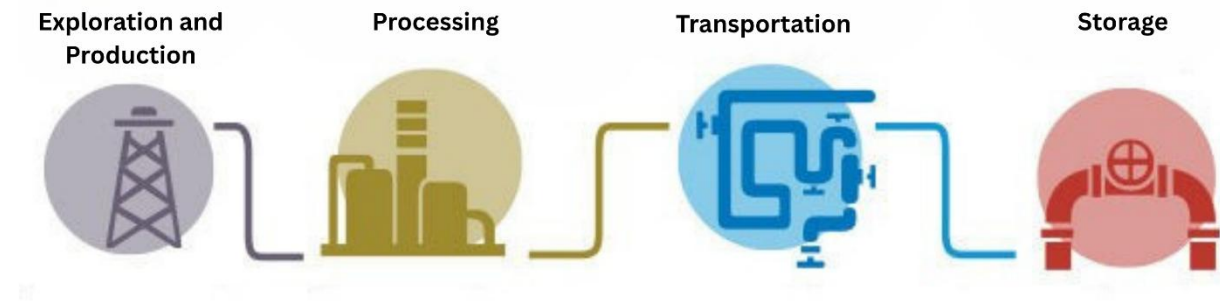


Figure III.2. Diagram of the natural gas industry

The International Energy Agency estimates that around 70% of methane emissions from fossil fuel operations could be reduced with existing technologies, with the oil and gas sector capable of reducing emissions by over 75% through well-known measures²⁸ The report also examines each stage of the natural gas industry, analyzes current practices and emerging technologies, and provides case studies of successful initiatives and projects worldwide.

2. Exploration and Production

2.1 Energy Efficiency

The exploration and production stage represents the most energy-intensive component of the natural gas industry, consuming substantial power for drilling operations, completion activities, and ongoing production maintenance. Power optimization in drilling operations has emerged as a primary focus area, with modern drilling rigs incorporating variable frequency drives, efficient mud pumps, and optimized lighting systems that can reduce energy consumption compared to conventional systems.

²⁸ International Energy Agency. (2024). Global Methane Tracker 2024. Paris: IEA Publications.

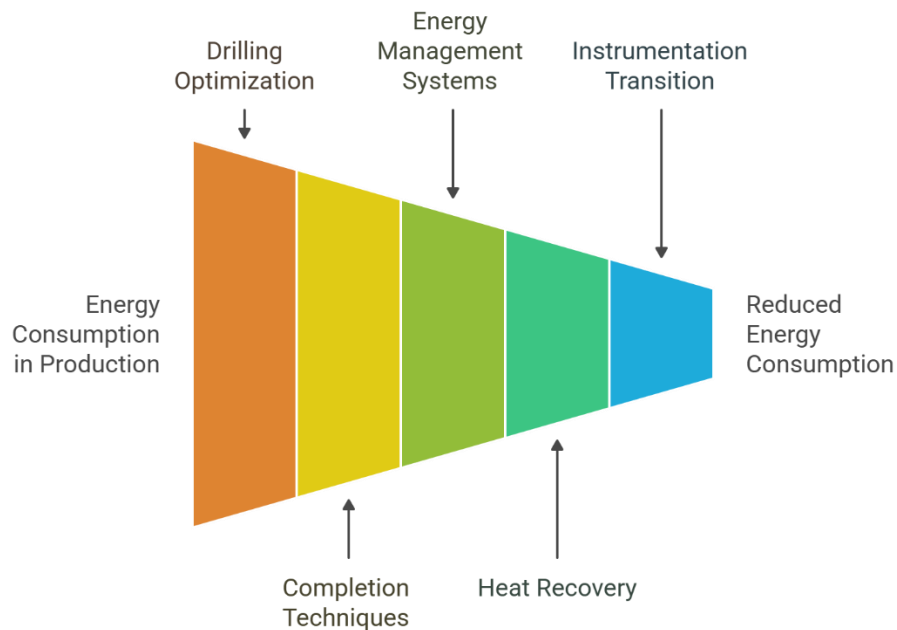


Figure III.3. Enhancing Energy Efficiency in Natural Gas Production

Efficient completion techniques have evolved significantly with the advancement of hydraulic fracturing technologies and horizontal drilling capabilities (Fig. III.4). The Society of Petroleum Engineers reports that the integration of new technologies and innovative approaches plays a pivotal role in driving sustainable advancements and value gains, enhancing operational efficiency while reducing environmental impacts.

Advanced completion designs optimize stage spacing and proppant placement to maximize production rates while minimizing the energy required per unit of gas recovered. The integration of electric-powered completion equipment, replacing traditional gas-powered units, has demonstrated energy intensity reductions of up to 40% in major production basins globally.

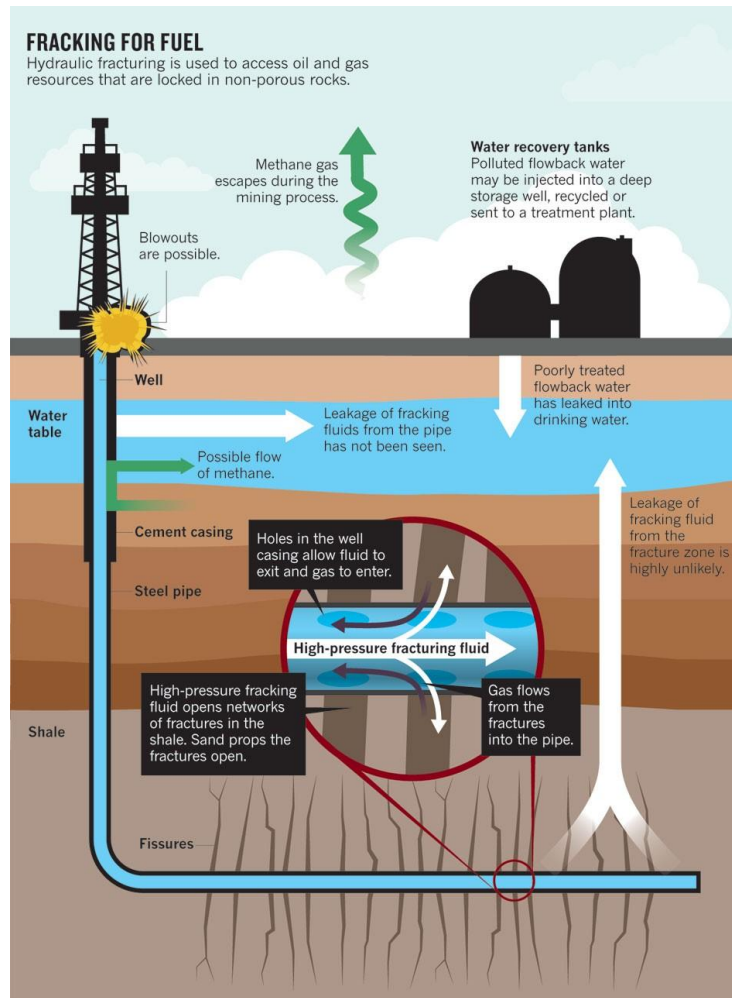


Figure III.4. Diagram of hydraulic fracturing technology

Energy management systems for production facilities encompass comprehensive monitoring and control technologies that optimize compressor operations, glycol dehydration units, and artificial lift systems. These systems utilize real-time data analytics to adjust operational parameters dynamically, achieving energy savings of 15-25% while maintaining production targets²⁹. Heat recovery and cogeneration opportunities at production sites capture waste heat from compressor engines and other thermal processes, converting it to useful power or process heat. The transition from pneumatic to electric instrumentation represents a fundamental shift in production facility design philosophy, eliminating the continuous venting of natural gas that characterizes traditional pneumatic controls while simultaneously improving energy efficiency and reducing fugitive emissions.

²⁹ <https://www.phoenixstrategy.group/blog/how-to-optimize-energy-use-in-manufacturing>

2.2 Reducing Fugitive Emissions

LDAR programs constitute the cornerstone of fugitive emissions reduction in exploration and production operations. The Oil and Gas Climate Initiative (OGCI) is a CEO-led initiative comprised of 12 of the world's leading energy companies focused on leading the industry's response to climate change and accelerating action to a net zero future consistent with the 2015 Paris Agreement. OGCI's members are Aramco, bp, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Petrobras, Repsol, Shell and TotalEnergies. OGCI reports that member companies have reduced upstream methane emissions by 55% since 2017 through systematic implementation of LDAR programs, while collectively investing USD 95.8 billion in low-carbon technologies³⁰. These programs employ multiple detection technologies, from handheld sensors for routine inspections to advanced optical gas imaging cameras that can identify leaks invisible to the naked eye.

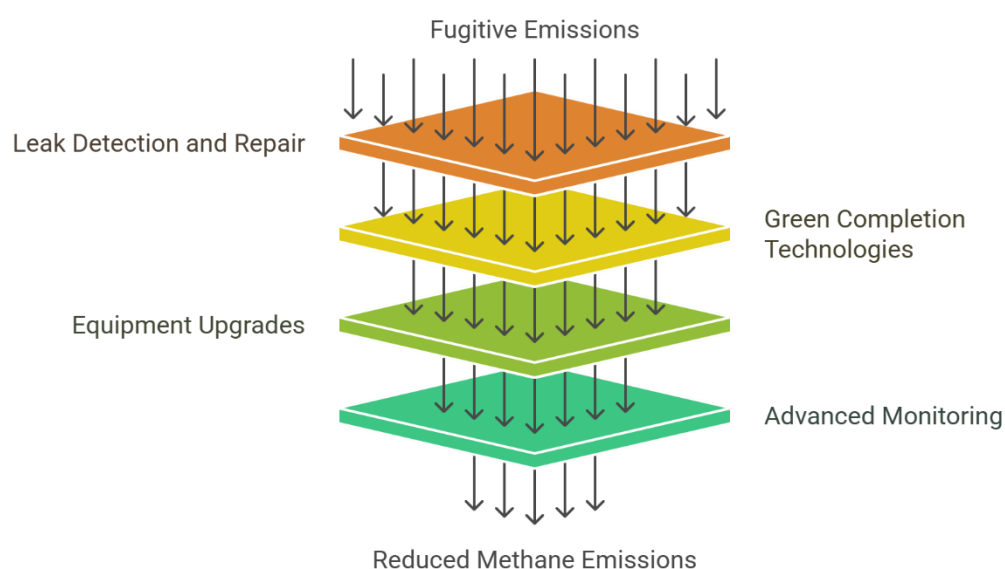


Figure III.5. Reducing Fugitive Emissions in Natural Gas Operations

Well completion and workover emission controls have undergone substantial improvement through the adoption of green completion technologies³¹ and reduced emission completions techniques. These methods capture gas that would traditionally be vented or flared during completion operations, routing it to sales lines or temporary storage systems. The Environmental Protection Agency estimates that enhanced completion techniques can reduce methane emissions by 90% compared to conventional venting practices, representing one of the most

³⁰ Oil and Gas Climate Initiative. (2024). Performance Data Hub - OGCI Emissions Data 2024. Retrieved from <https://www.ogci.com/our-progress/performance-data-hub>

³¹ Green completion technologies refer to practices and equipment used during well completions to minimize or eliminate the venting or flaring of natural gas, particularly during the flowback period after hydraulic fracturing.

effective near-term mitigation strategies available to the industry³².

Equipment design standards and best practices focus on eliminating high-emission components such as high-bleed pneumatic devices, unpacked wet seal centrifugal compressors, and atmospheric storage tanks. The replacement of these components with low-emission alternatives has become standard practice in developed markets, with regulatory frameworks increasingly mandating these upgrades. The American Gas Association reports that total methane emissions from natural gas systems were 173.1 MMTCO₂e in 2022, representing a nearly 21% decrease compared to 1990 emissions, demonstrating the effectiveness of systematic equipment upgrades and operational improvements³³.

Methane measurement and monitoring technologies have advanced dramatically with the deployment of continuous monitoring systems, satellite-based detection, and aerial surveillance programs. The International Energy Agency indicates that satellite systems detected more than 500 very large leaks from fossil fuel operations in 20 economies during 2022, enabling rapid response and mitigation efforts. The MIT Technology Review reports that advances in methane detection technology, including satellites like MethaneSAT and aerial surveys, are revealing that methane emissions are significantly higher than previously estimated, highlighting the critical importance of comprehensive monitoring programs³⁴.

