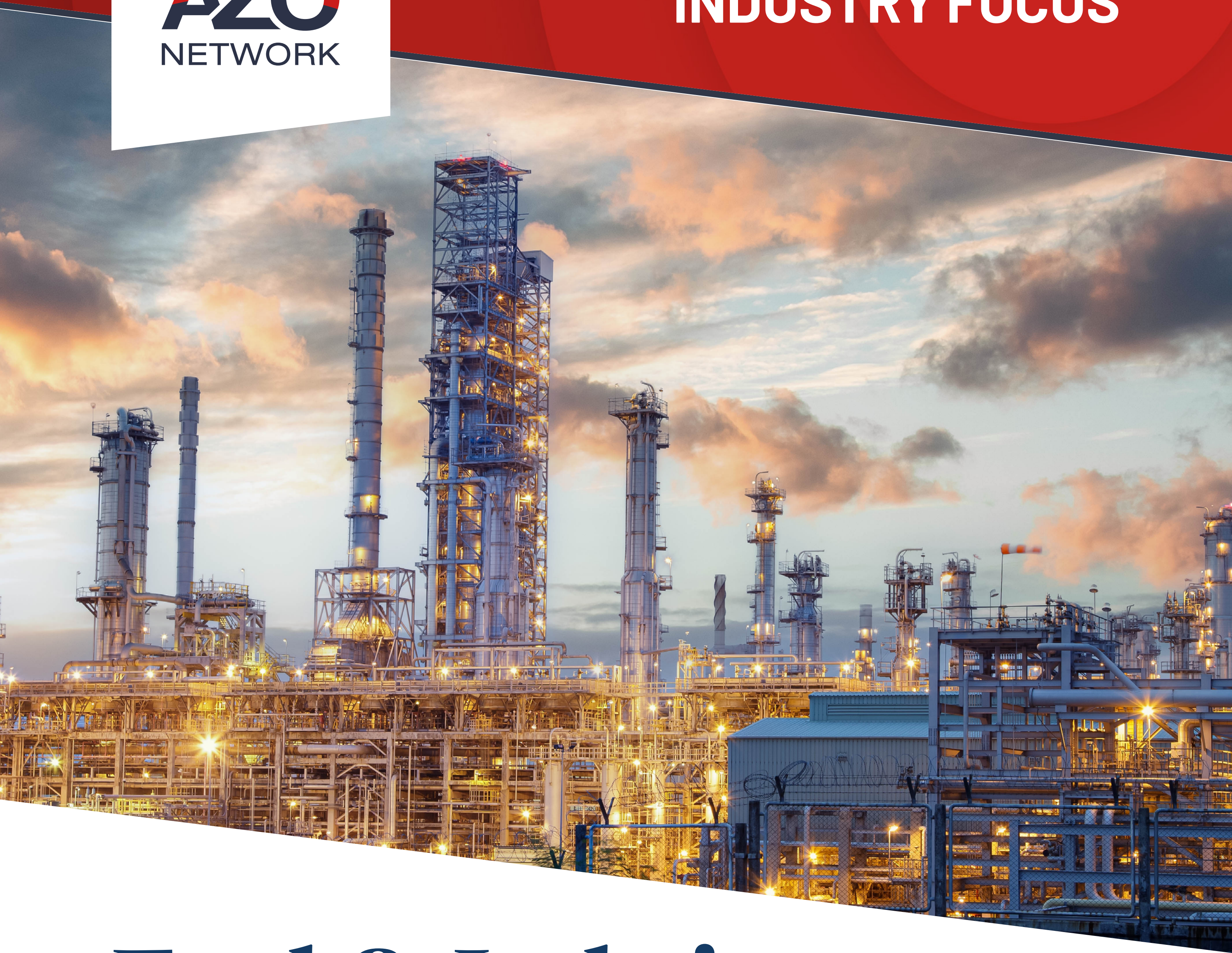
AZO NETWORK

INDUSTRY FOCUS



Fuel & Lubricant Analysis and Monitoring

An exclusive collection featuring top-tier articles, visionary experts, and essential industry insights

Sponsored by

Thermo Fisher SCIENTIFIC

November 2025 - Edition 2

TABLE OF CONTENTS

Foreword

Welcome to the latest edition of our Fuel and Lubricant Industry Focus eBook. As industries everywhere work to balance efficiency, sustainability, and performance, the push for next-generation fuel and lubrication solutions has never been more critical.

From powering heavy-duty mining operations to fine-tuning the performance of precision machinery, fuels and lubricants remain central to industrial function. But the landscape is shifting quickly. The global move toward decarbonization has intensified the need to cut emissions without sacrificing performance, driving a wave of innovation across the sector. Researchers and engineers are reimagining not just the chemistry of these substances, but also how they interact with new materials, mechanical systems, and regulatory demands.

In this edition, we look at how advanced fuel additives are being designed to extend engine life and enhance efficiency. We explore the rise of sustainable lubricants that minimize environmental impact while maintaining high standards for thermal stability and wear protection. You'll also find insights into how AI and sensor technologies are improving fuel monitoring and lubricant diagnostics, enabling smarter maintenance strategies and greater operational resilience.

This eBook also takes you beyond traditional applications, spotlighting how fuels and lubricants are supporting emerging technologies, from renewable energy infrastructure to advanced optical systems. Whether it's increasing the service life of mining equipment or minimizing friction in photonic devices, these materials are playing an increasingly vital and versatile role.

We hope this collection gives you valuable insights into the challenges and innovations shaping today's fuels and lubricants landscape.

Navigating the EU Methane Regulations with LDAR Strategies

What are the key components of the EU's new methane regulations for the energy sector?

The EU methane regulation, promulgated July 2024, aims to significantly cut methane emissions in the energy sector.

Within the EU, operators must monitor, report, and verify emissions, as well as conduct regular leak detection and repair (LDAR) surveys to identify and fix methane leaks.

Importers are required to disclose methane emissions associated with the energy they bring into the EU. The regulation takes a comprehensive approach by covering domestic and imported operations, ensuring a coordinated effort to reduce emissions.

Image Credit: Aunging/Shutterstock.com

How does the EU regulation define and apply Types 1 and 2 LDAR (Leak Detection and Repair)?

Type 1 LDAR focuses on detecting larger leaks using tools capable of measuring 7000 ppm (or approximately 17 grams per hour), such as optical gas imaging (OGI) cameras. Though conducted more frequently than smaller leak inspections, these surveys are crucial for identifying and addressing major leaks that contribute significantly to emissions.

Type 2 LDAR is used for detecting smaller leaks with high-precision instruments, such as flame ionization detectors (FIDs), which can detect leaks as small as 500 ppm (around 1 gram per hour). Though not as regularly deployed, these tools are valued for their accuracy and are typically used when rapid responses to minor leaks are required.

What is the role of methane in global climate change efforts?

Methane is the second-largest contributor to climate change after carbon dioxide (CO_2). Over 20 years, methane has 84 times the global warming potential of CO_2. Since the Industrial

Revolution, methane has been responsible for approximately 25–30% of global temperature increases.

Because methane has a shorter atmospheric lifespan than CO_2, reducing methane emissions can immediately impact slowing climate change. Addressing methane emissions is a crucial step in global efforts to mitigate temperature rise and its associated environmental impacts.

How does EU regulation affect energy imports and exporting countries?

The regulation imposes stringent requirements on imported energy, making the EU the first to enforce methane emission standards for imports. Importers must submit detailed methane emission reports and adhere to monitoring, reporting, and verification (MRV) requirements outlined in Article 12 or the OGMP 2.0 Level 5 framework. Emissions must be tracked and reported across the entire supply chain.

Compliance deadlines begin in 2027, with full contract alignment required by 2030. Exporting countries and energy suppliers will face increased scrutiny as their emission reports must be auditable and transparent. While non-compliance does not result in outright bans, severe financial penalties may be imposed.

What are the regulatory challenges and potential limitations?

A major challenge is the administrative burden placed on EU member states. Each country must establish at least one competent authority, allocate necessary funding, and enforce compliance, including penalty mechanisms. Penalties also vary by country, leading to inconsistencies in enforcement.

Meeting technical requirements—such as deploying advanced monitoring technologies and maintaining compliance documentation—can be resource-intensive for operators. There is also some uncertainty regarding how specific provisions will be interpreted and enforced, which may cause initial confusion.

According to EU regulations, what technologies are used for LDAR, and are there any limitations on technology selection?

The regulation does not mandate specific technologies but focuses on achieving desired outcomes, allowing operators to choose appropriate tools. Type 1 LDAR surveys typically utilize OGI cameras, which can quickly scan large areas for leaks but are highly sensitive to weather conditions and require skilled operators.

Type 2 LDAR employs flame ionization detectors (FIDs), known for their precision in detecting very small leaks. However, these instruments require frequent calibration and must withstand harsh industrial environments.

New technologies, such as continuous monitoring systems, are also being explored. The regulation encourages innovation while ensuring compliance with emission reduction targets by allowing flexibility in technology selection.

What are the penalties for noncompliance, and how are they determined?

Penalties vary across member states, as each government sets its own enforcement mechanisms. Common violations include improper instrument calibration, inadequate monitoring, and inaccurate emissions reporting.

Consequences may include fines, operational delays, and reputational damage. To avoid penalties, companies should establish robust LDAR programs, maintain accurate documentation, and invest in well-trained personnel and reliable technology.

How do global initiatives like OGMP 2.0 supplement the EU's methane regulations?

OGMP 2.0 is a framework aligned with EU regulations, promoting standardized methane emission reporting. It aims to reduce methane emissions by 75% by 2030 and encourages best practices, including source-level quantification and independent verification.

By participating in OGMP 2.0, operators meet EU compliance requirements and contribute to broader global efforts to reduce methane emissions. The initiative provides a consistent approach to methane monitoring and mitigation across industries.

What are the key timelines that operators and importers should be aware of?

Operators within the 27 EU member states must complete their first Type 2 LDAR surveys by

August 2025, while existing sites must submit their LDAR programs by May 2025. New sites must comply six months after becoming operational. Importers must submit data about methane emissions by April 2027, marking their initial reporting deadline.

Methane intensity reporting will be required for new contracts by 2028 and all by 2030.

These deadlines provide operators and importers with a structured compliance and implementation planning timeline.

How can operators best prepare for these regulations?

Operators should begin by updating or establishing their LDAR programs to align with the new regulations. Investing in technologies such as Optical Gas Imaging (OGI) cameras and Flame ionization Detectors (FID) will be essential. Equally important is ensuring personnel are trained to use these tools effectively and maintain accurate documentation.

Engaging third-party verifiers for independent audits helps identify compliance gaps. Early preparation minimizes the risk of penalties and facilitates a smooth transition to the new regulatory framework.

What are the regulation's key benefits and long-term implications?

The regulation creates a clear framework for reducing methane emissions and driving substantial improvements in the energy sector. It promotes the adoption of advanced monitoring technologies and enhances transparency throughout the supply chain.

In the long run, these efforts contribute to stabilizing global temperatures, improving environmental sustainability, and positioning businesses as leaders in climate responsibility. While initial implementation may be complex, the long-term environmental and industry benefits outweigh the challenges.

Missed the webinar? Catch up now!

About the Speaker

Bob Gallagher joined Thermo Fisher Scientific as the Product Line Manager for the Industrial Hygiene Strategy at the end of 2017. Bob has over 35 years of experience in Engineering and Product Management roles in the area of LDAR, site remediation, dust monitoring and other various industrial applications. Over Bob's career, he's worked for various technical companies such as Texas Instruments and Pentair and has successfully launched several innovative global products. Bob has a BS in Materials Science & Engineering from Penn State University and an MBA from Boston University.

ThermoFisher SCIENTIFIC

This information has been sourced, reviewed and adapted from materials provided by Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

For more information on this source, please visit Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

Thermo Scientific™ Multigas Portable Detectors

Fixed and portable handheld instruments engineered specifically to identify, detect, analyze or monitor gases and vapors. Suited for a variety of applications including environmental, oil & gas, and industrial.

TVA2020 Toxic Vapor Analyzer

The Thermo Scientific™ TVA2020 Toxic Vapor Analyzer is a portable, lightweight and intrinsically safe portable gas leak detector that allows rapid detection of fugitive emissions of inorganic and organic compounds for site remediation, LDAR applications and Method 21 compliance.

Cat. No. TVA2020

Request A Quote

OPGAL EyeCGas™ Optical Gas Camera

EyeCGas™ Multi, the world's most sensitive handheld Optical Gas Imaging (OGI) camera, quickly identifies fugitive gas emissions for 400+ hydrocarbon and VOC gases.

Cat. No. EYECGAS2

Request A Quote

Learn more at https://www.thermofisher.com/ih

What's Next for Oil and Gas Extraction? Exploring Cutting-Edge Technologies

The oil and gas industry is at a critical turning point. With demand patterns shifting, the push for decarbonization growing stronger, and reservoirs becoming more complex, companies are rethinking how they operate. Many are adopting technologies that improve extraction efficiency and environmental performance to stay competitive and responsible. This article looks at some of the latest scientific developments and proven technologies that are helping the industry move beyond traditional methods and tackle the challenges ahead more effectively.

Image Credit: Calin Tatu/Shutterstock.com

AI and Predictive Analytics: Transforming Subsurface Understanding

AI has evolved from a conceptual tool to an operational backbone in the oil and gas industry. Modern machine learning algorithms analyze seismic data alongside historical drilling records and real-time sensor information. This approach allows for more effective optimization of well placement and drilling parameters.

A recent study published in *Applied Sciences* showed that AI-driven seismic interpretation reduces computational time and improves the accuracy of reservoir characterization. These advanced systems utilize convolutional neural networks to identify subtle geological features that traditional methods may overlook, minimizing the risks associated with dry-hole drilling.[1,2]

The implementation of autonomous drilling technology signifies a considerable advancement in the field.

A recent *IPTC* report highlights that autonomous drilling systems used in Middle Eastern oil and gas wells achieved an average reduction of 70% in human intervention. This curve drilling technology has minimized human error, enhanced the accuracy of well positioning, and improved the quality of the drilling process and workover operations.

The findings demonstrate that this autonomous drilling technology can deliver improved well trajectories with minimal intervention, facilitate faster well delivery, and reduce operational costs.[3]

Predictive maintenance systems now employ advanced analytics to monitor equipment vibrations, thermal readings, and acoustic data to forecast failures weeks in advance.

According to a report from Cflow, these AI-driven techniques can reduce unplanned downtime by up to 40%, resulting in significant improvements in overall productivity. Moreover, integrating multi-modal data, which combines satellite imagery, reservoir simulations, and real-time drilling metrics, allows for dynamic adjustments in well trajectories, further enhancing efficiency.[4]

Smart Fields and Edge-to-Cloud Architectures

The digital oilfield has grown into a fully integrated ecosystem, combining Internet of Things (IoT) sensors, edge computing, and cloud-based analytics.

Today's offshore facilities rely on thousands of wireless industrial IoT sensors to track key metrics such as pressure, flow rates, and equipment condition. These sensors send data over low-power networks to onshore control centers, enabling remote monitoring and operations. The result is a safer working environment with fewer people required on-site and more efficient, real-time decision-making.[5]

On the other hand, edge computing addresses a critical challenge. It processes data in remote locations with limited bandwidth. Instead of sending raw sensor data to the cloud, edge devices perform preprocessing at the source. For instance, in pipeline monitoring, edge systems can analyze acoustic signatures for leak detection in just a few seconds and trigger automatic shutoffs when necessary.[5]

The integration of these technologies leads to the development of the digital twin, which serves as a dynamic virtual replica of physical assets. Creating a digital twin application for the oil and gas sector allows engineers to explore various scenarios for problem-solving without affecting the platform’s productivity.

By consolidating information from multiple sources, including physical objects and the insights of specialized staff, operational management and collaboration can be enhanced, reducing errors and the need for rework.[5]

Advanced Reservoir Modeling and Enhanced Recovery

Unconventional resources require a high level of precision in their management. Digital fracture mapping is a significant advancement in this area. Engineers create 3D models of fracture networks during hydraulic fracturing using microseismic data and distributed fiber-optic sensing. A recent study published in *MDPI Energies* focused on creating a 3D geomechanical model of a petroleum field in southeastern Algeria.[6]

This model employed seismic inversion based on Aki and Richards' approximation to assess wellbore stability. Researchers correlated the inversion results with well log data to optimize the drilling mud weight windows. This optimization improved wellbore stability and minimized reservoir damage caused by excessive use of surfactants. Such methodologies provide better planning for new wells and reduce exploration uncertainties while enhancing the characterization and productivity of reservoirs.[6]

For mature fields, enhanced oil recovery is being applied in new ways. Researchers in Algeria’s Hassi Messaoud field tested *Opuntia ficus-indica* mucilage as a sustainable alternative to synthetic polymers in enhanced oil recovery. The study published in *MDPI Processes* found that the novel material offers a cost-effective, eco-friendly, and thermally stable alternative to conventional polymers for enhanced oil recovery, particularly in saline and high-temperature reservoirs such as Hassi Messaoud.[7]

Sustainability-Driven Innovations

Sustainability-driven innovations are significantly reshaping priorities in resource extraction as the pressure for decarbonization increases. Carbon capture, utilization, and storage (CCUS) have become essential components of project economics. The UK is investing £22 billion in two northern carbon capture and storage clusters, which will facilitate the storage of emissions from offshore operations by connecting pipelines to depleted gas reservoirs.[8]

Advancements in methane monitoring within the oil and gas industry now include using hyperspectral satellites for advanced detection and drone-based light detection and ranging (LiDAR) for precise mapping. These technologies enhance the ability to identify leaks and assess emissions in real-time, ensuring greater environmental compliance.[9]

Projects Showcasing Technological Integration

- **Permian Basin Innovations**: The Matterhorn Express Pipeline, which became operational in November 2024, helps to alleviate gas takeaway constraints. Edge-based analytics are also used to optimize production scheduling. Operators employ AI to prioritize drilling in oil-rich areas, effectively reducing associated gas production and minimizing environmental impact.[10]
- **Oman's Miraah Project**: Oman's Miraah Project is a 1021 MW solar thermal facility that produces 6,000 tons of steam daily for enhanced oil recovery. This innovative design reduces annual gas consumption by 1.9 million British Thermal Units (BTUs) and features an enclosed trough that can withstand desert conditions while providing boiler replacement capability.[11]

Conclusion

The oil and gas extraction sector is moving toward a more digitally connected and lower-carbon future. Tools like AI-powered reservoir management, edge-based monitoring, and carbon capture, utilization, and storage (CCUS) are becoming central to more sustainable production practices. However, the real value comes from combining these technologies with deep geoscience expertise and supportive policy frameworks.

Rather than a full departure from hydrocarbons, the industry's path forward focuses on smarter, more efficient extraction methods that align with broader energy transition goals.

References and Further Reading

1. A. Lawal, Y. *et al.* (2024). Machine Learning in Oil and Gas Exploration: A Review. *IEEE Access, vol. 12, pp. 19035-19058.* DOI:10.1109/ACCESS.2023.3349216. https://ieeexplore.ieee.org/abstract/document/10418898
2. Purnomo, E. W. *et al.* (2023). Predicting Reservoir Petrophysical Geobodies from Seismic Data Using Enhanced Extended Elastic Impedance Inversion. *Applied Sciences*, *13*(8),

4755. DOI:10.3390/app13084755. https://www.mdpi.com/2076-3417/13/8/4755

3. Oliveira, V. *et al.* (2023). Novel Approach of Autonomous Drilling Using Rotary Steerable System in Middle Eastern Oil and Gas Wells. *International Petroleum Technology Conference*. *IPTC*. DOI:10.2523/iptc-22975-ms. https://onepetro.org/IPTCONF/proceedings-abstract/23IPTC/23IPTC/D031S033R003/517011
4. Oil and Gas Industry Technology Trends for 2025. (2025). *Cflow.* https://www.cflowapps.com/oil-and-gas-industry-technology-trends/
5. Knebel, F. P. *et al.* (2023). A study on cloud and edge computing for the implementation of digital twins in the Oil & Gas industries. *Computers & Industrial Engineering*, *182*, 109363. DOI:10.1016/j.cie.2023.109363. https://www.sciencedirect.com/science/article/abs/pii/S036083522300387X
6. Eladj, S. *et al.* (2022). 3D Geomechanical Model Construction for Wellbore Stability Analysis in Algerian Southeastern Petroleum Field. *Energies*, *15*(20), 7455. DOI:10.3390/en15207455. https://www.mdpi.com/1996-1073/15/20/7455
7. Bourkaib, K. *et al.* (2025). Comparative Study of Opuntia ficus-indica Polymers, HPAM, and Their Mixture for Enhanced Oil Recovery in the Hassi Messaoud Reservoir, Algeria. *Processes*, *13*(6), 1794. DOI:10.3390/pr13061794. https://www.mdpi.com/2227-9717/13/6/1794
8. UK announces £22 billion investment in carbon capture and storage. (2024). *ITN Business.* https://business.itn.co.uk/uk-announces-22-billion-investment-in-carbon-capture-and-storage/
9. Dineen, M. S. (2022). Monitoring Methane Emissions from Oil and Gas Operations. *Optics Express*. DOI:10.1364/oe.464421. https://opg.optica.org/oe/fulltext.cfm?uri=oe-30-14-24326
10. Navigating the Future: Key Trends Shaping the Oil and Gas Industry in 2025. (2025). *Energy Workforce & Technology Council.* https://www.energyworkforce.org/navigating-the-future-key-trends-shaping-the-oil-and-gas-industry-in-2025/
11. How Solar Energy Is Transforming Oil & Gas Production. (2024). *Oil & Gas and Renewable Industry Magazine to Follow in 2025 | Energies Media*. https://energiesmedia.com/how-solar-energy-is-revolutionizing-oil-and-gas-production/

Optimizing the Production of Synthesis Gas (SynGas) through Precise Gas Analysis MS

Synthesis gas, also known as syngas, is a fuel gas that contains a combination of carbon monoxide, hydrogen, and occasionally carbon dioxide. Its name stems from its utilization in the synthesis of important chemicals such as methanol and ammonia and the production of synthetic natural gas (SNG).

Additionally, it is a key intermediate in the Direct Reduction Iron (DRI) process, which reduces iron oxide to iron with the use of natural gas. With 50% of the energy density of natural gas, syngas cannot be burnt directly,[1] but it can be converted into various energy products.

Examples include synthetic petroleum production via the Fischer-Tropsch process and bioethanol production from biomass gasification. Syngas may be produced from a broad range of carbon-containing sources, such as coal, natural gas, organic waste, and wood.

The carbon source is reacted with carbon dioxide (dry reforming), steam (steam reforming), or oxygen (partial oxidation). Figure 1 displays some examples of sources and uses of syngas.

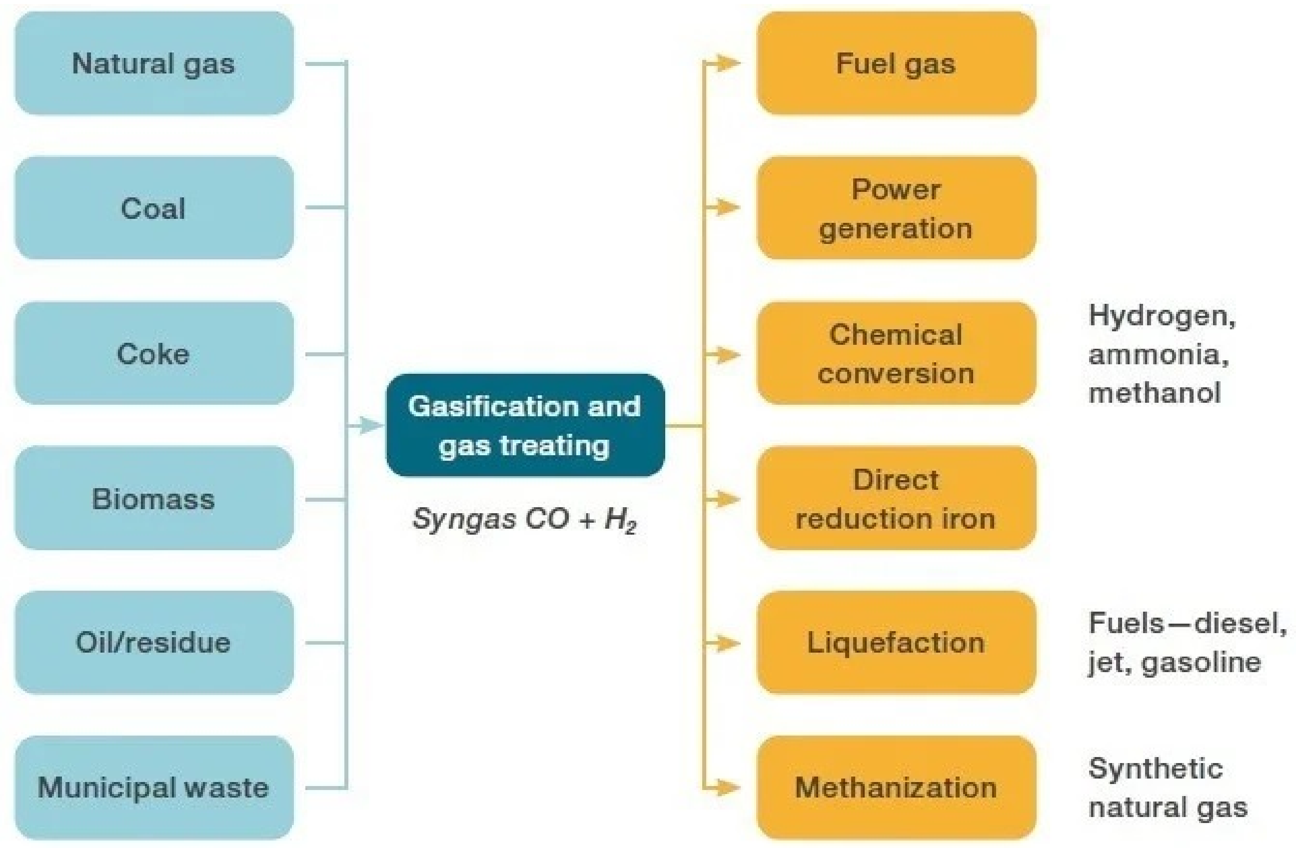


Figure 1. *Examples of sources and uses of syngas. Image Credit: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments*

The chemical composition of syngas differs considerably depending on the carbon source and the process utilized to produce the desired intermediate.