³² Environmental Protection Agency. (2024). Estimates of Methane Emissions by Segment in the United States. Retrieved from <https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states>

³³ American Gas Association. (2024). Understanding Greenhouse Gas Emissions from Natural Gas - EPA 2024 Inventory (1990-2022). Retrieved from <https://www.aga.org/research-policy/resource-library/>

³⁴ MIT Technology Review. (2024). Methane Leaks in the US Are Worse Than We Thought. Retrieved from <https://www.technologyreview.com/2024/03/13/1089725/methane-leaks-oil-gas/>

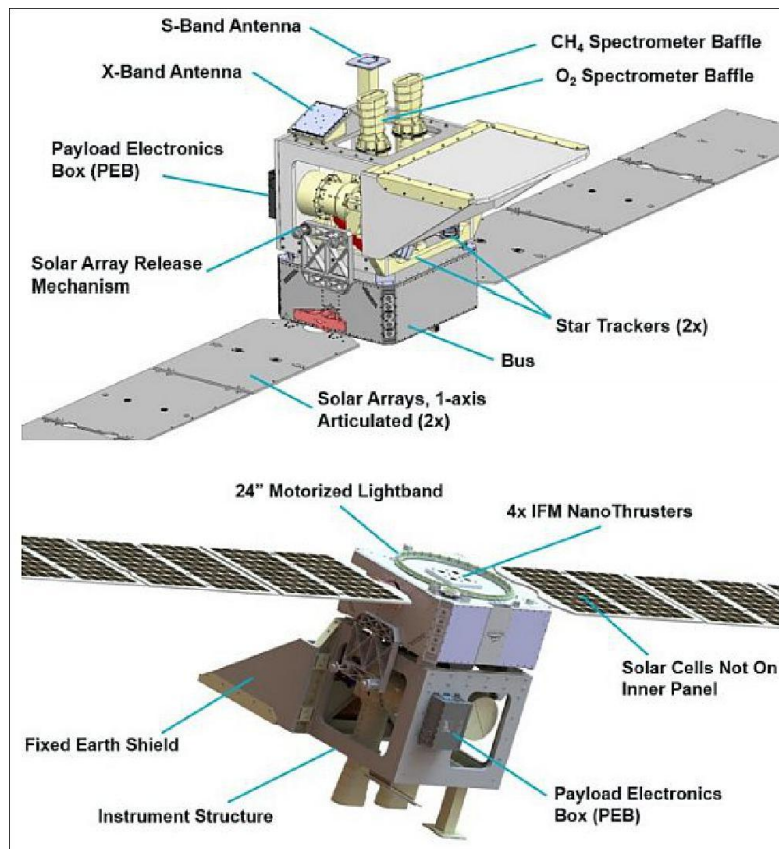


Figure III.6. Major components of the MethaneSAT flight system
(Source: MethaneSAT Team)

2.3 New Technology

Advanced drilling technologies continue to evolve, with directional drilling and extended reach capabilities reducing the surface footprint while accessing larger reservoir volumes. Advanced technologies such as satellites, global positioning systems, remote sensing devices, and 3-D and 4-D seismic technologies make it possible to discover natural gas reserves and drill fewer wells³⁵. Modern drilling systems incorporate automated drilling technologies, real-time formation evaluation, and advanced bit designs that optimize penetration rates while minimizing energy consumption. These innovations have reduced drilling time per well by 40-50% in major shale plays over the past decade.

³⁵ U.S. Energy Information Administration. (2024). Natural Gas and the Environment. Retrieved from <https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php>

Concept of Seismic Exploration

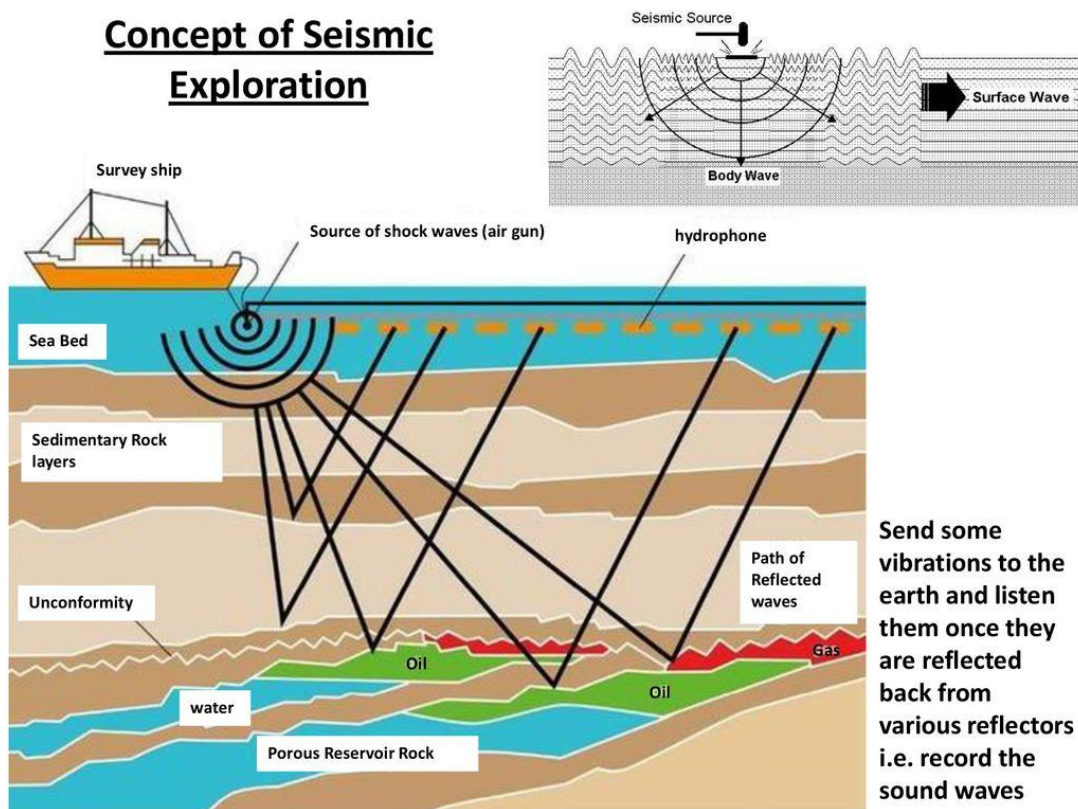


Figure III.7. 4D seismic technology for future oil and gas exploration

Smart sensors and Internet of Things applications enable continuous monitoring of equipment performance, wellhead pressures, and environmental conditions. These systems facilitate predictive maintenance strategies that prevent equipment failures before they occur, reducing both emissions and operational disruptions. The Society of Petroleum Engineers emphasizes that the integration of new technologies and innovative approaches is paramount for driving value gains in natural gas processing and handling, playing a crucial role in improving efficiency and reducing methane emissions. Artificial intelligence algorithms analyze vast datasets from these sensors to optimize production parameters and identify anomalous conditions that may indicate leaks or equipment degradation.

CO₂-enhanced gas recovery (CO₂-EGR) is a promising technology that improves hydrocarbon recovery while mitigating greenhouse gas emissions. By injecting CO₂ into depleted gas reservoirs, this process displaces remaining natural gas and enables long-term CO₂ storage, supporting both energy security and climate goals. The growing interest in CO₂-EGR stems from increasing global focus on carbon management and climate action. As a key component of carbon capture, utilization, and storage (CCUS) technologies, CO₂-EGR offers dual functionality: enhancing gas recovery while providing CO₂ sequestration. This creates economic advantages by offsetting CCUS costs through increased production, generating dual revenue streams for energy

companies³⁶.

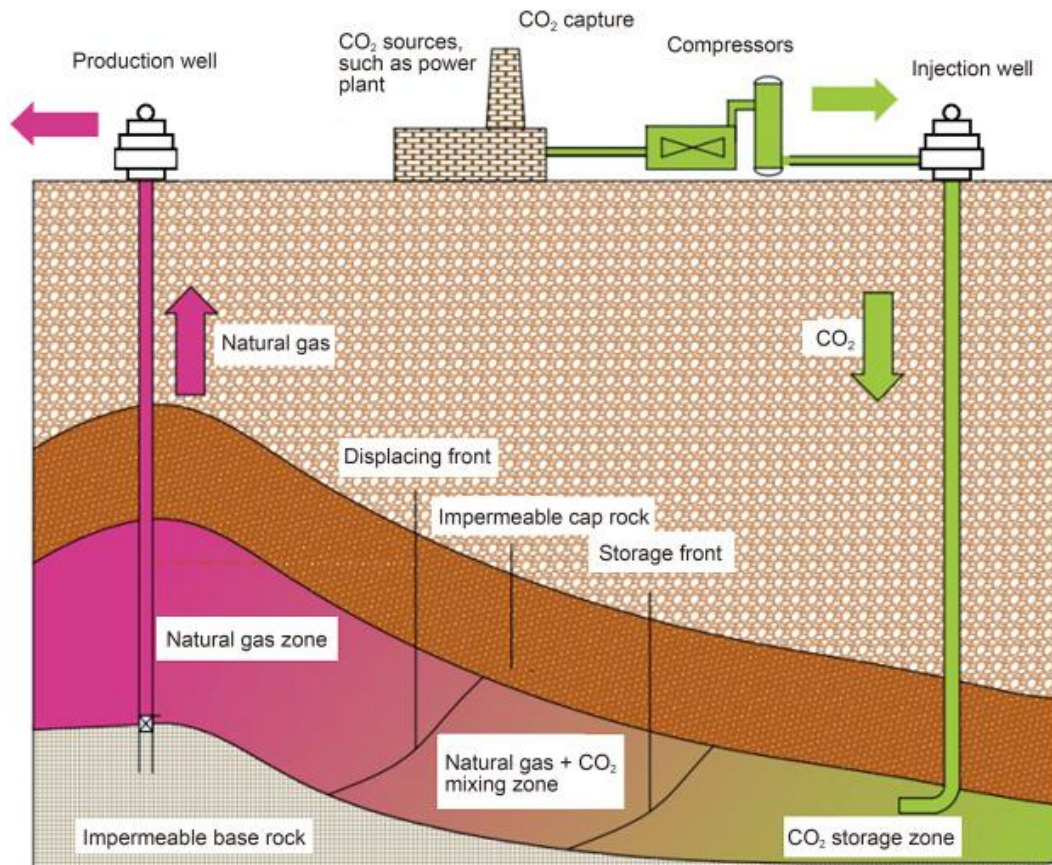


Figure III.8. Schematic diagram of CO₂-enhanced gas recovery technology

3. Processing

3.1 Energy Efficiency

Process optimization and integration represent fundamental approaches to improving energy efficiency in natural gas processing facilities. Modern plants employ advanced process simulation software and real-time optimization systems that continuously adjust operating parameters to minimize energy consumption while maintaining product specifications. Heat integration studies, using pinch analysis methodologies, identify opportunities to recover and reuse thermal energy throughout the processing train, typically achieving energy savings of 15-25%.

³⁶ Qing Ye et al. CO₂-Enhanced Gas Recovery (EGR) in Offshore Carbon-Rich Gas Reservoirs—Part 2: EGR Performance and Its Dependency. <https://doi.org/10.3390/pr13030698>



Figure III.9. Enhancing Energy Efficiency in Natural Gas Processing

Heat exchanger networks in processing facilities have been redesigned using advanced materials and enhanced heat transfer technologies. Plate heat exchangers, spiral heat exchangers, and compact heat exchangers provide superior thermal performance while reducing maintenance requirements. The optimization of heat exchanger networks through systematic retrofit programs has demonstrated energy intensity reductions in existing facilities, contributing significantly to overall industry efficiency improvements.

Compression efficiency improvements focus on the heart of gas processing operations, where significant energy consumption occurs during gas compression, refrigeration, and pumping operations. Variable speed drives, magnetic bearing compressors, and advanced compression cycle designs reduce energy consumption while improving reliability. The replacement of traditional reciprocating compressors with rotary screw or centrifugal alternatives can reduce energy consumption by 10-20% while providing more stable operation and reduced maintenance requirements.