The chemical processes that use syngas are usually multi-stage, have a variety of gas analysis needs, and are typically dynamic, i.e., they are dependent on process gas analysis for optimization. Rapid, multi-component, multistream gas analysis is a crucial element for efficiently controlling such processes.

Process Analytical Requirements

Carbon monoxide and hydrogen are always present in syngas, but depending on the process involved, they may be present in broadly different concentrations. A wide variety of other chemicals may also be present, and analysis of these is required for an efficiently controlled process and for the desired products to be generated.

These include carbon dioxide, methane, and other hydrocarbons and may also include nitrogen, ethanol, helium, and argon. Examples of the analytical requirements for some of the main syngas processes are discussed below, with Thermo Scientific™ Process Mass Spectrometers holding a strong track record in all these applications.

Ammonia Synthesis

Steam and natural gas undergo numerous processes to transform the hydrocarbon stream into a hydrogen-rich stream. This hydrogen is subsequently reacted with nitrogen from the air in a ratio of 3:1 to generate ammonia.

Eleven or more process streams need to be analyzed, and gas analysis mass spectrometry's combination of speed, multi-component analysis, and dynamic range enables one MS to analyze all the process streams.

For instance, it is crucial to provide the complete composition of the natural gas feed stream to establish the volume of steam needed to react with methane and the other present hydrocarbons; this parameter is the steam-to-carbon ratio.

Through monitoring the complete composition of natural gas, the costs of steam generation may be minimized by controlling the volume of steam to match the composition of the natural gas.

Table 1 shows an example of Prima PRO's specification for one of the key ammonia process streams, syngas feed to the ammonia converter. Analysis time, inclusive of stream switching, is approximately 20 seconds, and precision is measured over eight hours.

Table 1. Prima PRO analytical specification for ammonia process syngas analysis. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Concentration vol.%	Precision absolute %
Hydrogen	65.0 – 70.0	0.02
Methane	3.0 – 10.0	0.01
Helium	0.5 – 1.0	0.002
Nitrogen	20.0 – 26.0	0.01
Argon	0.1 – 5.0	0.002

At this point in the process, carbon monoxide has been removed from the syngas as it poisons the ammonia catalyst. Thermo Scientific™ Prima PRO conducts an analysis of all five components, including helium and argon.

The ammonia converter stream is recycled to increase the production of ammonia. This also increases the concentration of helium and argon. If their concentrations are too high, then the energy utilized for compression is wasted, and the ammonia yield is decreased.

The prices of raw materials are heavily impacted by the demand for power generation and heating fuels, and downstream fertilizer prices are impacted by economic, political, and environmental aspects. This places pressure on the ammonia production unit to maximize efficiency, and process analytical data plays a vital part in this.

The process analyzer requires a broad dynamic range to monitor methane slippage (the decrease in methane concentration from over 90% in natural gas to a few percent in the secondary reformer effluent) and rapid yet accurate measurement of both the steam-to-carbon ratio and the hydrogen-to-nitrogen ratio.

Ideally, syngas consists of 75% hydrogen and 25% nitrogen; in practice, it will also contain residual methane and inerts from the air. For optimum efficiency, it is essential to maintain the ratio of hydrogen and nitrogen to be as close as possible to the stoichiometric ratio of 3:1.

Prima PRO has a strong track record in fulfilling all of the above requirements.

Direct Reduction Iron

Iron is traditionally produced in blast furnaces, using coke to reduce iron ore. DRI does not require large stocks of coal to be converted to coke; instead, natural gas is converted to syngas, and iron oxide is reduced by carbon monoxide and hydrogen.

These 'reducing' gases are produced by the reaction of natural gas (methane) with the by-products of the DRI process:

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$

$CH_4 + H_2O \rightarrow CO + 3H_2$

Global DRI production increased from 78 million tonnes in 2016 to 111 million tonnes in 2019 and only reduced slightly to 104 million tonnes due to the COVID pandemic. Blast furnaces still produce the majority of the world's iron, but production has continued to be relatively flat at approximately 1,300 million tonnes.[2]

Several process stages are involved (typically eight to ten), similar to the ammonia process, and process MS provides the ability to quickly monitor all process streams fully. An example of Prima PRO's specification for the DRI syngas stream, typically named 'Reformed Gas' in the industry, is displayed in Table 2.

Table 2. Prima PRO analytical specification for direct reduction iron syngas analysis. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Concentration vol.%	Precision absolute %
Hydrogen	~ 58	0.05
Methane	~ 1	0.01
Carbon monoxide	~ 38	0.05
Nitrogen	~ 1	0.05
Carbon dioxide	~ 2	0.01

Analysis time, including stream switching, is approximately 20 seconds, with precision measured over eight hours.

For the DRI process to operate efficiently, rapid but accurate online monitoring is required of several gas streams containing numerous combinations of methane, hydrogen, carbon dioxide, carbon monoxide, and nitrogen over a broad range of concentrations.

Prima PRO has a strong track record of delivering the best combination of accuracy and speed in comparison to other methods of gas analysis, such as gas chromatographs or infrared analyzers.

It optimizes the DRI process by enhancing the generation of reducing gases, optimizing fuel gas mixing, and decreasing energy consumption.

Biomass Gasification

Biomass is usually reacted at temperatures exceeding 700 °C without combustion, with a controlled volume of steam and/or oxygen to generate syngas.

This may be utilized directly as a fuel (which is more efficient than direct combustion of the original biomass) or to generate biofuels using microorganisms to convert carbon monoxide and hydrogen to ethanol.

Thermo Scientific™ Prima BT and Prima PRO Mass Spectrometers have been utilized in a wide variety of processes involving biomass. An example of a performance specification for a syngas-based bioethanol process is displayed in Table 3.

Analysis time, inclusive of stream switching, is approximately 22 seconds, with precision being measured over eight hours.

A Prima PRO was utilized to assess the conversion of syngas and other gas mixtures into alcohols in continuously gassed batch cultivation experiments. Carbon monoxide was identified as the preferred electron and carbon source for the growth and production of alcohols.

However, the total yield of moles of carbon (mol-C) per electrons consumed was nearly identical across all setups, which highlights electron availability as the key aspect influencing product formation.[3]

Prima PRO delivers a rapid, linear, and reproducible measurement of alcohols such as ethanol; alcohol measurement is very reproducible with its magnetic sector analyzer, and the measurement of ethanol may be measured with high precision at concentrations as low as 10ppm.

Additionally, the Prima PRO offers valuable, reliable composition data on other species present in the process, such as nitrogen, hydrogen, oxygen, carbon dioxide, and argon.

Table 3. Prima PRO analytical specification for syngas based bioethanol process. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Concentration vol.%	Precision absolute %
Hydrogen	~ 60	0.05
Methane	~ 1	0.005

Carbon monoxide	~ 10	0.05
Nitrogen	~ 20	0.05
Carbon dioxide	~ 10	0.01
Argon	~ 1	0.002
Ethanol	~ 1 – 5	2% relative

Gas-to-Liquid Process Using Fischer-Tropsch

Breakthroughs in synthetic fuel, such as the Fischer–Tropsch GTL process, stemmed from the desire to be 'petroleum independent' following a national threat of war, crisis, or oil embargo.

At present, synthetic fuel catalyst research has expanded to thermochemical methods for converting anthropogenic carbon dioxide as intermediates for fuel and chemical production.

Along with the future developments in carbon dioxide capture from the environment and renewable energy, this provides encouraging solutions to mitigate anthropogenic carbon dioxide increases.4

The two key components of a GTL plant are:

1. A steam reformer to react natural gas with steam for the generation of syngas that is rich in carbon monoxide and hydrogen. Natural gas feed is observed to determine the ratio of steam to carbon.
   A complete composition analysis is necessary to establish the volume of steam needed to react with the methane and other hydrocarbons present in natural gas.
2. A Fischer-Tropsch reactor for the conversion of carbon monoxide and hydrogen into liquid hydrocarbons. The reactor requires the H_2/CO ratio to be 2:1, but the steam reformer usually produces a ratio of approximately 5:1. Any excess hydrogen must be removed, and gas analysis is utilized to control this removal.
   Excess hydrogen is utilized as fuel for the reformer or as a fuel or feedstock for an alternative process on an adjoining plant. Analysis of this gas is also required, and if it is to be utilized as fuel for the reformer, then its air requirement and calorific value must be monitored.
   The light gas outlet of the Fischer-Tropsch reactor also requires monitoring as this is recycled using the reformer.

There are various types of Fischer-Tropsch reactors, such as fluidized-bed, fixed-bed, and slurry-phase reactors. Prima PRO offers a rapid, precise, and complete analysis of all significant gaseous components in all process streams.

Table 4. Example of Prima PRO analytical specification for Fischer-Tropsch GTL process. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Concentration vol.%	Precision absolute %
Hydrogen	Balance	0.05
Methane	5.5	0.01
Carbon Monoxide	15	0.05
Nitrogen	2	0.02
Ethene	0.3	0.002
Ethane	0.3	0.002
Argon	1	0.002
Propene	0.3	0.002
Carbon Dioxide	10	0.01
Propane	0.3	0.002
Butene	0.2	0.002
N-Butane	0.2	0.002
Pentene	0.15	0.002
N-Pentane	0.15	0.002
Hexene	0.15	0.002

Not all components are measured in every type of sample stream, but Table 4 displays a typical Prima PRO performance specification for a Fischer-Tropsch GTL process. Analysis time is 30 seconds, including stream switching time, with precision measured over eight hours.

One Prima PRO instrument is able to analyze several gas samples; it delivers a rapid, precise, and complete analysis of all significant gaseous components, including inorganics such as oxides of carbon and hydrogen to hydrocarbons from C1 up to C6.

In some processes, H2S is analyzed at ppm levels to observe natural gas being desulfurized.

Prima PRO's detailed natural gas composition data is utilized to reduce the costs of steam generation by controlling steam production to fit the natural gas composition.

Reformer outlet stream composition is utilized for the optimization of the reformer, and the Fischer-Tropsch reactor's light gas outlet also requires monitoring as it is recycled via the reformer.

Additionally, Prima PROs are being utilized to improve and advance processes through the evaluation of the performance of various catalysts in both the reformer and the Fischer-Tropsch reactor.

Benefits of Magnetic Sector Mass Spectrometry

Two main types of mass spectrometers may be utilized for process gas analysis, with the magnetic sector MS offering better stability and precision than the quadrupole MS. The quadrupole generates a Gaussian peak, dissimilar to the flat-topped peak produced by the magnetic sector.

This means it is 'fault sensitive,' i.e., any shift in the mass scale will cause an error in the peak height measurement by measuring intensity on the shoulder of the peak instead of the peak maxima. This needs to be corrected by increasing the frequency of calibration.

Figure 2 presents a schematic of the magnetic sector analyzer, combined with the characteristic flat-top peaks it generates.