3.2 Reducing Fugitive Emissions

Vapor recovery units represent critical infrastructure for capturing and processing gas vapors that would otherwise be vented or flared during processing operations. Modern Vapor Recovery Unit systems incorporate advanced separation technologies, membrane systems, and adsorption units that can achieve recovery efficiencies exceeding 98%. The advancement in data collection and the use of new technologies such as drones and infrared imagery reveal that upstream methane emissions can be much more significant than previously estimated, making effective vapor recovery systems essential for comprehensive emissions management³⁷.

³⁷ World Bank. (2024). Summary Report on Methane Emissions. Retrieved from <https://flaringventingregulations.worldbank.org/summary-report>



Figure III.10. Comprehensive Emissions Management Strategies

Improved seal and gasket technologies address fundamental sources of fugitive emissions throughout processing facilities. Advanced elastomer materials, mechanical seal designs, and magnetic drive pumps eliminate traditional sources of leakage. The systematic replacement of conventional pump seals with dual mechanical seals or magnetic drive systems can reduce emissions by 95% while improving equipment reliability and reducing maintenance costs over the facility lifecycle.

Process design for emission minimization incorporates leak-tight design principles from the initial engineering phase. Closed-loop systems, welded connections, and elimination of unnecessary process vents reduce potential emission sources. The Society of Petroleum Engineers highlights that breakthrough lean gas flare-tip technology (Fig. III.11) and annular injection mixer concepts for heavy hydrocarbon evaporation represent innovative approaches to emissions reduction in natural gas processing applications³⁸.

³⁸ Society of Petroleum Engineers. (2024). Natural Gas Processing and Handling-2024. Journal of Petroleum Technology.

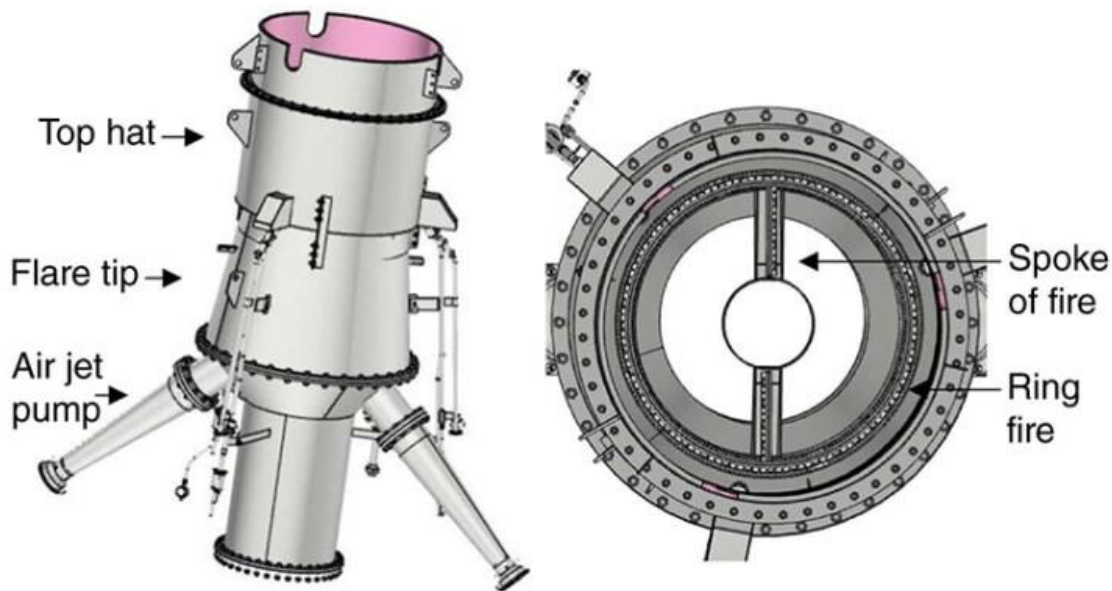


Figure III.11. Extremely Low-BTU flare-tip design (elevation view and top view)
(Source: SPE)

Maintenance protocols for equipment integrity emphasize proactive inspection schedules, predictive maintenance technologies, and rapid response procedures for addressing identified leaks. Carbon capture and utilization at processing facilities represents an emerging opportunity to address process emissions while creating value-added products. Captured carbon dioxide can be utilized for enhanced oil recovery operations, converted to useful chemicals, or permanently stored in geological formations, with several natural gas processing facilities implementing pilot-scale carbon capture systems with plans for commercial-scale deployment.

3.3 New Technology

Modular natural gas processing technologies enable flexible, efficient processing capabilities that can be deployed rapidly in remote locations or scaled according to production requirements. These systems incorporate standardized process units, skid-mounted equipment, and automated control systems that reduce construction time and operational complexity while maintaining high efficiency standards. The modular approach allows for optimized factory construction, reduced field installation time, and enhanced quality control compared to traditional stick-built facilities.

Advanced separation techniques, including membrane separation, molecular sieves, and

cryogenic separation, provide enhanced selectivity and energy efficiency compared to conventional separation methods (Fig. III.12). Membrane technologies offer reduced energy consumption for gas sweetening, dehydration, and nitrogen rejection applications, with recent developments in polymer membrane materials achieving improved permeability and selectivity characteristics. Digital twin technology for process optimization creates virtual models of processing facilities that enable real-time optimization, predictive maintenance, and scenario planning without disrupting actual operations.

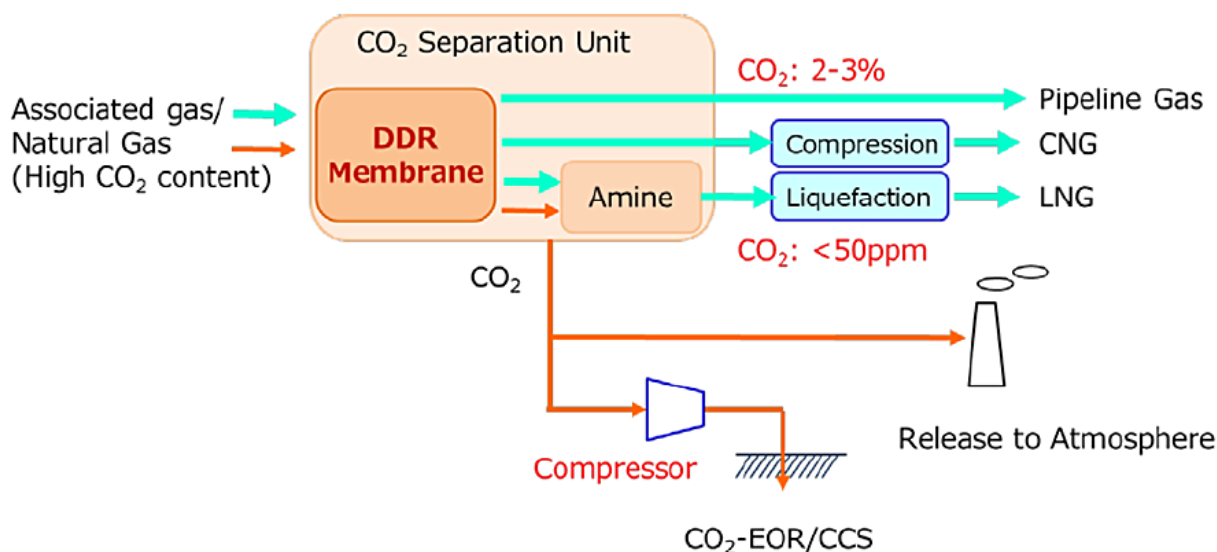


Figure III.12. DDR Membrane - CO₂ Separation for Natural Gas Treatment³⁹
(Source: JGC)

Catalytic processes for emission reduction incorporate advanced catalyst systems that convert methane and other hydrocarbons to less harmful compounds or useful products. Methane oxidation catalysts, selective catalytic reduction systems, and thermal oxidation technologies provide effective emission control while potentially recovering energy value from waste streams.

4. Transportation

4.1 Energy Efficiency

Pipeline compression optimization represents the largest opportunity for energy efficiency improvement in natural gas transportation systems. Modern compressor stations incorporate variable speed drives, advanced control systems, and optimized compression ratios that reduce energy consumption by 15-25% compared to traditional constant-speed systems.

³⁹ DDR membrane process is a high-efficiency CO₂ separation technology using a DDR-type zeolite membrane.

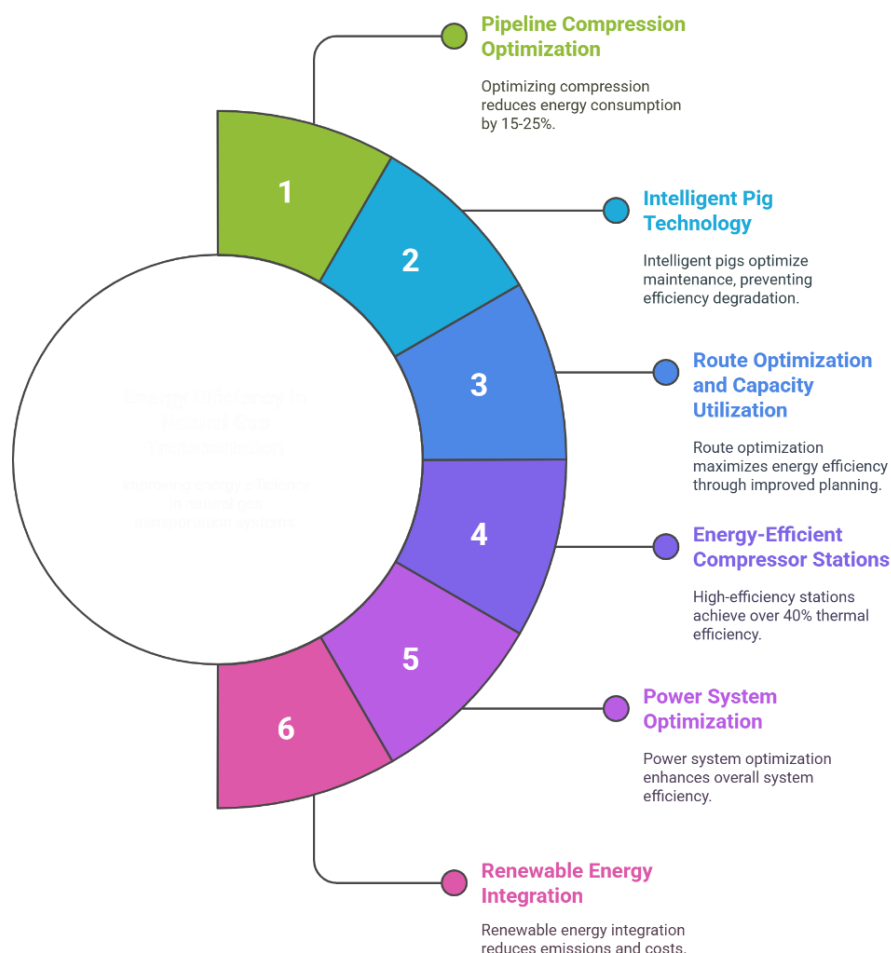


Figure III.13. Enhancing Energy Efficiency in Natural Gas Transportation

The deployment of intelligent pig technology for pipeline integrity management enables optimized maintenance schedules that prevent efficiency degradation due to internal corrosion or deposits. Advanced inline inspection tools provide detailed information about pipeline condition, allowing operators to prioritize maintenance activities and optimize operational parameters. Route optimization and capacity utilization strategies maximize the energy efficiency of transportation networks through improved hydraulic modeling and operational planning, using advanced pipeline simulation software to optimize flow rates, pressure profiles, and compressor operations.

Energy-efficient compressor stations incorporate high-efficiency gas turbines, electric motor drives, and heat recovery systems that achieve overall thermal efficiencies exceeding 40%. The integration of waste heat recovery systems, combined cycle configurations, and advanced control systems enables compressor stations to achieve significant efficiency improvements while

reducing operational costs. Power system optimization includes the electrical infrastructure supporting compressor stations, including power factor correction, variable frequency drives, and energy storage systems that enhance overall system efficiency.

The integration of renewable energy sources, particularly solar and wind power, with compressor station operations provides opportunities for further emissions reduction and energy cost optimization. Several pipeline operators have successfully implemented renewable energy integration projects that reduce grid electricity consumption while providing operational flexibility and cost savings.

4.2 Reducing Fugitive Emissions

Pipeline integrity management systems provide comprehensive monitoring and maintenance programs that prevent leaks before they occur. These systems combine internal inspection tools, external corrosion monitoring, and geospatial analysis to identify potential failure points and prioritize maintenance activities. The Environmental Protection Agency emphasizes that strict government regulations and industry standards are in place to ensure safe transportation, storage, distribution, and consumption of natural gas, with comprehensive integrity management forming the foundation of safe and environmentally responsible operations⁴⁰.

Modern pipeline construction incorporates improved welding techniques, enhanced quality control procedures, and advanced coating systems that provide superior protection against corrosion and mechanical damage, which can contribute to reduce methane emissions.

Compressor station emission controls focus on eliminating or capturing emissions from compressor seals, blowdown systems, and storage tanks. Dry gas seals have largely replaced oil-lubricated seals in modern compressor installations, reducing both methane emissions and maintenance requirements while improving operational reliability. Valve and fitting emission reduction strategies emphasize the use of bellows-sealed valves, welded connections, and double-block-and-bleed systems that minimize potential leak points throughout the transportation infrastructure.

Emergency response and leak mitigation protocols ensure rapid detection and repair of pipeline leaks through automated shutdown systems, continuous monitoring, and trained response teams. The deployment of fiber optic sensing systems along pipeline routes enables real-time detection of leaks, third-party interference, and other integrity threats, providing operators with immediate notification of potential issues and enabling rapid response to minimize environmental impact.

⁴⁰ U.S. Energy Information Administration. (2024). Natural Gas and the Environment. Retrieved from <https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php>

4.3 New Technology

Smart pipeline monitoring systems integrate multiple sensing technologies, including acoustic monitoring, infrared detection, and chemical sensors, to provide comprehensive surveillance of pipeline networks. These systems utilize artificial intelligence algorithms to distinguish between normal operational variations and potential integrity concerns, reducing false alarms while ensuring rapid response to genuine threats.

Satellite-based leak detection has emerged as a transformative technology for large-scale pipeline monitoring. The MIT Technology Review reports that satellites equipped with methane-sensitive sensors can detect and quantify emissions over vast geographic areas, providing operators with early warning of potential leaks and enabling regulatory agencies to verify compliance with emission reduction targets⁴¹. Recent developments in satellite technology have improved detection sensitivity and reduced the time required for data processing and analysis.

Advanced pipeline inspection technologies, including ultrasonic testing, electromagnetic acoustic transducers, and magnetic flux leakage tools, provide detailed assessment of pipeline condition without interrupting operations. These technologies enable operators to identify potential integrity issues before they result in leaks or failures, supporting proactive maintenance strategies that enhance safety and environmental performance.

5. Storage

5.1 Energy Efficiency

Injection and withdrawal optimization strategies maximize the energy efficiency of underground storage operations through advanced reservoir modeling and operational planning. These systems balance injection and withdrawal rates to minimize compression energy requirements while maintaining storage capacity and deliverability targets.

Compression system efficiency improvements focus on the compressors and associated equipment used for gas injection and withdrawal operations. Variable speed compressors, intercooling systems, and heat recovery technologies reduce energy consumption while providing operational flexibility to respond to changing market conditions. Modern compression systems incorporate advanced control algorithms that optimize compression ratios and staging to minimize energy consumption across varying operational scenarios.

Facility design for energy conservation incorporates passive cooling systems, efficient lighting, and building envelope improvements that reduce auxiliary energy consumption. The integration

⁴¹ MIT Technology Review. (2024). Methane Leaks in the US Are Worse Than We Thought. Retrieved from <https://www.technologyreview.com/2024/03/13/1089725/methane-leaks-oil-gas/>

of advanced building management systems, LED lighting technologies, and high-efficiency HVAC systems can reduce facility energy consumption by 20-30% compared to conventional designs while improving operational comfort and equipment performance.

Integration with renewable energy sources enables storage facilities to utilize wind and solar power for compression operations, reducing grid electricity consumption and associated emissions. Several storage operators have implemented renewable energy projects that provide cost-effective power while reducing the carbon footprint of storage operations. Smart grid integration capabilities allow storage operators to provide ancillary services to the electrical grid while optimizing their own energy consumption patterns, creating additional revenue streams while supporting grid stability.

5.2 Reducing Fugitive Emissions

Underground storage integrity monitoring includes comprehensive surveillance of storage wells, surface facilities, and surrounding areas to detect and prevent methane emissions. Advanced monitoring systems include continuous methane detectors, soil gas surveys, and groundwater monitoring programs that provide early warning of potential integrity issues.

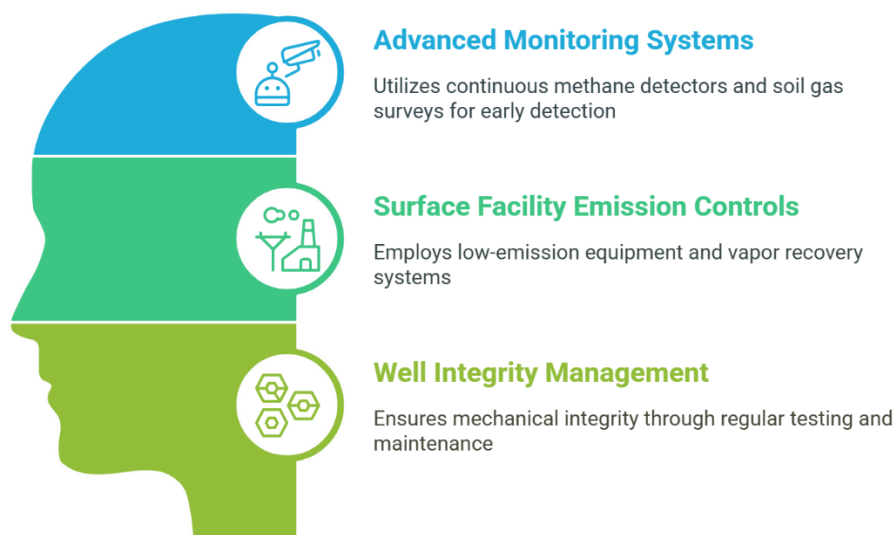


Figure III.14. Comprehensive Methane Emission Management

Surface facility emission controls address potential emission sources including wellheads, compressors, dehydration units, and measurement stations. These facilities employ low-emission

equipment designs, vapor recovery systems, and leak detection technologies similar to those used in production operations. Well integrity management programs ensure that storage wells maintain mechanical integrity throughout their operational life through regular testing, maintenance, and monitoring protocols that comply with regulatory requirements and industry best practices.

5.3 New Technology

Advanced reservoir monitoring technologies, including micro-seismic monitoring, distributed temperature sensing, and pressure transient analysis, provide detailed insight into storage reservoir behavior and performance. These systems enable operators to optimize injection and withdrawal strategies while ensuring safe and efficient storage operations throughout the reservoir lifecycle. Real-time monitoring capabilities support dynamic operational adjustments that enhance storage efficiency while maintaining integrity and safety standards.

Salt cavern storage innovations incorporate advanced cavern development techniques, brine management systems, and monitoring technologies that maximize storage capacity while minimizing environmental impacts. Recent developments in salt cavern technology include improved leaching techniques, enhanced cavern geometry optimization, and advanced monitoring systems that provide real-time assessment of cavern stability and performance.

LNG storage efficiency improvements focus on boil-off gas management, tank insulation systems, and regasification technologies that reduce methane emissions and energy consumption. The International Energy Agency notes that methane leaks can occur during LNG shipping if boil-off gas is vented or not fully combusted in ship engines, emphasizing the importance of efficient boil-off gas management systems that recirculate or reliquefy boil-off gas rather than venting it to the atmosphere.

6. Case Studies

6.1 Fugitive Emissions Management in Alberta, Canada

The Alberta Methane Field Challenge (AMFC) phases 1 and 2 were field campaigns conducted in 2019 to assess the performance of new methane leak detection and quantification technologies at producing oil and gas facilities⁴².

Two separate field trials were conducted in 2019 across 50 oil and gas producing sites near Rocky Mountain House, Alberta. The 50 sites were selected by the AMFC's science team, based on several considerations, including ease of access, site density to minimize travel time between sites,

⁴² Petroleum Technology Alliance Canada, Advancing To Net-Zero: Development, Field Testing, and Deployment of Methane Detection and Mitigation Technologies.

vegetation type, production, and resource characteristics.

The field trials tested five different types of leak detection methods: fixed continuous monitoring systems; handheld devices; truck-mounted sensors; drone-mounted sensors; and aerial systems. In addition, in the second trial, controlled release testing (CRT) was deployed at one site to provide calibration for Quantitative Optical Gas Imaging (QOGI) and as a further comparative to other leak detection methods.

Overall, 12 technologies were field tested as part of AMFC. The leak detection technologies were chosen through a rigorous application and selection process that took into consideration technological capabilities, prior testing experience, deployment and scalability, and cost. Although the development of new sensors, technologies, and platforms showed faster and more cost-effective methane leak detection than existing approaches in controlled test conditions, there were remaining questions around their field deployment viability. The AMFC program was commissioned to address this critical gap in evaluation of new methane leak detection technologies.

The AMFC was the first large-scale field trials of new methane detection technologies.

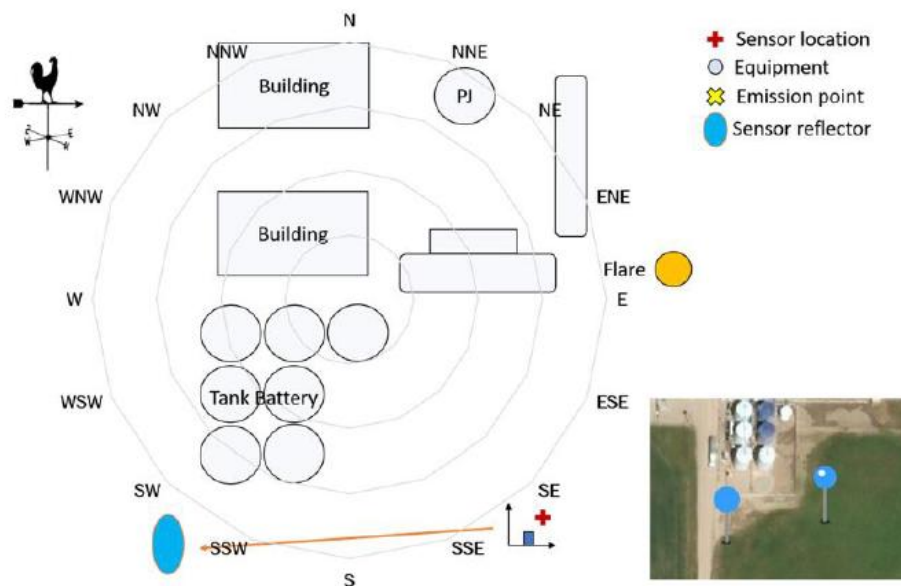


Figure III.15. Schematic of the site and the location of the Heath Consultants' fixed sensor deployed in AMFC phase 1

(Source: PTAC)⁴³

The AMFC yielded several key insights, including:

⁴³ Final Report of Alberta Methane Field Challenge

- QOGI, as a baseline technology is effective in providing comprehensive estimates of aggregate methane emissions at oil and gas facilities. Future studies on the precision of QOGI quantification are recommended.
- Most technologies evaluated in the AMFC are effective at detecting atmospheric methane and quantification.
- Accurate quantification remains challenging – some technologies can provide good order of magnitude estimates of site-level emissions compared to QOGI.
- In-field controlled releases are effective in assessing the quantification capabilities of new technologies that account for local weather conditions.

This study provided valuable data for operators, regulators, and technology developers to better understand the operational challenges involved in methane emissions detection and quantification using a variety of technologies and platforms.

6.2 Policy and Regulatory Drivers in the United States

The impact of environmental regulations on efficiency improvements is exemplified by the U.S. EPA's methane regulations, which require comprehensive measurement, monitoring, and reporting of methane emissions while mandating specific technology standards for emission control. The Environmental Protection Agency reports that these regulations have driven industry-wide adoption of best practices and accelerated technology deployment, with the Waste Emissions Charge starting at USD 900 per metric ton of wasteful emissions in 2024, increasing to USD 1,500 for 2026 and beyond⁴⁴. These economic incentives complement regulatory requirements to create powerful drivers for emissions reduction and efficiency improvement.