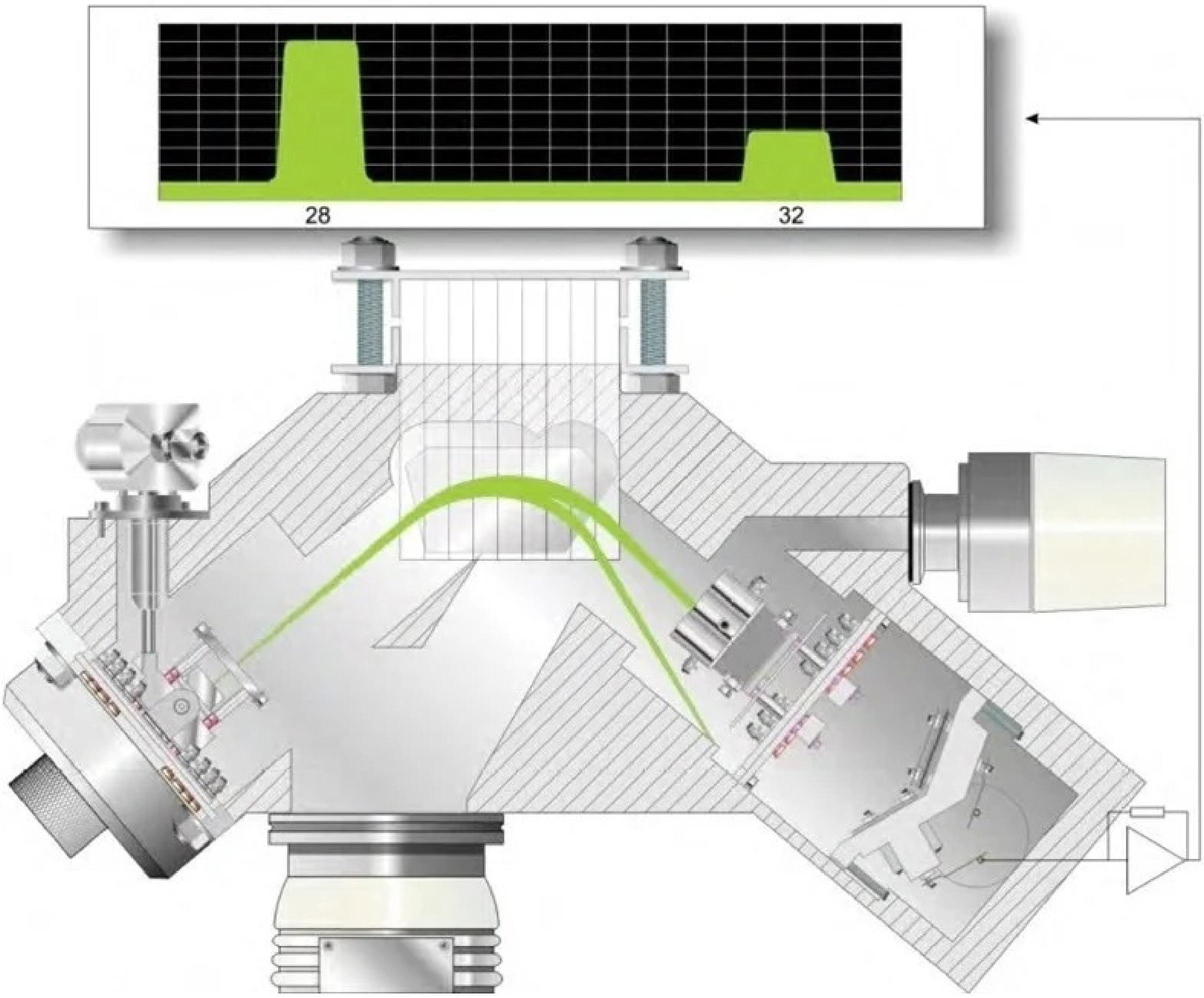


Figure 2. *Schematic of Thermo Scientific™ Magnetic Sector Analyzer and flat-topped peaks for mass 28 (nitrogen) and mass 32 (oxygen). Image Credit: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments*

Table 5 displays the magnetic sector analyzer's capability of running for long periods without calibration and still meeting the demands of the performance specification. On a customer site, a Prima PRO had been running for eight months without calibration.

It was subsequently utilized for analysis of a 16-component certified calibration cylinder for 11 consecutive analyses. The analyzer remained within specification, and the user is confident the MS could run for up to a year without calibration being required.

Table 5. Example of Prima PRO calibration check after 8 months without calibration. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Cylinder certified value	Prima PRO data		
		Mean	Absolute standard deviation	%RSD
Helium	0.2	0.196	0.001448	0.7384
Hydrogen	43.997	44.103	0.020100	0.0456
Methane	10	9.961	0.001592	0.016
Carbon Monoxide	25	25.039	0.016700	0.0667
Nitrogen	2.001	1.937	0.025400	1.3128
Ethylene	0.301	0.3	0.000689	0.2293
Ethane	0.4	0.399	0.001228	0.308
Argon	1.001	1.004	0.000702	0.0699
Propylene	0.299	0.292	0.001488	0.5093
Carbon Dioxide	15	14.972	0.006544	0.0437
Propane	0.5	0.498	0.000824	0.1654
Butene	0.3	0.296	0.001263	0.4271
N-Butane	0.4	0.401	0.000404	0.1008
Pentene	0.2	0.2	0.000444	0.2223
N-Pentane	0.2	0.201	0.000834	0.4155
Hexene	0.1	0.101	0.000452	0.4484
N-Hexane	0.1	0.1	0.000686	0.6841
H_2/CO Ratio	1.76	1.761	0.000991	0.0563

Independent Tests on Magnetic Sector MS

In accordance with ISO10723, the Prima PRO was tested for fuel gas quality metering in Effectech UK's ISO17025 accredited laboratory, Calibration of the MS for relative sensitivity was conducted with a single calibration gas containing the nine components displayed in Table 6.

Subsequently, eight different fuel mixes were prepared, containing the same nine components but over a wide range of concentrations, to test the repeatability and linearity of the MS.

Each gas was analyzed for 30 cycles over 5 minutes (10-second cycle time). Figure 3 displays the linearity plots, while Table 7 displays the Coefficients of Determination (R^2) for the nine components.

Table 6. ISO 17025 accredited calibration gas used for relative sensitivities. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Concentration %mol
Nitrogen	9.00 ± 0.0150
Carbon dioxide	5.00 ± 0.0150
Methane	9.00 ± 0.0200
Ethane	5.00 ± 0.0130
Propane	10.00% 0.0250
Ethylene	5.00 ± 0.0015
Propene	5.00 ± 0.0130
Hydrogen	43.00 ± 0.0700
Carbon monoxide	9.00 ± 0.0150

Table 7. Coefficients of Determination for nine components shown in Figure 3. Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Linearity Test: Coefficients of Determination (R^2)	
H_2, CH_4, C_2H_4, C_2H_6, C_3H_6	1.0000
C_3H_8	0.9999
CO_2	0.9995
CO, N_2	0.9994

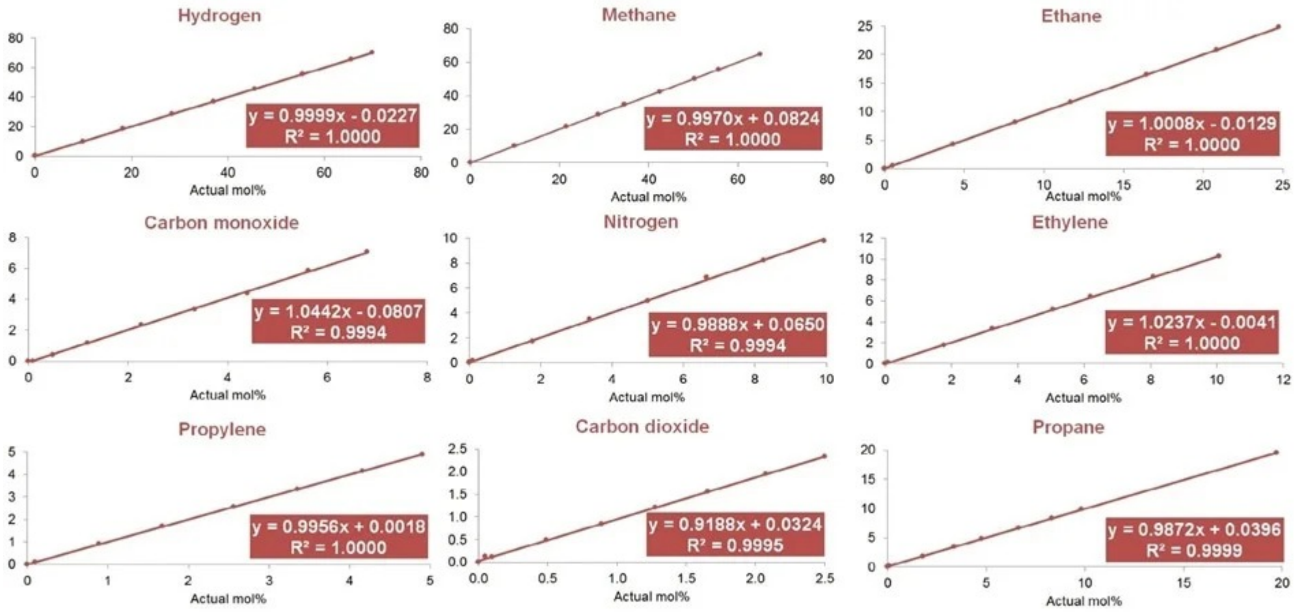


Figure 3. *Linearity data for nine fuel gas components. Image Credit: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments*

Rapid Multistream Sampling

For the MS to monitor all process streams, a quick, reliable method of switching between streams is necessary. Since rotary valves have poor reliability and solenoid valve manifolds have too much dead volume, the unique RMS Rapid Multistream Sampler was developed.

It provides a superior combination of reliability and sampling speed and enables sample selection from either one of 32 or one of 64 streams. Stream settling times depend on the application and are fully configurable by the user.

The RMS includes digital sample flow recording for every chosen stream. This may be utilized to trigger an alarm if the sample flow decreases, such as when a filter in the sample conditioning system becomes blocked.

The Prima PRO RMS may be heated to a temperature of 120 °C, and the location of the stream selector is optically encoded for reliable, software-controlled stream selection. Position and temperature control signals are communicated using the internal network of Prima PRO.

Figure 4 displays a schematic of the RMS. The RMS has a three-year warranty as standard, with no alternative multistream sampling devices offering the same level of proven reliability.

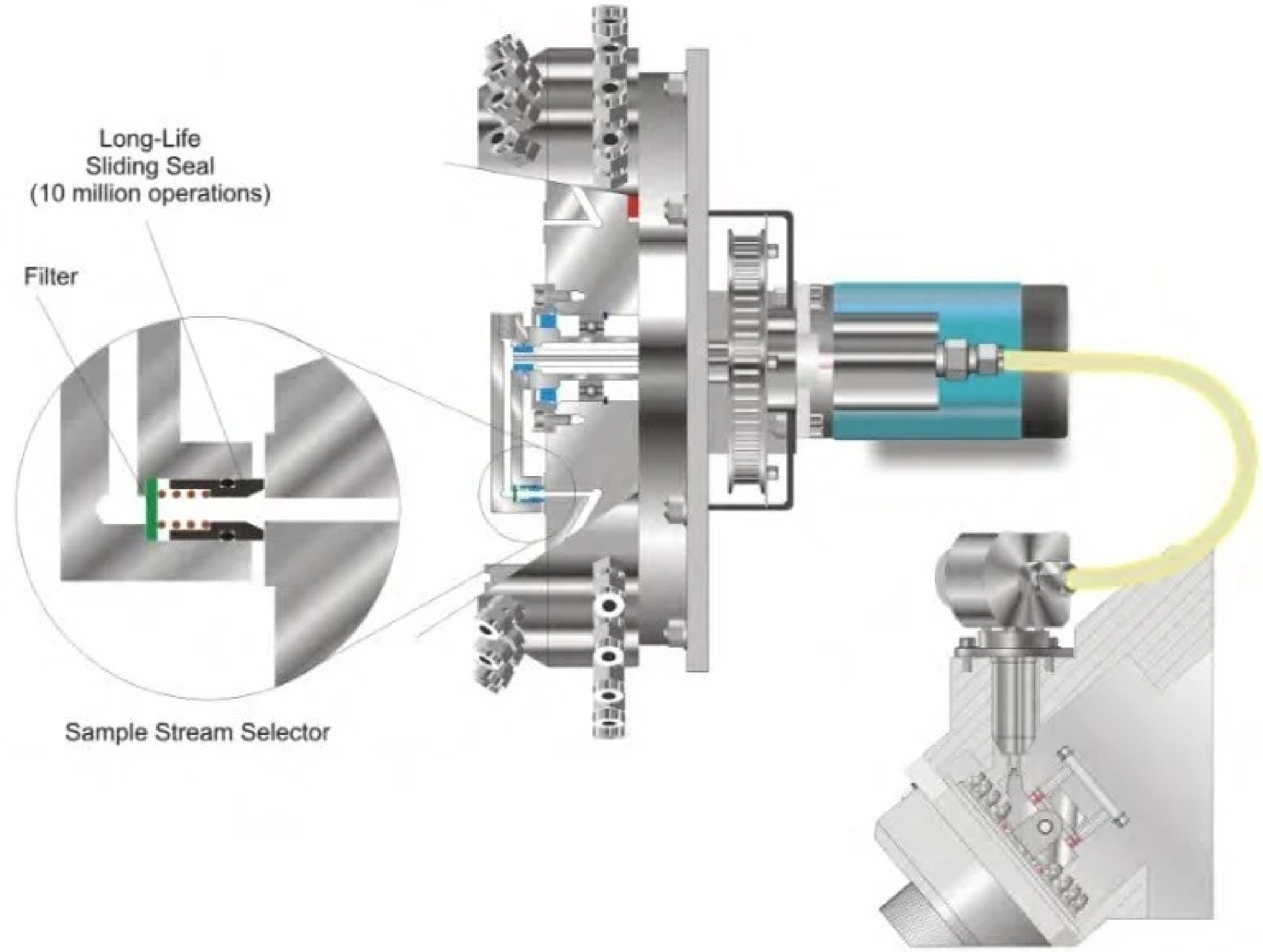


Figure 4. *Rapid multistream sampler. Image Credit: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments*

Software

Thermo Scientific™ GasWorks™ Software supports the analysis of an unlimited quantity of components per stream as well as an unlimited quantity of user-defined calculations (named Derived Values), such as the ratio of hydrogen-to-carbon monoxide.