⁴⁴ Environmental Protection Agency. (2024). EPA Finalizes Rule to Reduce Wasteful Methane Emissions and Drive Innovation in the Oil and Gas Sector.

Characteristic	Waste Emissions Charge	Clean Air Act Standards	Financial & Technical Assistance
Purpose	Incentivizes methane reduction	Limits methane from operations	Supports methane monitoring, mitigation
Applicability	High-emitting oil/gas facilities	New and existing oil/gas	Oil and gas sector
Mechanism	Charge per ton of emissions	Regulatory compliance exemption	Monitoring and mitigation support
Incentive	Avoid the charge	Compliance for exemption	Better performance

Figure III.16. EPA's Methane Emissions Reduction Rule

Incentive programs and their effectiveness include the U.S. Inflation Reduction Act's Methane Emissions Reduction Program, which provides over USD 1 billion in funding for methane monitoring and mitigation while implementing waste emissions charges that create economic incentives for emissions reduction. The Environmental Protection Agency emphasizes that these measures incentivize affected facilities to reduce emissions in advance of compliance requirements under oil and gas standards, demonstrating how policy frameworks can accelerate voluntary action beyond regulatory minimums.

6.3 Lean Gas Flare Tip Technology Breakthrough in the Gulf of Thailand

PTTEP (PTT Exploration and Production) developed breakthrough flare tip technology that can combust extremely low heating value gas at just 110 BTU/scf, compared to the 200 BTU/scf minimum required by existing commercial flare tips. This innovation addresses a critical challenge in offshore gas processing where new CO₂ removal membrane technologies produce permeate gas with very low heating values (as low as 160 BTU/scf with 85% CO₂ content).

Previously, when permeate gas exceeded 80% CO₂ content, operators had to reinject valuable hydrocarbon gas to maintain the minimum 200 BTU/scf heating value required for conventional flare tips. This practice resulted in significant economic losses (up to USD 15 million annually) and substantial greenhouse gas emissions (100,000 tons CO₂ equivalent per year) for a typical 5 MMscfd operation.

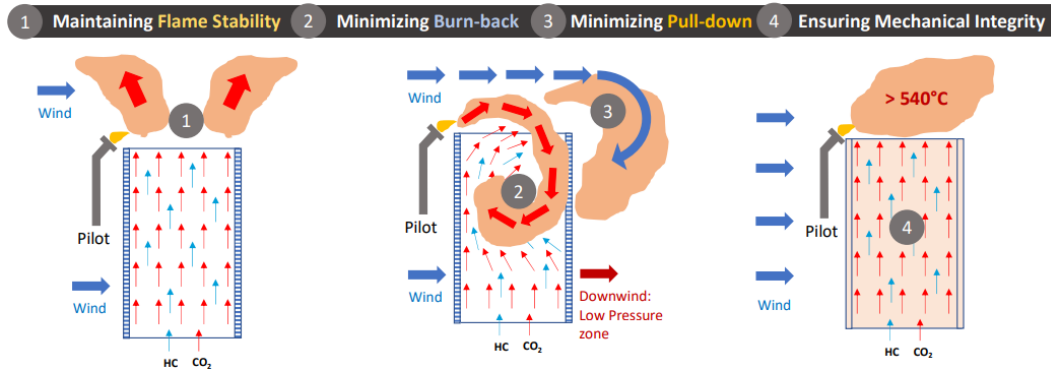


Figure III.17. Problem definition and challenges
(Source: PTTEP)

The technology was developed through a comprehensive multi-year program starting in 2018, involving partnership with John Zink Hamworthy Combustion. The development included extensive research, computational fluid dynamics modeling, and rigorous prototype testing with over 130 test runs across 40 different operating conditions. Testing simulated harsh offshore environments including strong crosswinds up to 20 mph.

The new flare tip design successfully overcomes four critical technical challenges: maintaining flame stability, minimizing burn-back, minimizing pull-down effects, and ensuring mechanical integrity under extreme operating conditions. The technology demonstrates reliable combustion performance and structural durability in offshore environments.

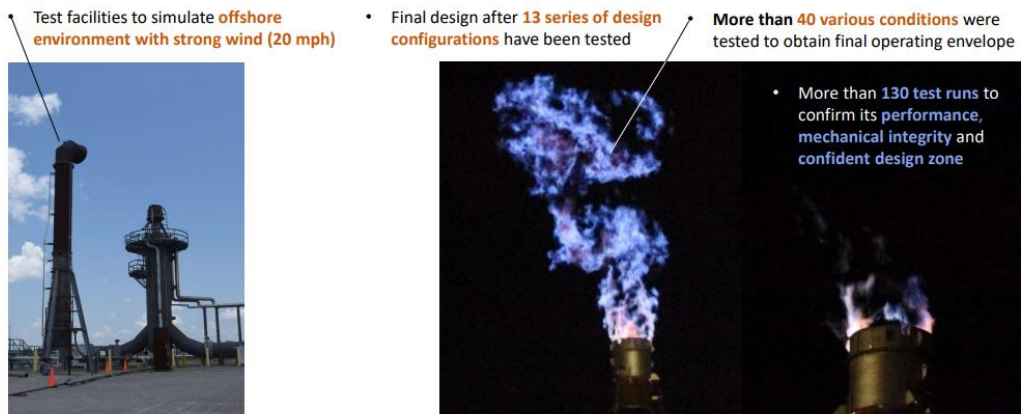


Figure III.18. Prototype testing
(Source: PTTEP)

The first commercial installation was completed in 2024 at the Greater Bongkot South platform in the Gulf of Thailand. This technology breakthrough enables annual cost savings of USD 6-30 million and greenhouse gas reductions of 40,000-100,000 tons CO₂ equivalent per year, supporting PTTEP's decarbonization strategy and net-zero emissions goals.

IV. Coal industry

1. Overview

Understanding the coal industry requires viewing it as an interconnected system where efficiency gains or losses at one stage cascade through subsequent operations. This comprehensive industry includes four critical stages (Fig. 1), beginning with extraction and mining, which forms the foundation of the coal supply chain where raw coal is extracted through surface or underground operations. This stage involves energy-intensive processes including drilling, blasting, and material handling. The second stage, processing and preparation, involves raw coal undergoing beneficiation to remove impurities and improve quality.

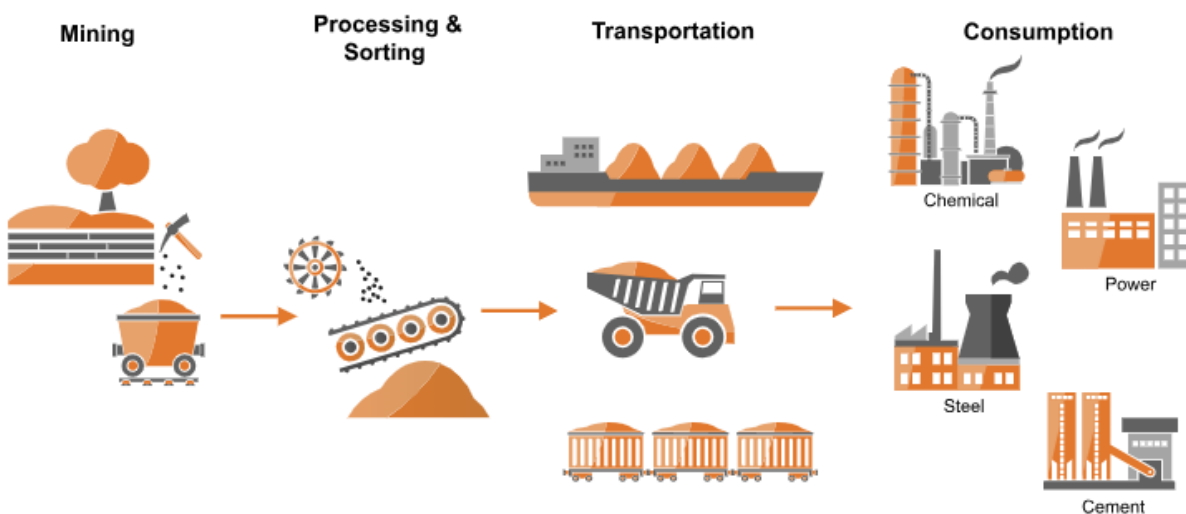


Figure IV.1. Diagram of the coal industry.
(Source: MoviTHERM)

Transportation and logistics represents the third stage, where coal moves through complex networks of haul trucks, conveyors, railways, and ships. The fourth stage includes consumption and end-use, primarily electricity generation in thermal power plants, where global average efficiency remains at just 33%⁴⁵.

The potential for efficiency improvements across this industry is substantial. Energy intensity in coal operations has been trending upward as high-grade, easily accessible reserves become depleted, making efficiency gains not just environmentally beneficial but economically essential. Mining operations can reduce ventilation energy consumption by 30-60% through Ventilation on

⁴⁵ Global Energy Monitor. (2024). *Coal combustion efficiency*. Retrieved from https://www.gem.wiki/Coal_combustion_efficiency

Demand systems⁴⁶, while processing plants can achieve 5-10% overall energy reductions through digital optimization⁴⁷. Transportation systems can cut logistics emissions by over 50% through modal shifts and electrification⁴⁸, and power plants can boost efficiency from 33% to over 45% with ultra-supercritical technology⁴⁹.

The drive for increased efficiency in the coal industry is accelerating globally, propelled by converging economic, environmental, and regulatory forces. Carbon pricing mechanisms now cover 23% of global greenhouse gas emissions, creating direct financial incentives for efficiency improvements⁵⁰.

The coal industry is experiencing a technological renaissance driven by digitalization, automation, and electrification. The convergence of Internet of Things (IoT) sensors, artificial intelligence, and advanced materials is enabling precision control and optimization previously impossible. From autonomous haulage systems reducing fuel consumption by 10-15% to digital twins optimizing plant operations in real-time, technology is transforming what efficiency means in coal operations⁵¹.

Perhaps most significantly, the integration of renewable energy directly into coal operations—from solar-powered mining equipment to wind farms on reclaimed mine sites—is creating hybrid energy ecosystems toward a diversified energy future.

The following sessions examine each stage of the coal industry in detail, except end-use stage, identifying specific opportunities for efficiency enhancement, quantifying potential benefits, and presenting proven technologies and strategies.

2. Mining Operations

Mining operations represent the energy-intensive foundation of the coal industry, where massive machinery extracts millions of tons of coal annually through surface and underground methods. This stage presents strong opportunities for efficiency gains through advanced technologies and operational improvements, with the potential to significantly cut energy use and greenhouse gas emissions.

2.1 Energy Efficiency

⁴⁶ ABB. (2024). *Underground mine ventilation- how to improve safety and half energy costs*.

⁴⁷ BHP. (2025). *The role of digital twins and AI in enhancing decision-making in the mining industry*.

⁴⁸ ResearchGate. (2009). *Energy efficiency and steam coal transport over long distances*. Retrieved from <https://www.researchgate.net/publication/309222922>

⁴⁹ GE Vernova. (2018). *High-efficiency, low-emissions coal plants*. Retrieved from <https://www.gevernova.com/gas-power/resources/articles/2018/come-hele-or-high-water>

⁵⁰ World Bank. (2023). *State and Trends of Carbon Pricing 2023*. Washington, DC: World Bank.

⁵¹ Mining Technology. (2024). *Autonomous haulage systems for mining industry: Leading manufacturers*. Retrieved from <https://www.mining-technology.com/features/autonomous-haulage-systems/>

The energy profile of modern coal mining is dominated by two primary consumption categories: diesel fuel for mobile equipment (approximately 46% of total energy use) and electricity for stationary operations including critical ventilation systems (15% of total energy use)⁵². This concentration creates clear targets for efficiency interventions.

Surface mining operations depend heavily on energy-intensive equipment, including draglines, electric shovels, haul trucks, and bulldozers. The fuel efficiency of these machines varies dramatically based on operational parameters, equipment design, and critically, operator behavior. Research has demonstrated that inefficient operating practices can increase fuel consumption by up to 80% without any productivity benefit⁵³.

A systematic approach to mobile equipment efficiency involves several interconnected strategies. Real-time telemetry systems can identify inefficient driving patterns, excessive idling, and suboptimal equipment utilization, with studies showing that data-driven operator coaching can reduce fuel consumption by 10-20% across mining activities⁵⁴. Equally important is equipment rightsizing, where matching the size and capacity of loading equipment to haulage fleets optimizes loading cycles and minimizes wait times, reducing overall fuel consumption while improving productivity. Additionally, AI-powered systems can forecast equipment failures before they occur, enabling proactive maintenance that maintains peak efficiency and avoids the energy waste associated with degraded performance⁵⁵.

In underground coal mines, ventilation systems can consume up to 50% of total electricity usage, making them the primary target for efficiency improvements⁵⁶. Traditional ventilation operates at constant maximum capacity regardless of actual air quality needs or personnel locations, resulting in massive energy waste. The shift toward intelligent ventilation management represents one of the highest-impact efficiency opportunities in mining. Modern systems use real-time monitoring of air quality, gas concentrations, and personnel locations to deliver precisely the required airflow where and when needed (Fig. 2).

⁵² U.S. Department of Energy. (2007). *U.S. Mining Industry Energy Bandwidth Study*. Retrieved from https://www1.eere.energy.gov/manufacturing/resources/mining/pdfs/mining_bandwidth.pdf

⁵³ Komatsu. (2024). *Case Study: Reduce Haul Truck Fuel Consumption*. Retrieved from <https://www.komatsu.com/en/case-studies/reduce-haul-truck-fuel-consumption/>

⁵⁴ Komatsu. (2024). *Case Study: Reduce Haul Truck Fuel Consumption*. Retrieved from <https://www.komatsu.com/en/case-studies/reduce-haul-truck-fuel-consumption/>

⁵⁵ Mining Technology. (2024). *Intelligent mining: How the Internet of Things is revolutionising the mining industry*. Retrieved from <https://www.mining-technology.com/sponsored/intelligent-mining-how-the-internet-of-things-is-revolutionising-the-mining-industry/>

⁵⁶ ABB. (2024). *Underground mine ventilation- how to improve safety and half energy costs*. Retrieved from <https://new.abb.com/mining/digital-applications/advanced-process-control/abb-ability-ventilation-optimizer/underground-mine-ventilation-how-to-improve-safety-and-half-energy-costs>

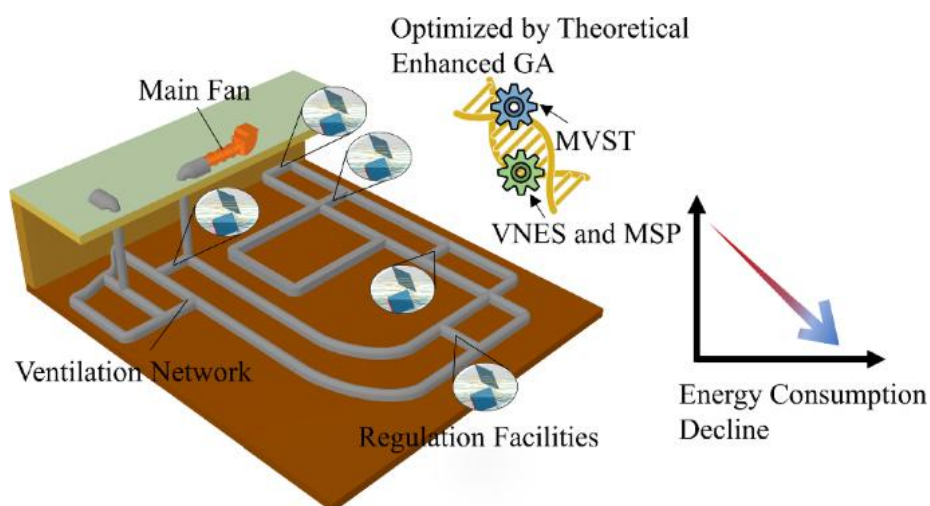


Figure IV.2. Real-time ventilation network monitoring for energy optimization

(Source: Wentian Shang & Jinzhang Jia)

2.2 Reducing Fugitive Emissions

Coal mining contributes an estimated 4-7% of global GHG emissions through multiple pathways⁵⁷. Understanding and addressing these emissions sources is crucial for the industry's environmental performance and regulatory compliance.

According to IEA Global Methane Tracker 2024, the global methane emissions from different sources are 331 Mt in 2023. This includes emissions from agriculture, energy, and waste. In the energy sector, IEA estimates that the production and use of fossil fuels resulted in nearly 120 million tons of methane emissions in 2023⁵⁸.

In 2023, methane emissions from global coal mines were one-third of total emissions from fossil fuels. Accordingly, global coal mine methane emissions were 40 Mt, compared to 49 Mt from oil and 29 Mt from natural gas production.

Underground mines release methane naturally contained in coal seams, with Ventilation Air Methane (VAM) accounting for approximately 70% of all methane emissions from underground operations⁵⁹. Given methane's global warming potential—over 80 times that of CO₂ over a 20-year period⁶⁰—these emissions represent a critical intervention point.

Effective methane management strategies encompass multiple approaches working in concert (Fig. IV.3). Pre-drainage of methane from coal seams before mining captures high-concentration

⁵⁷ Climate Risk and Decarbonization. (2020). McKinsey & Company.

⁵⁸ IEA Global Methane Tracker 2024

⁵⁹ International Energy Agency. (2023). *Strategies to reduce emissions from coal supply -- Global Methane Tracker 2023*. Retrieved from <https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-coal-supply>

⁶⁰ Cimarron Energy. (2024). *Coal Mine Methane*. Retrieved from <https://cimarron.com/coal-mine-methane/>

gas suitable for electricity generation or pipeline injection, while thermal oxidation systems convert dilute methane emissions to CO₂, significantly reducing their climate impact. Perhaps most promising is the conversion of captured methane into valuable energy resources, creating economic incentives for emission reduction that align environmental benefits with business objectives.

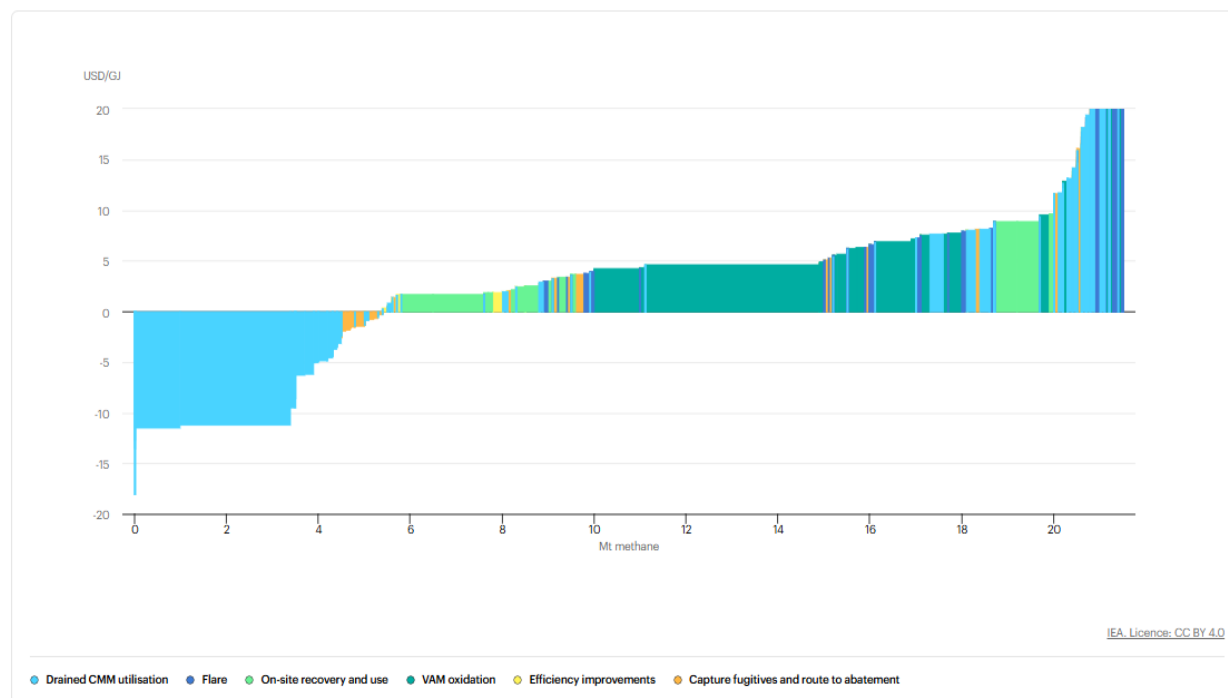


Figure IV.3. Methane marginal abatement cost curve for coal mine emissions, 2022

(Source: IEA, 2023)⁶¹

2.3 New Technology

The mining sector is experiencing rapid technological transformation driven by digitalization, automation, and electrification. These technologies are creating opportunities for efficiency enhancement and operational optimization.

Ventilation on Demand (VoD) system represents a paradigm shift from static to dynamic ventilation management. These systems deploy networks of sensors throughout mine workings to continuously monitor air quality, gas concentrations, and personnel locations (Fig. IV.4). Advanced control algorithms process this data in real-time to optimize fan speeds and airflow distribution. The impact is substantial: VoD systems can reduce ventilation energy consumption

⁶¹ International Energy Agency. (2023). *Strategies to reduce emissions from coal supply -- Global Methane Tracker 2023*. Retrieved from <https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-coal-supply>

by 30-60% while improving safety through better air quality management⁶². Implementation case studies demonstrate simple payback periods of 0.5 to 1.2 years, making VoD one of the highest-return investments available in mining efficiency⁶³.

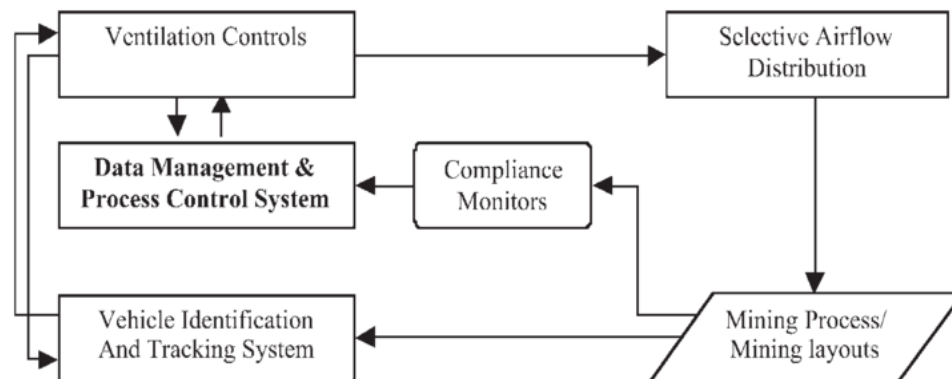


Figure IV.4. Ventilation-on-Demand Based System

(Source: Charles Kocsis, 2023)

Autonomous Haulage Systems (AHS) are revolutionizing surface mining operations by eliminating human operators and optimizing vehicle performance through precise computer control. Leading manufacturers including Caterpillar and Komatsu now offer commercial AHS solutions deployed at mines worldwide⁶⁴. AHS delivers multiple efficiency benefits through continuous operation without shift changes or breaks, increasing fleet utilization by up to 30%. Computer-controlled acceleration, braking, and routing reduces fuel consumption by 10-15%⁶⁵, while integrated sensors enable condition-based maintenance, reducing downtime and maintaining peak efficiency.

The foundation of mining's digital transformation is comprehensive sensor deployment creating real-time visibility into all aspects of operations (Fig. IV.5). IoT sensors monitor equipment performance, environmental conditions, and material flows, while AI algorithms analyze this data to identify optimization opportunities. Key applications include predictive analytics for forecasting equipment failures, maintenance needs, and operational bottlenecks, dynamic route optimization calculating the most efficient haulage routes based on current conditions, and real-time energy management optimizing power consumption across all mine systems⁶⁶.