An unlimited quantity of analytical methods may be set up, enabling different analyses to be defined for different process streams. Analog signals from pressure and temperature sensors may also be logged, displayed, and utilized in calculations of Derived Values.

A variety of industry-standard protocols are available for communication with plant process control systems.

Performance Specification

There is no single composition specification for syngas. However, Table 8 provides a 'typical'

Prima PRO syngas performance specification.

Analysis cycle time is around 20 seconds, inclusive of stream settling time, and performance is demonstrated during on-site commissioning by periodic analysis with a certified calibration gas over 16 hours. Additional components may also be monitored if required, with a consultation with the manufacturers advised.

Table 8. Example of typical Prima PRO syngas performance specification.Source: Thermo Fisher Scientific – Environmental and Process Monitoring Instruments

Component	Range %mol	Prima PRO precision %mol	Prima PRO Lower Detection Limit %mol
Hydrogen	0 – 75	≤0.05	≤0.01
Carbon Monoxide	0 – 25	≤0.05	≤0.3
Carbon Dioxide	0 – 25	≤0.02	≤0.01
Methane	0 – 10	≤0.02	≤0.01
Nitrogen	0 – 50	≤0.05	≤0.3

Summary

Syngas production requires rapid, multi-component, multistream gas analysis, and Thermo Scientific gas analysis mass spectrometers are being utilized for rapid, accurate analysis of a wide variety of syngas-based processes:

- Direct Reduction Iron
- Production of ammonia and methanol
- Biofuels
- GTL process via Fischer-Tropsch

The magnetic sector analyzer delivers good long-term stability and high precision, with lengthy periods between calibration and exceptional contamination resistance.

Thermo Scientific Prima PRO and Prima BT Magnetic Sector Mass Spectrometers are delivering rapid but precise off-gas analysis through laboratory research to trial plant and full-scale production for this crucially important industry.

Prima BT offers a bench-top solution for monitoring on a laboratory scale, configured with six calibration and 15 sample gas inlets.

Prima PRO is able to monitor over 60 sample streams and is available for Zone 1 and Class 1 Div 2 hazardous area installation. The highly precise and complete gas composition measurements given by both models are straightforward to incorporate into a process control system.

Acknowledgments

Produced from materials originally authored by Daniel Merriman at Thermo Fisher Scientific, Cheshire, UK.

References

1. Biofuels UK, What is Syngas? (http://biofuel.org.uk/what-is-syngas.html)
2. 2021 World Steel in Figures, page 18, World Steel Association (https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf)
3. Electron availability in CO2, CO and H2 mixtures constrains flux distribution, energy management and product formation in Clostridium ljungdahlii, Hermann, Teleki, Weitz, Niess, Freund, Bengelsdorf, Takors, Institute of Biochemical Engineering, University of Stuttgart, Microbial Biotechnology, July 2021 (https://sfamjournals.onlinelibrary.wiley.com/doi/full/10.1111/1751-7915.13625)
4. Synthetic Fuel Development, Future Energy (Third Edition) 2020, Pages 561-580 (https://www.sciencedirect.com/science/article/abs/pii/B9780081028865000268)

This information has been sourced, reviewed and adapted from materials provided by Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

For more information on this source, please visit Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

New Study Proposes Smarter Framework for CCUS-EOR

A recent study published in *Engineering* introduces a fresh framework for optimizing carbon capture, utilization, and storage (CCUS) integrated with enhanced oil recovery (EOR), with a focus on carbon dioxide (CO_2)-EOR. The research outlines how this approach can simultaneously boost energy production and enable long-term carbon sequestration, cutting emissions and improving resource efficiency.

The findings position CCUS-EOR as a vital strategy for climate mitigation and sustainable energy development, especially in the global push toward carbon neutrality.

Image Credit: Keshi Studio/Shutterstock.com

The Role of CCUS-EOR in Climate Action

Tackling global climate change, one of the defining challenges of the 21st century, requires scalable, effective solutions for reducing carbon emissions. Among these, CCUS is a key technology that captures CO_2 from industrial sources and stores it deep underground.

Within the suite of CCUS approaches, CO_2-EOR remains the most widely adopted, making up about 77% of global carbon capture efforts. This method involves injecting captured CO_2 into depleted oil reservoirs to extract more oil while securely storing the gas below the surface.

According to the International Energy Agency (IEA), CO_2-EOR projects have sequestered over 400 million tons of CO_2, the equivalent of emissions from roughly 100 million gasoline-powered cars annually. As the method scales to new fields and larger projects, its relevance in clean energy strategies continues to rise.

A Two-Stage Framework for CCUS-EOR

The study examines key factors that influence the performance of CCUS-EOR, focusing on reservoir characteristics, fluid properties, and operational settings. Researchers proposed a two-stage framework to better understand and enhance the process.

In the first stage, during active CO_2 injection, the gas mixes with crude oil, reducing viscosity and improving flow. Depending on reservoir conditions, this mixing may occur either miscibly or immiscibly. At the same time, CO_2 occupies pore spaces within the reservoir, contributing to physical storage.

In the second stage, after the injection ends, CO_2 gradually dissolves into the formation water and reacts with the surrounding minerals. These reactions form stable carbonate compounds that securely trap the gas over time.

The study breaks down several critical variables across both stages, including:

- **Reservoir factors**: Porosity, permeability, temperature, pressure, and mineral makeup
- **Fluid properties**: Oil composition, water salinity, gas impurities
- **Operational parameters**: Injection pressure, rate, and methods

By mapping out the interactions among these elements, researchers identified key ways to improve oil recovery and CO_2 storage. They also reviewed advanced techniques such as water-alternating-gas (WAG) injection and the use of smart, eco-friendly materials to further enhance efficiency.

Factors That Shape CO_2 Storage and Recovery Performance

Results showed that permeability and porosity are central to CO_2 movement and storage capacity. While higher permeability generally improves oil recovery, too much variation can lead to uneven gas flow and reduced efficiency. Optimal oil recovery was observed in reservoirs with permeability between 10 and 31.6 millidarcies (mD), though CO_2 storage behavior within this range proved more complex and non-linear.

When CO_2 reaches supercritical conditions (above 304.2 K and 7.39 MPa), its low viscosity and high density enhance mixing with crude oil. Increased pressure raises density and solubility of CO_2, which benefits oil recovery and storage. However, very high temperatures (over 150 °C) and pressures (above 60 MPa) raise leakage risks and lower storage reliability.

Mineral composition ALSO plays a significant role. Minerals rich in calcium, magnesium, aluminum, and iron react with CO_2 to form solid carbonates, improving storage by altering pore structures and permeability over time.

Oil composition also affects recovery and storage. CO_2 tends to extract lighter hydrocarbons (C1–C9), which improves oil recovery but lowers CO_2 retention. Heavier hydrocarbons (C20+) adsorb more CO_2 but are less miscible.

Injection pressure must exceed the oil's minimum miscibility pressure to ensure adequate recovery and storage. Meanwhile, formation water chemistry—especially salinity and pH—also influences outcomes. Lower salinity improves CO_2 solubility and storage potential, while high salinity reduces it due to the salting-out effect. Acidic conditions support CO_2 dissolution; alkaline conditions tend to result in free gas, decreasing overall storage efficiency.

Implications for the Energy Sector

These findings have practical implications for the energy industry. By improving CCUS-EOR technologies, companies can increase oil yields while locking away carbon, helping to meet sustainability and net-zero targets.

The study also recommends adopting advanced tools such as AI-based optimization methods, smart hydrogel agents, and integrated monitoring systems to enhance CCUS-EOR performance. Economic evaluations that factor in carbon credits, project costs, and regulatory risks are also essential for gauging viability.

Researchers emphasize the importance of cross-industry collaboration and data sharing to speed up CCUS-EOR deployment. They also call for ongoing technological and practice innovation to keep pace with evolving climate and energy demands.

Conclusion

CCUS-EOR offers a practical and scalable approach to balancing energy production with effective carbon management. This research provides a comprehensive reference for scientists, engineers, and policymakers working to refine these technologies. It underscores the need for continued innovation and collaboration to develop reliable, long-term carbon strategies that support a more sustainable, climate-resilient future.

Source:

Rui, Z., & *et al*. (2025). Investigating the Synergistic Impact of CCUS-EOR. *Engineering*, 48, 16-40. DOI: 10.1016/j.eng.2025.04.005,
https://www.sciencedirect.com/science/article/pii/S2095809925001997

Configurable Flow Software Can Help Boost Custody Transfer

Custody transfer systems in the oil and gas industry depend on accurate and efficient flow assessment to ensure precise transactions of physical materials like crude oil and natural gas.

Image Credit: afotostock/Shutterstock.com

Errors in metering systems, influenced by factors such as pressure drop, temperature, and flow rate, can lead to costly disputes and non-compliance with industry standards like those set by the American Petroleum Institute (API).

By integrating configurable flow software with advanced instruments like flow computers, turbine meters, and flow meters, custody transfer applications can achieve greater precision, optimize pressure and temperature adjustments, and ensure regulatory compliance.

This guide explores how this software improves metering accuracy while adhering to industry standards, offering practical insights for its effective implementation.

Improving System Configuration

Modern flow software allows operators to make real-time adjustments using software-configurable I/O modules. This capability enables users to map devices and protocols directly in the field, simplifying setup and modifications.

With predefined logical registers, the integration of SCADA (Supervisory Control and Data Acquisition) systems is seamless, facilitating smooth monitoring and control.

This configurability reduces downtime and enhances operational flexibility, as technicians can make on-site adjustments without needing specialized hardware modules. Such adaptability is especially valuable in remote or challenging locations where quick adjustments are essential.

Using Intelligent Data Management

Advanced flow systems use real-time data analytics and machine learning to enhance custody transfers. By integrating historical data, network conditions, and asset metadata into operational decisions, these platforms enhance the precision and speed of transfers.

For example, dynamic analysis of flow parameters makes it possible for systems to accommodate fluctuations in pipeline conditions, enabling consistent performance. Predictive analytics further make it possible for operators to predict maintenance needs, diminishing unexpected downtime and optimizing operational continuity.

Precision in Flow Measurement

Custody transfer systems require exceptional accuracy in measuring parameters such as volumetric flow, pressure, and temperature. Advanced measurement technologies are crucial in meeting these demands:

- **Mass Flow Meters:** Coriolis flow meters provide highly accurate measurements, even under fluctuating operational conditions.
- **Ultrasonic Meters:** Dual-configuration ultrasonic systems enable real-time performance verification and redundancy, minimizing measurement uncertainty.
- **Cross-Validation Techniques:** Using meter provers ensures consistency across multiple devices, enhancing reliability and accuracy.

These instruments work together to make sure every custody transfer is accurate and verifiable, reducing discrepancies and disputes.

Ensuring Data Security and Regulatory Compliance

As digital transformation progresses, custody transfer systems face growing cybersecurity risks. Configurable flow software integrates advanced security features like encryption, authentication, and real-time threat monitoring to protect sensitive data and safeguard the integrity of transfer operations.

Regulatory compliance is equally crucial. Flow software automates data logging and reporting, ensuring a reliable audit trail. By adhering to industry standards, such as those from the American Gas Association (AGA) or the API, operators can ensure their processes comply with or exceed required benchmarks.

Seamless System Integration

Custody transfer operations often involve various interconnected components, including flow meters, SCADA systems, and control platforms. Configurable flow software ensures seamless integration, allowing all components to work together efficiently.

This level of integration enables systems to adapt to fluctuating operating conditions, including changes in product types or flow rates. By ensuring interoperability, operators can maintain accurate assessments and streamline processes, even as system parameters evolve.

Optimizing Operational Efficiency

Proactive maintenance approaches underscored by configurable flow software help to diminish operational costs and prolong system longevity. Diagnostic instruments continuously track system performance, detecting anomalies early and providing timely intervention.

By making use of these insights to guide maintenance schedules, operators are able to diminish downtime and prevent expensive equipment failures. This method both ensures operational efficiency and lessens the total cost of ownership over the system's life cycle.

Real-World Effects

Organizations that use configurable flow software typically report considerable improvements in their custody transfer operations. For instance, real-time data insights, together with sophisticated measuring tools, can minimize discrepancies, enhance stakeholder trust, and ensure compliance with strict regulatory criteria.

Furthermore, the ability to adapt systems dynamically in the field translates to more agility in responding to operational difficulties. These advantages make configurable flow software an indispensable tool in the quest for both precision and efficiency.

Moving Forward

The intricate nature of custody transfers in the oil and gas industry calls for creative solutions that surpass conventional approaches. Configurable flow software tackles these challenges by integrating precise measurement, advanced analytics, and robust security features.

As the industry evolves, adopting such technologies will be crucial for companies looking to optimize operations, reduce costs, and maintain a competitive edge. Investing in configurable flow software is not just a technological upgrade—it's a strategic advantage for the future of custody transfers.

By leveraging these solutions, operators can confidently meet the demands of modern hydrocarbon transportation, ensuring that each transfer is accurate, efficient, and compliant.

ThermoFisher SCIENTIFIC

This information has been sourced, reviewed and adapted from materials provided by Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

For more information on this source, please visit Thermo Fisher Scientific – Environmental and Process Monitoring Instruments.

Why Use Spectroscopy in Oil and Gas Analysis

The oil and gas industry operates in a high-stakes environment where precise chemical analysis plays a critical role in both upstream exploration and downstream processing. The ability to accurately characterize hydrocarbon mixtures can influence operational efficiency, safety, and regulatory compliance. In this context, spectroscopy emerges as a vital analytical tool that provides non-destructive and real-time data essential for understanding the complex composition of crude oil and natural gas.

Image Credit: MR.Zanis/Shutterstock.com

Spectroscopy facilitates the identification and quantification of various components within these mixtures by leveraging the unique interactions between electromagnetic radiation and matter, thus enhancing decision-making processes and optimizing resource management in the oil and gas sector.[1,2]

The Optical Science Behind Spectroscopy

Spectroscopy operates through three fundamental mechanisms: absorption, emission, and scattering of light. In absorption spectroscopy, molecules absorb specific wavelengths of light that correspond to their unique molecular structures, resulting in characteristic spectral patterns. These patterns help identify and quantify different compounds within a sample.

Emission spectroscopy, on the other hand, focuses on the light emitted by atoms or molecules as they return to lower energy states after being excited. The emitted wavelengths provide valuable information about the elemental or molecular composition of the substance being analyzed. Raman spectroscopy detects inelastic scattering where incident photons interact with molecular vibrations, producing wavelength shifts that reveal molecular composition.[3]

Three optical principles enable spectroscopic analysis in petroleum applications. Wavelength selectivity allows different molecules to absorb or emit light at distinct wavelengths, enabling component identification in mixtures. Light-matter interactions depend on molecular structure and concentration, providing both qualitative and quantitative information. Detection sensitivity determines the minimum measurable concentration, with laser-based systems now achieving parts-per-billion detection limits for compounds like methane and ethane.[4]

Several spectroscopic techniques are used in oil and gas analysis. Near-Infrared (NIR) spectroscopy (780-2500 nm) characterizes hydrocarbon groups and has become standard for downhole fluid analysis because it penetrates sample containers and operates under harsh conditions.[5] Fourier-Transform Infrared (FTIR) spectroscopy provides molecular fingerprints by measuring absorption across the mid-infrared region, enabling identification of functional groups and compound classes. Raman spectroscopy complements infrared techniques by detecting vibrations that may be infrared-inactive, useful for analyzing symmetric molecules and gas mixtures.[6] Laser-Induced Breakdown Spectroscopy (LIBS) creates plasma on sample surfaces for rapid elemental analysis in field applications.

Real-World Applications in Oil and Gas

Exploration & Production (Upstream)

Real-time downhole fluid analysis using spectroscopy has significantly improved how operators characterize reservoir fluids. Wireline tools equipped with visible and near-infrared spectrometers enable direct measurement of formation fluid composition, gas-oil ratio, and contamination levels during sampling operations. By providing immediate, in-situ data, these tools help reduce uncertainty, improve sampling efficiency, and support more accurate reservoir evaluation decisions.

This capability reduces reliance on laboratory analysis while improving reservoir characterization.[7] Recent systems using laser diodes and neural networks identify fluid types in real-time with accuracies exceeding 95% under downhole conditions reaching 175°C and

20,000 psi.[8]

Hydrocarbon detection distinguishes oil from gas condensate, affecting completion strategies and production forecasts. Water cut measurements determine oil-water interface locations for optimizing production intervals. Hydrogen sulfide detection protects personnel and equipment from this toxic and corrosive gas, with photoacoustic sensors detecting H2S below 1 ppm.

Refining & Processing (Midstream/Downstream)

Composition analysis in crude and refined products enables process optimization and quality control. NIR spectroscopy combined with regression models predicts crude oil properties including density, viscosity, and distillation curves from spectral data collected in seconds.[9] This speed allows refiners to adjust processing parameters in real-time rather than waiting for laboratory results.

Monitoring specific compounds ensures product quality and regulatory compliance. Sulfur content determination via infrared spectroscopy helps refineries meet environmental regulations limiting sulfur in fuels. Aromatic compound quantification affects octane ratings and combustion characteristics. Moisture detection prevents corrosion and ensures fuel stability. BTEX (benzene, toluene, ethylbenzene, xylene) monitoring addresses product specifications and workplace exposure limits, with mid-infrared laser spectrometers achieving better than 2% accuracy for these species.

Environmental & Safety Monitoring

Emission detection supports compliance with environmental regulations and voluntary emissions reduction programs. Open-path laser absorption spectroscopy enables standoff detection of methane leaks from several hundred meters, allowing rapid surveys of facilities. Portable systems based on tunable diode laser absorption spectroscopy quantify fugitive emissions, supporting leak detection and repair programs.

Volatile organic compound monitoring protects worker health and meets air quality requirements. Photoacoustic spectroscopy systems simultaneously detect methane, ethane, and propane in natural gas processing, providing compositional data that distinguishes thermogenic from biogenic sources during environmental investigations.[4] Remote sensing for spill detection employs fluorescence spectroscopy to identify and classify oil slicks, with excitation-emission matrix techniques differentiating crude oils by geographic origin and weathering state.

Recent Technological Innovations

Miniaturization and ruggedization have enabled deployment in previously inaccessible environments. Spectrometers built around micro-electromechanical systems now fit within standard wireline tools while withstanding shock loads exceeding 500 g and temperature cycling from -40°C to 200°C. Quantum cascade lasers provide compact mid-infrared sources that enable portable gas analyzers small enough for handheld operation yet sensitive enough to detect parts-per-billion concentrations.[10]

Fiber-optic-based inline spectroscopy systems transmit light between process streams and remotely located spectrometers, eliminating sample extraction while maintaining measurement accuracy. These systems monitor crude oil properties in real-time along pipelines, providing early warning of contamination or off-specification material.

Integration with artificial intelligence has transformed spectroscopy from a measurement technique into a predictive tool. Convolutional neural networks extract features from complex spectra, improving prediction accuracy for crude oil viscosity by up to 40% compared to conventional models. Edge computing platforms process spectral data locally, enabling millisecond response times for process control applications.

Challenges and Industry Needs

Calibration remains a major challenge in spectroscopy, especially when dealing with complex mixtures where component interactions lead to nonlinear spectral responses. Partial least squares (PLS) models, commonly used for quantitative analysis, depend on large calibration datasets, which often fall short of capturing the full range of real-world field conditions.

Moreover, transferring calibration models between instruments with different optical characteristics typically requires additional recalibration, adding to the time and resource demands of deployment.

Interference from sample impurities or extreme conditions complicates measurements. Overlapping absorption bands between chemically similar compounds like propane and butane limit quantification accuracy. Temperature and pressure variations shift spectral features, requiring corrections. Particulate matter in crude oil scatters light, degrading signal-to-noise ratios and measurement precision.

Industry requires faster, more automated analysis methods with minimal operator intervention. Current systems often need skilled personnel to interpret results and diagnose problems. The goal is systems that non-specialists can operate reliably.

The Future of Optical Spectroscopy in Oil and Gas

Hyperspectral imaging captures complete spectra at each pixel in a two-dimensional image, enabling spatial mapping of composition across reservoir cores or refinery process units. Femtosecond lasers enable time-resolved spectroscopy that probes reaction mechanisms during refining processes. Quantum cascade laser technology continues advancing toward room-temperature operation and broader wavelength coverage, expanding the range of detectable species.

The development of fully autonomous analysis systems combines ruggedized spectrometers, real-time edge computing, and predictive algorithms into integrated platforms requiring minimal human intervention. Such systems would continuously monitor production fluids, adjust process parameters automatically, and alert operators to anomalies requiring attention. Real-time edge computing eliminates data transmission delays, enabling control loops operating at sub-second timescales.

Spectroscopy's role in sustainability and regulatory compliance will expand as carbon intensity metrics and emissions monitoring become standard practice. Continuous methane monitoring via laser spectroscopy will verify emissions reductions under voluntary programs and regulatory frameworks. Rapid crude oil characterization will enable optimization of energy-intensive separation processes, reducing both costs and carbon emissions. The convergence of spectroscopic measurement, analytics, and automated control positions optical spectroscopy as a key technology for improving efficiency and reducing environmental impact in oil and gas operations.

References and Further Reading

1. Elserw, M. I., Mahmoud, M. E., & Nabil, G. M. (2024). Recent advances in GC-VUV as a new analytical toolbox in qualitative and quantitative detection of petroleum and petrochemical derivatives. *Applied Spectroscopy Reviews*. https://doi.org/10.1080/05704928.2024.2436056
2. Kiefer, J. (2015). Recent advances in the characterization of gaseous and liquid fuels by vibrational spectroscopy. *Energies, 8*(4), 3165–3197. https://doi.org/10.3390/EN8043165
3. Cooper, J. B., Wise, K. L., Welch, W. T., Sumner, M. B., Wilt, B. K., & Bledsoe, R. R. (1997). Comparison of near-IR, Raman, and mid-IR spectroscopies for the determination of BTEX in petroleum fuels. *Applied Spectroscopy, 51*(11), 1613–1620. https://doi.org/10.1366/0003702971939596

4. Sampaolo, A., Csutak, S., Patimisco, P., Giglio, M., Menduni, G., Passaro, V. M. N., Tittel, F. K., Deffenbaugh, M., & Spagnolo, V. (2019). Methane, ethane and propane detection using a compact quartz enhanced photoacoustic sensor and a single interband cascade laser. *Sensors and Actuators B: Chemical*, *282*, 952–960. https://doi.org/10.1016/J.SNB.2018.11.132
5. Andrews, A. B., Sullivan, M., Deger, E., Hakim, B., Messonnier, T., Thibodeaux, B., Mahmmodaghdam, E., Jackson, R., Taylor, S. D., & Mullins, O. C. (2023). Validation of downhole fluid analysis and machine-learning compositional determination. *SPWLA 64th Annual Logging Symposium*. https://doi.org/10.30632/spwla-2023-0020
6. Karas, B. Y., & Grishkanich, A. S. (2020). Portable Raman dual-laser spectrometer for oil and gas. *Proceedings of SPIE, 11486*. https://doi.org/10.1117/12.2574603
7. Go, F., Mullins, O. C., Dong, C., Carnegie, A., Betancourt, S. S., Terabayashi, T., Yoshida, S., Jaramillo, A. R., & Haggag, M. (2003). Analyzing reservoir fluid composition in-situ in real time: Case study in a carbonate reservoir. *SPE Annual Technical Conference and Exhibition*. https://doi.org/10.2118/84092-MS
8. Chen, Z., Ni, H., Pei, X., & Zhang, S. (2024). A real-time downhole fluid identification system empowered by efficient quadratic neural network. *Electronics*, *13*(24), 5021. https://doi.org/10.3390/electronics13245021
9. Li, Z. (2022). Predicting crude oil properties using Fourier-transform infrared spectroscopy (FTIR) and data-driven methods. *Digital Chemical Engineering*, *3*, 100031. https://doi.org/10.1016/j.dche.2022.100031
10. Scheuermann, J., Kluczynski, P., Siembab, K., Straszewski, M., Kaczmarek, J., Weih, R., Fischer, M., Koeth, J., Schade, A., & Höfling, S. (2021). Interband cascade laser arrays for simultaneous and selective analysis of C1–C5 hydrocarbons in petrochemical industry. *Applied Spectroscopy*, *75*(3), 336–342. https://doi.org/10.1177/0003702820978230

The Operational Challenges of Oil and Gas Extraction

Oil and gas extraction is essential for the global energy supply, but the industry faces various types of operational challenges that extend from the reservoir to the rig and beyond. The complexity inherent in extracting hydrocarbons requires a blend of technical expertise, advanced equipment, and innovative strategies to achieve safe, efficient, and profitable operations. This article examines the multifaceted nature of these operational difficulties and technological responses from field operations and service providers.