⁶² ABB. (2024). *Underground mine ventilation- how to improve safety and half energy costs*. Retrieved from <https://new.abb.com/mining/digital-applications/advanced-process-control/abb-ability-ventilation-optimizer/underground-mine-ventilation-how-to-improve-safety-and-half-energy-costs>

⁶³ Chart Industries. (2024). *VentSim™ CONTROL Ventilation on Demand (VOD)*. Retrieved from https://files.chartindustries.com/Howden_VentsimVOD_Mining_Cases.pdf

⁶⁴ Hatch. (2024). *Challenges and opportunities for the adoption of autonomous hauling trucks in mining*. Retrieved from <https://www.hatch.com/About-Us/Publications/Blogs/2024/07/Challenges-and-opportunities-for-the-adoption-of-autonomous-hauling-trucks-in-mining>

⁶⁵ Mining Technology. (2024). *Autonomous haulage systems for mining industry: Leading manufacturers*. Retrieved from <https://www.mining-technology.com/features/autonomous-haulage-systems/>

⁶⁶ MDPI. (2023). *Energy Saving and Emission Reduction Potential Evaluation of a Coal Mine Based on Fuzzy Hierarchical Analysis*.

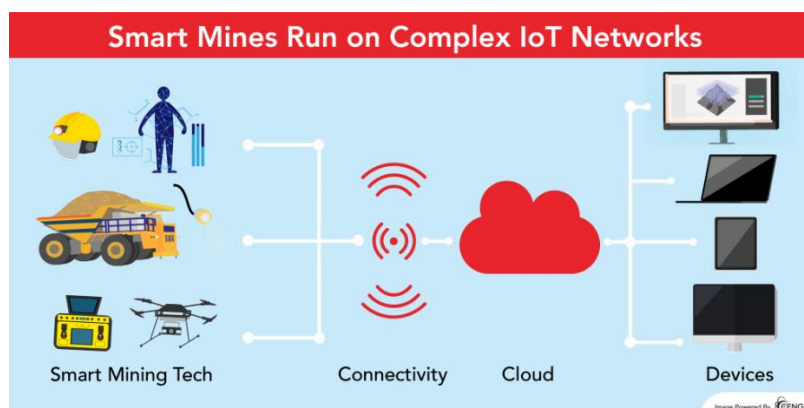


Figure IV.5. Smart Mines Run on Complex IoT Networks
(Source: CENGN)

Mining operations, particularly those in remote locations, are increasingly integrating on-site renewable energy generation. Solar and wind installations can displace expensive diesel generation while providing price hedging against volatile fuel costs. The trend toward "brownfields to brightfields"—converting former mine sites to renewable energy installations—demonstrates the natural synergy between mining infrastructure and clean energy development. These projects leverage existing land, roads, and transmission infrastructure while creating new economic opportunities for mining communities.



Figure IV.6. Komatsu battery-electric haul truck trials in the Pilbara, Australia
(Source: Komatsu)

The transition from diesel to electric-powered equipment eliminates on-site emissions and can dramatically reduce energy costs. Battery-electric haul trucks offer 65% energy cost reductions compared to diesel alternatives⁶⁷, though implementation requires substantial infrastructure investment and operational adjustments. Intermediate technologies like trolley-assist systems provide immediate benefits by electrifying vehicles on fixed, high-traffic routes while maintaining diesel backup for flexible operations.

3. Coal Processing and Preparation

Coal processing and preparation, often called beneficiation, serves as a critical leverage point in the industry where investments in energy and technology yield substantial downstream benefits. This stage transforms raw coal into a cleaner, more consistent product that burns more efficiently and produces fewer emissions when consumed.

3.1 Energy Efficiency

Coal preparation plants are significant electricity consumers, with energy intensity varying dramatically based on technology choices and operational optimization. Understanding these energy patterns is essential for identifying efficiency opportunities.

Modern preparation plants typically consume 1.2 to 5 kWh per ton of raw coal processed, depending on the beneficiation technology employed⁶⁸. Hydraulic jigging, a common gravity separation method, operates at the lower end of this range, while dense medium separation—though more energy-intensive—provides superior separation precision and product quality. The most energy-intensive processes within preparation plants include comminution through crushing and grinding operations that liberate impurities from coal particles, pumping systems for dense medium circulation requiring continuous high-volume pumping, and dewatering to remove moisture from cleaned coal products⁶⁹.

Energy optimization in coal preparation focuses on matching energy input to actual processing requirements rather than operating at constant maximum capacity. Process control optimization involves fine-tuning separation parameters such as medium density and cut-point gravity to balance product quality with energy consumption. Equipment efficiency upgrades replace older, energy-intensive equipment with modern, high-efficiency alternatives, while system integration coordinates multiple process steps to minimize overall energy consumption.

⁶⁷ SRK Consulting. (2024). *Decarbonizing Mining: Diesel vs Electric Haul Trucks on Cost and Efficiency*. Retrieved from https://cdn-web-content.srk.com/upload/user/image/SGhosh-SGain-SDe_DecarbonizingMiningDieselVsElectricHaulTrucksOnCostAndEfficiency_2024.pdf

⁶⁸ ResearchGate. (2014). *An Optimization Model for Reducing Energy Usage of Coal Washing Plants*. Retrieved from <https://www.researchgate.net/publication/271724290>

⁶⁹ CEEC International. (2021). *Mining Energy Consumption 2021*. Retrieved from https://www.ceecthefuture.org/component/cck/?task=download&file=publication_file&id=3701

The true value of processing efficiency extends far beyond the preparation plant itself. Producing cleaner coal with reduced ash and moisture content creates significant downstream benefits through improved combustion efficiency where cleaner coal burns more efficiently in power plant boilers, reduced transportation costs by eliminating waste material and reducing shipping volumes and costs, and lower emissions by removing sulfur and ash before combustion to reduce downstream pollutant emissions. Studies of Indian coals demonstrate that washing to reduce ash content from 42% to 30% can decrease CO₂ emissions per kilowatt-hour from 1.11 kg to 1.045 kg—a substantial improvement that justifies processing energy investment⁷⁰.

3.2 Reducing Fugitive Emissions

Fugitive emissions in coal processing plants, primarily methane and dust, can be reduced through several strategies. These include improving equipment maintenance and sealing leaks, upgrading to low-emission technologies, and implementing best practices for coal handling and storage, such as indoor storage solutions. s

3.3 New Technology

Advanced technologies are transforming coal preparation from a largely mechanical process to a sophisticated, digitally controlled operation capable of real-time optimization and continuous improvement.

Digital twins—dynamic virtual replicas of physical processing plants—represent a revolutionary approach to process optimization (Fig. IV.7). These systems create and continuously update virtual models using real-time sensor data, enabling operators to simulate "what-if" scenarios by testing the impact of parameter changes in the virtual environment before implementing them physically. They can identify bottlenecks by analyzing data to pinpoint underperforming equipment or process constraints, optimize performance using AI algorithms to identify optimal operating parameters for maximum yield, minimum energy consumption, or specific product quality targets, and enhance safety by modeling and optimizing safety-related investments and procedures. The path to optimization requires comprehensive data collection as a foundation. Plants that cannot accurately measure their performance in real-time cannot effectively control or improve it.

⁷⁰ Office of Fossil Energy. (2020). *What Is Coal Preparation?* U.S. Department of Energy. Retrieved from https://fossil.energy.gov/international/Publications/Coal_Beneficiation_Workshop/3rd_Mark_Coal_Preparation_R1.pdf

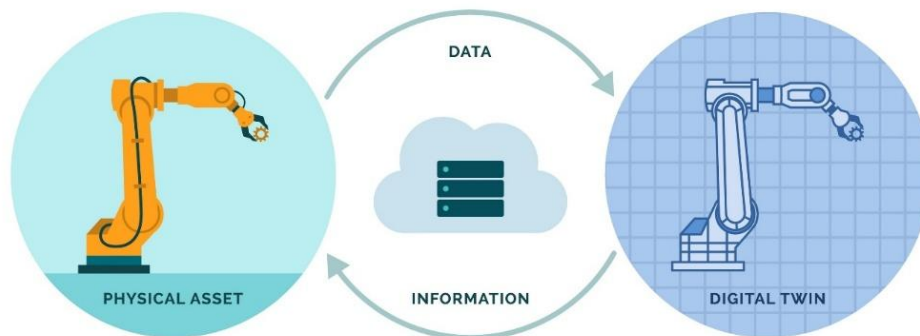


Figure IV.7. Example of the continuous data exchange between a physical asset and the digital twin.

(Source: BHP)

Modern preparation plants increasingly deploy intelligent centralized control systems based on programmable logic controllers (PLCs) that monitor and manage entire process flows. These systems automatically adjust pump speeds to optimize circulation rates in dense medium systems, control valve positions for flow distribution throughout the plant, and manage reagent dosages for chemical additions in flotation processes. Advanced Energy Management Control Systems (EMCS) implement sophisticated strategies including demand-limiting, where non-critical equipment is temporarily powered down to avoid peak electricity charges⁷¹.

Next-generation beneficiation technologies achieve higher separation efficiency, meaning they recover more valuable coal while rejecting more impurities. Modern equipment includes large-diameter cyclones (Fig. IV.8) for improved separation efficiency for coarse particles, high-efficiency column flotation for enhanced recovery of fine coal particles, and magnetic separators for targeted removal of specific mineral impurities.

⁷¹ Encyclopedia.com. (2024). *Energy Management Control Systems*. Retrieved from <https://www.encyclopedia.com/environment/encyclopedias-almanacs-transcripts-and-maps/energy-management-control-systems>



Figure IV.8. Large-diameter cyclones for improved separation efficiency
(Source: STEFMET TECHNOLOGIES)

4. Coal Transportation

Transportation and logistics form the critical link connecting coal mines to end-users, involving complex networks of haul trucks, conveyors, railways, and ships. This stage presents substantial opportunities for efficiency improvements and emission reductions through fuel optimization, modal shifts, and transformative technologies.

4.1 Energy Efficiency

Transportation can account for up to 70% of delivered coal costs, making efficiency improvements both environmentally and economically critical⁷². The energy intensity of coal logistics varies dramatically with distance—long-haul transport over 5,000 km can consume energy equivalent to 9-15% of the coal's energy content, while shorter 300 km journeys consume only 0.5-0.6%⁷³.

Different transportation modes exhibit vastly different energy intensities. Rail transport produces approximately 22g CO₂ per ton-kilometer, while road transport generates approximately 62g CO₂ per ton-kilometer, and maritime/inland waterways offer even lower emissions for long-haul transport⁷⁴. Strategic modal shifts from higher-emission to lower-emission transport modes

⁷² IEA-ETSAP. (2014). *Coal Mining and Logistics*. Retrieved from https://iea-etsap.org/E-TechDS/PDF/P07-08_Coal%20M&L_KV_April2014_GSOK.pdf

⁷³ ResearchGate. (2009). *Energy efficiency and steam coal transport over long distances*.

⁷⁴ IEA-ETSAP. (2014). *Coal Mining and Logistics*. Retrieved from https://iea-etsap.org/E-TechDS/PDF/P07-08_Coal%20M&L_KV_April2014_GSOK.pdf

represent immediate opportunities for substantial efficiency gains⁷⁵. For instance, shifting coal transport from trucks to rail can reduce emissions by more than 50% per ton-kilometer⁷⁶. Comprehensive logistics optimization reduces total vehicle-kilometers traveled, eliminates empty journeys, and minimizes idling time. These systemic improvements create proportional reductions in fuel consumption and emissions.

Improving the efficiency of individual transport assets involves multiple strategies working together. Haul truck optimization uses AI models to analyze operational parameters including load weight, route grades, and operator behavior to identify optimal combinations minimizing fuel consumption. Conveyor system advances employ modern belt conveyors with advanced materials and designs that can reduce energy consumption by up to 50% compared to conventional systems⁷⁷. Rail efficiency focuses on optimizing train lengths, reducing empty backhauls, and deploying more efficient locomotives.

Systematic optimization using advanced planning tools can minimize total energy consumption across entire logistics networks. Multi-objective optimization models consider transportation costs, transit times, and carbon emissions simultaneously to identify optimal route and mode combinations.

Immediate emission reduction opportunities encompass fuel efficiency improvements through optimizing vehicle operation, maintenance, and routing, anti-idling policies that reduce unnecessary engine operation during loading and waiting, and transitioning to alternative fuels including lower-carbon options such as natural gas, biofuels, and ultimately hydrogen.