Image Credit: Another77/Shutterstock.com

Drilling Hazards and Subsurface Uncertainty

Drilling wells in high-pressure, high-temperature (HPHT) zones comes with numerous challenges. These reservoirs, typically found at depths over 15,000 feet, experience temperatures above 300 °F and pressures exceeding 15,000 psi. Such conditions can compromise drilling fluids, impact equipment reliability, and contribute to wellbore instability and thermal expansion or contraction of components. The risk of formation fluid influx, stuck pipe incidents, and lost circulation increases in HPHT environments, potentially leading to unplanned downtime or even abandonment of wells.[1,2]

Operators often face unexpected reservoir conditions such as fault slips and fluid migration. In ultra-deep or fractured reservoirs, limited data can hinder accurate predictions, leading to unreliable reserve estimates until enough production data is gathered. This uncertainty in subsurface geology challenges investment decisions and requires adaptable drilling strategies. In some cases, well abandonment is required when severe faults or uncontrolled influxes damage infrastructure and compromise safety.[3]

Well Integrity and Maintenance Failures

Maintaining well integrity is important for safe and sustainable extraction. Issues such as casing collapse, annular pressure buildup, and compromised zonal isolation in aging wells can reduce productivity and safety. Corrosion, mechanical wear, and cement bond failures are common culprits, especially in older wells or during enhanced recovery operations.[4]

Technological advances have led to the deployment of real-time well integrity monitoring systems. Machine learning (ML) algorithms and predictive analytics can analyze operational data to identify potential integrity failures. Similarly, digital twin technology helps operators simulate conditions and evaluate non-destructive testing results.

Companies such as TotalEnergies use acoustic and electromagnetic monitoring tools to detect early signs of corrosion and mechanical damage, allowing timely intervention to maintain safety and operational efficiency.[4]

Surface Equipment and Infrastructure Challenges

Pumps, compressors, and separator units frequently face failures in mature oil and gas fields. The suppressive effect of corrosive fluids such as hydrogen sulfide, carbon dioxide, and brine accelerates the degradation of key components. In these conditions, corrosion monitoring becomes crucial, and operators should follow established pipeline pigging frequencies to manage microbial growth and prevent blockages.[5]

Downtime associated with equipment failure leads to deferred production and can become prolonged if replacement parts are not readily available or predictive maintenance is improperly managed.

Internet of Things (IoT) sensors and automated alerts can aid in predictive maintenance and minimize production delays. However, the complexity of operating multiple legacy systems often restricts the seamless integration necessary for complete reliability. Maintenance strategies must evolve to enhance efficiencies and ensure consistent performance.[5]

Remote and Harsh Environment Operations

Extraction in offshore, Arctic, and deep desert environments comes with unique challenges - chief among them isolation, extreme weather, and limited infrastructure. Oman's oil fields offer a clear example: moving equipment and personnel deep into the desert involves complex logistics, while sandstorms, salt exposure, and intense heat take a toll on human health and equipment durability.[6]

Limited access for maintenance further compounds the risk. If a critical system fails, repair crews may face long delays and higher costs before work can begin. In Arctic regions, permafrost thaw and severe winter storms add yet another layer of operational hazard.

To mitigate these issues, some companies - such as those operating offshore platforms in Norway - have shifted toward remote operations with fewer on-site staff. Industrial IoT systems, edge AI, and digital twins help sustain safety and efficiency in these environments. Robotic inspection units, fitted with cameras and sensors, can navigate hard-to-reach areas and provide real-time condition reports, allowing operators to address problems before they escalate.[7]

Flow Assurance and Production Chemistry

Hydrate formation, wax deposition, and asphaltene buildup in pipelines are major flow assurance obstacles. These phenomena obstruct fluid movement from the reservoir, lowering flow rates and necessitating frequent pigging or chemical treatments. Hydrate and solid plugs are primarily found in subsea pipelines, where removal can be expensive and hazardous.[8]

Chemical injection, thermal treatments, and next-generation inline monitoring systems have become important tools. Operators increasingly use sensor arrays to track the onset of blockages and adjust inhibitor dosing in real-time. The problems intensify in mature fields, where increased water fraction heightens the likelihood of emulsions and scaling. Breaking stable emulsions and removing scale require cost-effective interventions and constant innovation in fluid management techniques.[9]

Workforce Availability and Onsite Safety

There is a shortage of experienced drillers and field engineers, and oil field operations continue to be among the most hazardous workplaces. High-pressure zones, confined spaces, and exposure to toxic chemicals significantly elevate accident risks. Data from the U.S. Bureau of Labor Statistics shows that oil and gas extraction workers are much more likely to die on the job than across other sectors.[10]

Fatigue from long shifts and safety lapses caused by rotation inefficiencies contribute to human error. To counter this, real-time safety monitoring and improved protective equipment, combined with more effective rotation schedules, can reduce accident rates. Additionally, training on new hazards and routine safety audits are now a central part of on-site risk management strategies.[10]

Digitalization Challenges in Oil and Gas

Integrating data streams across drilling, production, and processing remains a significant challenge. Old IT infrastructure often lacks the bandwidth for IoT and AI deployment, affecting real-time monitoring and predictive analytics. Limited interoperability between vendor platforms and company software further introduces inefficiencies, slows troubleshooting, and complicates asset health management.[11]

Companies are investing heavily in digital transformation to address these bottlenecks. For example, the digital oilfield model employs cloud computing and big data analytics to analyze operational data and optimize workflows. Although there is an understanding of the importance of digitalization, the need to adapt and upgrade existing systems remains a key barrier in realizing its full potential.[12]

Environmental Compliance in Operations

Operational non-compliance with regulations can lead to costly shutdowns and legal action. Issues such as spills, gas flaring, and emissions breaches require constant monitoring, thorough documentation, and accurate reporting on-site. To address these challenges, technologies for methane leak detection are advancing, and their use carries regulatory implications, particularly in U.S. shale fields where emissions standards have tightened.[13]

To enhance compliance efforts, environmental monitoring platforms have emerged that integrate sensor networks, data loggers, and artificial intelligence. These systems work together to identify leaks or violations, promptly addressing potential issues. Automated reporting and audit trails also streamline the response process. However, the complexity and variability of real-world field conditions make compliance a daily challenge.[13]

Logistical and Supply Chain Disruptions

Geopolitical instability and global transport bottlenecks often disrupt the flow of critical spare parts and chemicals to remote energy sites. Extended lead times for specialist equipment - such as electric submersible pumps and subsea connectors - can put operational continuity at risk. With limited on-site storage for essential consumables, operators must balance precise inventory control with robust contingency planning, adding further complexity to supply chain management.[14]

To reduce these vulnerabilities, companies are diversifying their supplier base, developing local manufacturing capabilities, and adopting advanced inventory tracking systems. Predictive analytics and supply chain modeling play a central role, enabling operators to forecast demand for parts and chemicals with greater accuracy. By anticipating needs and identifying potential delays early, these tools help minimize downtime caused by shipping holdups or customs processes, keeping operations running smoothly.[14]

Future Prospects and Conclusion

Industry leaders are increasingly using technology to manage operational risks. Companies such as Halliburton offer advanced well monitoring solutions, while Baker Hughes designs corrosion-resistant tools for environments with high CO_2 levels. Today, modern extraction operations rely on robotic systems, AI-driven predictive maintenance, and real-time monitoring.

In the future, collaboration between equipment manufacturers, service providers, and operators will lead to innovations that alleviate operational challenges. Integrating digital twins, edge computing, and cloud-based analytics enhances efficiency and asset reliability.[15]

In conclusion, oil and gas extraction features a landscape characterized by intrinsic complexity and evolving technical demands. The constant drive for safer, more efficient, and environmentally compliant operations encourages the adoption of innovative solutions. As the industry navigates increasingly remote, harsh, and uncertain environments, addressing operational challenges through rigorous engineering, digital advancement, and strategic resource management remains vital for long-term success.

References and Further Reading

1. Challenges of Drilling High-Pressure, High-Temperature wells. *Drillopedia*. https://www.drillopedia.com/challenges-hpht-formations
2. Adefemi, A. *et al.* (2024). Exploring technological and operational challenges in high-pressure: High-temperature drilling techniques. *Global Journal of Engineering and Technology Advances*, *19*(3), 037–049. DOI:10.30574/gjeta.2024.19.3.0088. https://gjeta.com/content/exploring-technological-and-operational-challenges-high-pressure-high-temperature-drilling
3. Wang, H., et al. (2023). Progress and challenges of drilling and completion technologies for deep, ultra-deep and horizontal wells of CNPC. *China Petroleum Exploration*, 28(3), 1–11. DOI:10.3969/j.issn.1672-7703.2023.03.001. http://www.cped.cn/EN/10.3969/j.issn.1672-7703.2023.03.001
4. Erinle, O. G. *et al.* (2024). Ensuring Well Integrity in Oil and Gas: Advanced Engineering Practices and Technological Innovations. *International Journal Of Engineering Research And Development*, *20*(9), 55–67. http://www.ijerd.com/paper/vol20-issue9/20095567.pdf
5. Goswami, G. (2023). Challenges and Opportunities - Mature Oil Field. *International Journal of Scientific Research in Engineering & Technology*, *3*(2), 9–12. https://www.ijsreat.com/archiver/archives/challenges_and_opportunities_mature_oil_fields.pdf
6. Challenges of Remote Oilfield Operations: Insights from Oman's Oil and Gas Sector. (2025). *LinkedIn*. https://www.linkedin.com/pulse/challenges-remote-oilfield-operations-insights-from-omans-oil-06def
7. Remote Operations in Oil & Gas: Smarter, Safer, Leaner. (2025). *IIoT World.* https://www.iiot-world.com/smart-manufacturing/process-manufacturing/remote-operations-in-oil-and-gas/
8. Flow Assurance. *METTLER TOLEDO.* https://www.mt.com/in/en/home/applications/L1_AutoChem_Applications/L2_ParticleProcessing/Solids-Droplets-Crude-Oil.html
9. Patel, Z. D. *et al.* (2022). Flow Sssurance in Petroleum Industry. *International Journal of Innovative Research in Engineering & Management (IJIREM*, *9*(3), 119–128. DOI:10.55524/ijirem.2022.9.3.20. https://ijirem.org/DOC/20-flow-assurance-in-petroleum-industry.pdf
10. Josh. (2025). Workplace Safety in Oil and Gas: Hazards, Causes, and Solutions. *Safe T Pros*. https://www.safetpros.com/workplace-safety-oil-and-gas-hazards-causes-and-

solutions/
11. Oil & Gas: Digital Transformation for Enhanced Operations. *ShareVault | Virtual Data Room.* https://sharevault.com/blog/virtual-data-room/the-role-of-digital-transformation-in-enhancing-oil-and-gas-operations
12. Oil and gas: digital technology challenges. (2025). *Statista*. https://www.statista.com/statistics/1190625/oil-and-gas-market-digital-technology-challenges/
13. Halsey, T. *et al*. (2023). Grand Challenges for the Oil and Gas Industry for the Next Decade and Beyond. *JPT*. https://jpt.spe.org/grand-challenges-for-the-oil-and-gas-industry-for-the-next-decade-and-beyond
14. Zhang et al. (2024). A review of reservoir damage during hydraulic fracturing of deep and ultra-deep reservoirs. *Petroleum Science*, 21(1), 384–409. DOI:10.1016/j.petsci.2023.11.017. https://www.sciencedirect.com/science/article/pii/S1995822623003242
15. Remote Operations in Oil & Gas: Smarter, Safer, Leaner. (2025*). IIoT World.* https://www.iiot-world.com/smart-manufacturing/process-manufacturing/remote-operations-in-oil-and-gas/

Raman Spectroscopy in Upstream, Midstream, and Downstream Operations

Raman spectroscopy is subtly reshaping oil and gas operations. This light-scattering technique offers real-time, molecular-level insights that boost safety and precision, from exploration to refining. The industry is taking note.

Image Credit: noomcpk/Shutterstock.com

At its simplest, Raman spectroscopy is a light-scattering technique. When monochromatic light, usually from a laser, hits a sample, most of it returns unchanged. But a small portion scatters inelastically, changing energy as it interacts with molecular vibrations. These shifts form a spectral fingerprint, revealing what a substance is made of.