4.2 Pollution Reduction

The logistics sector represents a major source of global GHG emissions, primarily CO₂, CH₄, and N₂O from fossil fuel combustion. For coal, upstream transportation emissions range from 0.7 to 2.6 kg CO₂-equivalent per gigajoule of energy⁷⁸.

4.3 New Technology

Transportation is experiencing technological transformation through electrification, automation, and intelligent systems that promise dramatic efficiency improvements.

Battery-electric haul trucks eliminate on-site emissions and can reduce energy costs by up to 65%

⁷⁵ Theoretical and Natural Science. (2024). *Path Selection of Multimodal Transport for Coal Based on Economic and Environmental Benefits*. Retrieved from <https://www.ewadirect.com/proceedings/tns/article/view/22951>

⁷⁶ IEA-ETSAP. (2014). *Coal Mining and Logistics*. Retrieved from https://iea-etsap.org/E-TechDS/PDF/P07-08_Coal%20M&L_KV_April2014_GSOK.pdf

⁷⁷ University of Newcastle. (2024). *Revolutionary conveyor system reduces energy use*. Retrieved from <https://www.newcastle.edu.au/research/stories/research-impact/revolutionary-conveyor-system-reduces-energy-use>

⁷⁸ IEA-ETSAP. (2014). *Coal Mining and Logistics*. Retrieved from https://iea-etsap.org/E-TechDS/PDF/P07-08_Coal%20M&L_KV_April2014_GSOK.pdf

compared to diesel alternatives⁷⁹. However, implementation faces significant challenges including high capital costs, limited range, long charging times, and infrastructure requirements. Intermediate solutions include trolley-assist systems where diesel-electric trucks connect to overhead power lines on fixed, steep routes. While on the trolley line, trucks operate electrically, saving substantial diesel fuel and enabling higher speeds on grade.

Autonomous Haulage Systems (AHS) offer multiple efficiency benefits through increased utilization where near-continuous 24/7 operation increases fleet productivity by up to 30%, optimized operation through computer-controlled acceleration, braking, and routing that reduces fuel consumption, and perfect discipline where automated systems execute optimal operating procedures consistently⁸⁰. The synergy between automation and electrification is particularly compelling. Autonomous systems can manage charging logistics with perfect discipline, automatically dispatching vehicles for charging at optimal times and executing precise maneuvers for automated connections.

Digital technologies are creating intelligent, responsive supply chains through real-time visibility using IoT sensors to provide continuous tracking of vehicle location, status, and condition, predictive analytics where AI algorithms predict disruptions and delays, enabling proactive responses, dynamic route optimization through continuous calculation of most fuel-efficient paths adapting to changing conditions, and blockchain integration for secure, tamper-proof tracking of shipments and coal quality verification.

Revolutionary conveyor designs eliminate traditional energy losses through innovations including rail-running systems where wheeled carts on low-friction tracks replace conventional idlers, advanced belt materials using high-strength, low-mass fabrics that reduce weight and internal friction, and intelligent controls employing variable-speed drives and smart routing to minimize energy consumption.

5. Case Studies in Energy Efficiency Implementation

Real-world implementation provides compelling evidence of energy efficiency technologies' practical viability and quantifiable benefits. These case studies demonstrate successful applications across the coal industry, illustrating both technical achievements and economic returns.

5.1 Ventilation on Demand Success Stories

⁷⁹ SRK Consulting. (2024). *Decarbonizing Mining: Diesel vs Electric Haul Trucks on Cost and Efficiency*. Retrieved from https://cdn-web-content.srk.com/upload/user/image/SGhosh-SGain-SDe_DecarbonizingMiningDieselVsElectricHaulTrucksOnCostAndEfficiency_2024.pdf

⁸⁰ Mining Technology. (2024). *Autonomous haulage systems for mining industry: Leading manufacturers*. Retrieved from <https://www.mining-technology.com/features/autonomous-haulage-systems/>

Howden's VentSim™ CONTROL VOD system implementation across three underground mines demonstrates the technology's substantial impact (Fig. IV.9). The systems dynamically controlled ventilation networks, adjusting fan speeds and airflow based on real-time operational needs rather than maintaining constant maximum capacity. Results were impressive across all sites, achieving direct operating savings of CAD 2.07 to 2.44 per tonne of material mined, net life-of-mine savings of CAD 0.77 to 1.63 per tonne after accounting for system costs, energy reduction of 43-63% savings from main fans, auxiliary fans, and air heating/cooling systems, and payback periods of 0.5 to 1.2 years, demonstrating exceptional return on investment⁸¹.

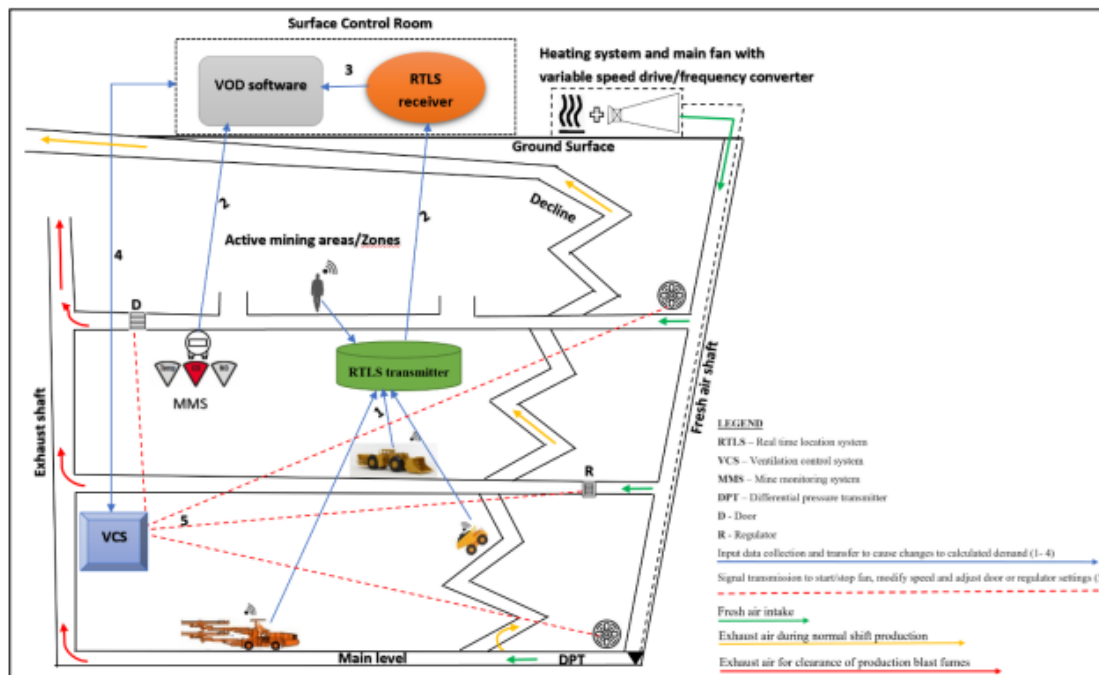


Figure IV.9. Ventilation-on-Demand Control System at Konsuln Mine, Sweden
(Source: Seth Gyamfi, 2020).

5.2 Haul Truck Fuel Optimization

An Indonesian coal mine experiencing high fuel consumption used Komatsu's Performance Assurance team to diagnose root causes including incorrect fuel injector pressure and timing. Establishing custom alerts and standardized maintenance workflows achieved fuel consumption reduction of over 18% decrease from 373 to 305 liters per hour, annual savings of nearly USD 3.4 million across the affected fleet portion, through an approach that integrated real-time monitoring with proactive maintenance (Fig. IV.10)⁸².

⁸¹ Chart Industries. (2024). *VentSim™ CONTROL Ventilation on Demand (VOD)*. Retrieved from https://files.chartindustries.com/Howden_VentsimVOD_Mining_Cases.pdf

⁸² Komatsu. (2024). *Indonesia coal mine reduces haul truck fuel consumption by 18% with MineCare and Performance Assurance*. Retrieved from <https://www.komatsu.com/en/case-studies/indonesia-coal-mine-reduces-haul-truck-fuel-consumption/>

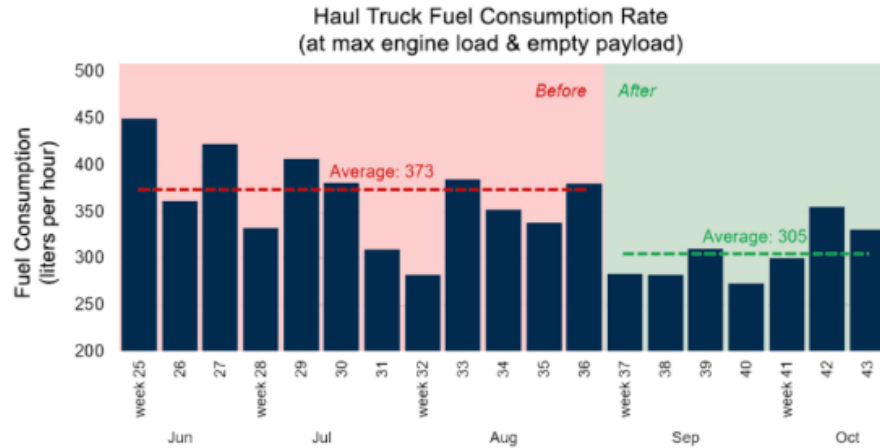


Figure IV.10. The mines haul truck fuel consumption rate before and after applying Komatsu's solution in Indonesian coal mine
(Source: Komatsu, 2024).

5.3 Renewable Energy Integration at Mine Sites

Glencore's Raglan Mine in Quebec installed a 3 MW wind turbine that offsets over 10 million liters of diesel fuel annually⁸³, demonstrating renewable integration in active mining operations (Fig. IV.11). These projects provide compelling "just transition" pathways, showing that coal communities can continue serving as energy hubs in a decarbonized future⁸⁴.



Figure IV.11. Glencore's Raglan Mine in Quebec, Canada
(Source: CIM Magazine, 2021).

⁸³ IISD. (2023). *IGF Case Study: Achieving a Successful Post-Mining Transition With Renewable Energy*. Retrieved from <https://www.iisd.org/publications/igf-case-study-post-mining-transition-renewable-energy>

⁸⁴ Harvard Kennedy School. (2024). *The Future of Coal Regions: Challenges and Opportunities*. Retrieved from <https://www.hks.harvard.edu/centers/wiener/programs/economy/our-work/future-coal-regions-challenges-and-opportunities>

V. Conclusions

The report discusses potential for improving the energy efficiency and reducing pollution in the fossil energy operations. Following are key findings:

The oil industry demonstrates mature efficiency technologies with proven track records. Norwegian offshore electrification programs achieve 86% emission reductions by replacing gas turbines with renewable electricity from shore. Advanced process control systems in refineries reduce energy consumption by 5-10% while improving product yields. Comprehensive leak detection and repair programs using optical gas imaging reduce fugitive emissions by 70% from baseline levels. The integration of artificial intelligence for predictive maintenance delivers 30% reductions in unplanned downtime while generating substantial cost savings.

The natural gas sector presents exceptional opportunities for methane emission reduction, with the International Energy Agency estimating that 70% of methane emissions from fossil fuel operations could be reduced using existing technologies. Vapor recovery systems achieve 98% capture efficiency for gases previously vented or flared. Green completion technologies reduce methane emissions by 90% compared to conventional venting practices. Advanced compression optimization reduces energy consumption by 15-25% through variable speed drives and intelligent control systems.

The coal industry is experiencing technological transformation through digitalization and automation. Ventilation on Demand systems reduce underground mine energy consumption by 30-60% while improving safety. Autonomous haulage systems increase fleet utilization by 30% while reducing fuel consumption by 10-15%. Advanced coal preparation technologies achieve energy savings of 2-5% while producing cleaner coal that burns more efficiently in power plants.

The report also reveals a rich pipeline of technologies across different maturity levels. Many high-impact efficiency measures utilize mature, commercially available technologies ready for immediate deployment. Advanced process control, leak detection systems, and equipment optimization represent proven solutions with established supply chains and experienced implementation partners.

Emerging technologies, including artificial intelligence, advanced materials, and hybrid renewable-fossil energy systems, promise even greater efficiency gains. These technologies are transitioning from demonstration to commercial scale, with early adopters gaining competitive advantages while supporting technology maturation.