That fingerprint is proving indispensable in oil and gas. From the reservoir to the refinery, Raman systems are delivering rapid, accurate, and non-destructive chemical analysis, often in real time. For an industry built on tight margins and complex processes, the ability to monitor materials without halting production is a game-changer.[1-2]

Upstream Applications Made Smarter and Safer

Upstream operations in the oil and gas industry focus on exploration and production. The geological complexity and variability of hydrocarbons make them difficult to analyze; Raman spectroscopy, with its sensitivity and accuracy, holds potential for rapid, direct analysis of geological samples, drilling fluids, and gas compositions.

Geologists use Raman analysis during exploration to assess the maturity of organic matter in rock formations. This technique allows analysts to identify the best extraction zones and estimate the potential of source rocks. Recent research efforts have combined the power of machine learning with Raman spectra to more precisely evaluate organic maturity. The result is more accurate predictions and fewer costly drilling missteps.[3,4]

Drilling operations benefit, too. Online Raman systems can monitor gases emerging from the borehole in real time, simultaneously detecting hydrocarbon and non-hydrocarbon gases. This rapid feedback is vital for identifying productive zones and, more importantly, for spotting gas kicks early enough to prevent blowouts. In a high-risk environment, that kind of early warning system is invaluable.[5,6]

Upstream production also relies on fluid characterization and phase analysis. Raman spectroscopy can directly monitor oil, gas, and water contents in multiphase streams. Not sensitive to water, it is particularly effective for processes that involve high moisture or aqueous environments, and its fast response time means analysis can be performed *in situ*, minimizing delays and supporting continuous operations.[1]

Midstream: Transport and Transfer

Midstream operations, like pipeline transport, storage, and liquid natural gas (LNG) transfer, require meticulous monitoring to meet safety and regulatory demands. Raman spectroscopy fits seamlessly here, offering compositional analysis without time-consuming sample prep. Inline or online Raman analyzers can be installed on pipelines or at custody transfer points to provide real-time compositional data.[7]

It's particularly useful in LNG transfer. Raman systems with immersion probes can directly sample LNG to determine its composition without the need for sample vaporization or elaborate pre-treatment. This direct analysis method reduces operational complexity, improves measurement traceability, and shortens stabilization times, delivering reliable results regardless of changes in process pressure, temperature, or flow rate.[7]

Raman analyzers routinely track methane, ethane, propane, heavier hydrocarbons, and inert gases, providing the data needed for custody transfer, pricing, and regulatory compliance. This data ensures that products meet contract specifications and operators receive appropriate value for delivered energy. And because the technology works inline or online, operators can react to composition changes immediately, avoiding delays or out-of-spec deliveries.[6,8]

The same applies to crude and refined product pipelines. Continuous Raman monitoring helps spot contamination and confirms product integrity, reducing the risk of costly cross-contamination or fines.[2]

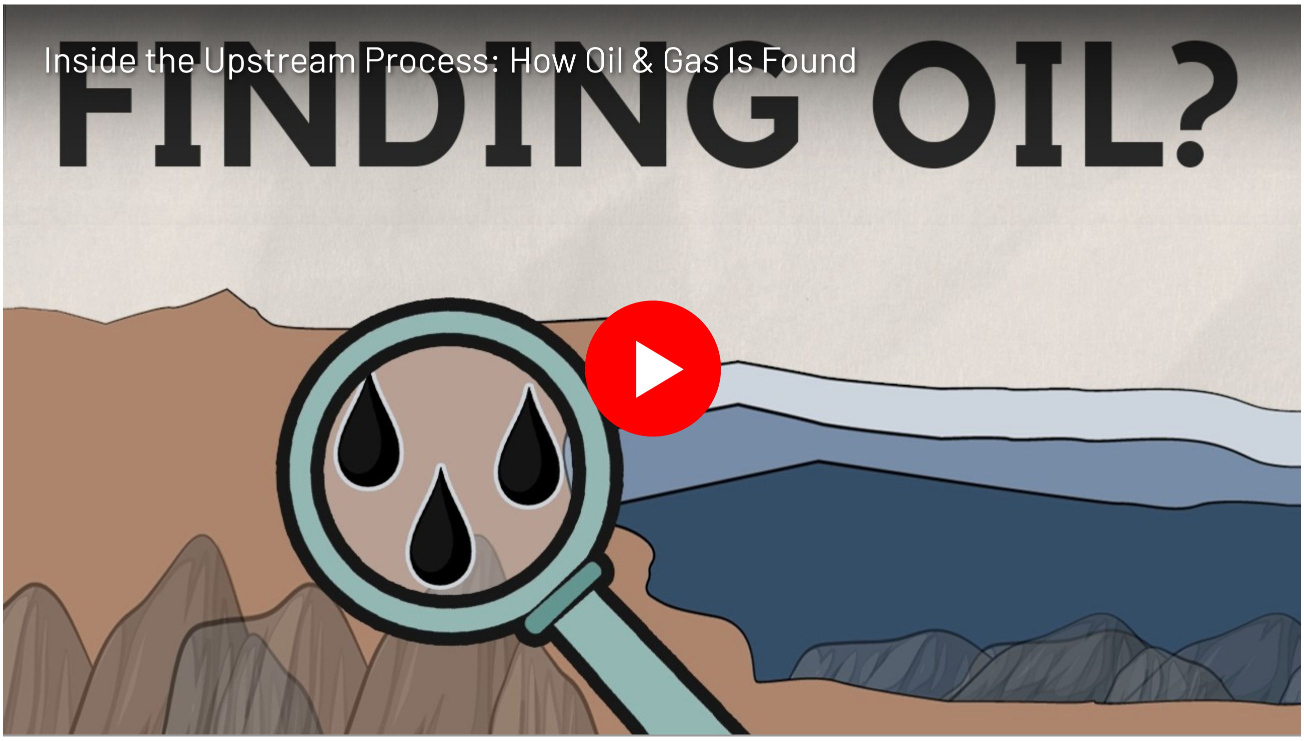
Downstream Applications

Downstream oil and gas operations revolve around refining, petrochemical processing, and the distribution of finished products. All of these processes rely on a tight timeline and stringent quality assurance. Raman spectroscopy addresses these needs with real-time, non-destructive process analysis across multiple streams and processing units.[2,9]

Inside the refinery, Raman systems are used during distillation, reforming, and blending to track chemical reactions and quantify key components like olefins. There's no need for complicated sample prep, and data can be fed directly into digital control systems for closed-loop optimization. That means fewer manual interventions, fewer errors, and faster decisions.[2,9,10]

Raman systems are directly integrated into production lines for quality control to verify fuel quality, detect adulterants, and confirm that finished products conform to specifications. This integration is necessary in environments where rapid product changes occur or where consistency between batches is critical.[1,11]

Additionally, refineries benefit from the flexibility of Raman analysis in advanced manufacturing. For example, solid-state Raman analyzers allow on-site, rapid assessment of blended and component fuels. The data informs both operational decisions and regulatory reporting, supporting improved product safety and environmental stewardship.[2,10]



Innovation and Future Outlook

Today's Raman instruments are more capable than ever. Multiple-pass and multi-channel designs can detect trace components at parts-per-million levels, even in high-pressure or high-temperature environments. These capabilities make them suitable for remote deployments or harsh field conditions.[6]

Software is evolving, too. Machine learning models trained on Raman data can identify patterns and anomalies that even expert analysts might miss, adding a layer of predictive insight. In upstream settings, this improves geological assessments. In downstream operations, it boosts throughput and consistency. Digital integration allows Raman systems to directly report measurements to distributed control systems, closing the loop for autonomous process optimization.[2,3]

Research is also expanding the utility of Raman spectroscopy beyond hydrocarbons. Analysts are applying it to monitor conversion processes for renewable feedstocks, such as biomass-to-fuel applications, reflecting the industry's shift towards sustainability and alternative energy sources.[12]

Conclusion

Raman spectroscopy delivers critical analytical capabilities throughout the oil and gas value chain. Its molecular precision, rapid response time, and non-destructive approach strengthen quality assurance, process efficiency, and operational safety in upstream, midstream, and downstream settings. Continuing innovation in sensor technology and data-driven analysis is set to further establish Raman spectroscopy as a cornerstone of modern oil and gas process analytics.

References and Further Reading

1. Raman and GC: Enhancing Analytical Methods. *MarqMetrix All-In-One Process Raman-Lösung.* https://www.marqmetrix.com/raman-and-gc-enhancing-analytical-methods/
2. Richmond, J. (2024). How Do I Use Inline Raman Spectroscopy in Downstream Oil & Gas Applications? *ThermoFisher.* https://www.thermofisher.com/blog/mining/how-do-i-use-inline-raman-spectroscopy-in-downstream-oil-gas-applications/
3. Almeida Carvalho, A. M., *et al.* (2025). Raman Spectroscopy Integrated with Machine Learning as a Tool for Maturity Assessment of Organic Matter. *ACS Earth and Space Chemistry*. DOI:10.1021/acsearthspacechem.5c00068, https://pubs.acs.org/doi/full/10.1021/acsearthspacechem.5c00068
4. Lin, Y. *et al.* (2024). Application of Raman Spectroscopy in Oil and Gas Geological Research. *Journal of GeoEnergy*, *2025*(1), 3984723. DOI:10.1155/jge5/3984723. https://onlinelibrary.wiley.com/doi/full/10.1155/jge5/3984723
5. Rathmell, C. (2018). Data-Driven Raman Spectroscopy in Oil and Gas: Rapid Online Analysis of Complex Gas Mixtures. *Spectroscopy Online.* https://www.spectroscopyonline.com/view/data-driven-raman-spectroscopy-oil-and-gas-rapid-online-analysis-complex-gas-mixtures
6. Shen, C. *et al.* (2021). A Versatile Multiple-Pass Raman System for Industrial Trace Gas Detection. *Sensors*, *21*(21), 7173. DOI:10.3390/s21217173. https://www.mdpi.com/1424-8220/21/21/7173
7. Raman method for the determination and measurement of LNG composition. (2021). *GERG – The European Gas Research Group.* https://www.gerg.eu/wp-content/uploads/2019/10/Raman-for-LNG-custody-transfer_Final_3_1_1_.pdf
8. Majumder, D. *et al.* (2025). Raman gas sensing technology: A new horizon? *Sensors and Actuators Reports*, *9*, 100311. DOI:10.1016/j.snr.2025.100311. https://www.sciencedirect.com/science/article/pii/S2666053925000293
9. Gieleciak, R. *et al.* (2023). Exploring the Potential of Raman Spectroscopy for Characterizing Olefins in Olefin-Containing Streams. *Energy & Fuels*. DOI:10.1021/acs.energyfuels.3c02014. https://pubs.acs.org/doi/10.1021/acs.energyfuels.3c02014
10. Alvarado-Olivo, S. (2024). Revolutionizing Refined Fuel Analysis with Solid-State Raman

Spectroscopy. *ThermoFisher.* https://www.thermofisher.com/blog/mining/revolutionizing-refined-fuel-analysis-with-solid-state-raman-spectroscopy/
11. Picardi, G. *et al.* (2024). Rapid screening of designer fuel fraud by Raman spectroscopy. *Talanta Open*, *9*, 100333. DOI:10.1016/j.talo.2024.100333. https://www.sciencedirect.com/science/article/pii/S266683192400047X
12. Raman spectroscopy helps create petroleum products from renewable sources. *HORIBA.* https://www.horiba.com/int/scientific/resources/spectroscopy-matters/raman-spectroscopy-helps-create-petroleum-products-from-renewable-sources/

Hydrogen Fuel and Cooling System Promises Leap in Zero-Emission Aviation

A recent study published in *Applied Energy* proposed an integrated framework for liquid hydrogen (LH_2) storage, thermal management, and transfer control for hybrid-electric aircraft. The system aims to improve fuel efficiency and balance hydrogen's dual role as a propellant and coolant, addressing storage and thermal challenges in hydrogen-powered aviation.

Image Credit: Bulent camci/Shutterstock.com

The Promise and Challenges of Hydrogen in Aviation

Aviation significantly contributes to carbon dioxide (CO_2) emissions, making hydrogen a promising alternative due to its high energy density, 2.8 times greater than conventional kerosene, and clean combustion. However, its low ambient density complicates long-haul storage.

Hydrogen is stored as a saturated liquid (70.8 kg/m3) at cryogenic temperatures to improve storage efficiency. However, full storage, thermal management, and transfer control integration remain underexplored. The Integrated Zero Emission Aviation (IZEA) project focuses on short-range hydrogen-powered aircraft for environmental sustainability.

Introducing an Efficient Storage and Transfer System

Researchers have developed a hybrid-electric aircraft with a blended wing body design, capable of carrying 100 passengers. The aircraft is powered by hydrogen fuel cells, hydrogen-fueled combustion turbines, and high-temperature superconducting (HTS) electric generators.

This configuration enhances efficiency and reduces emissions by utilizing fuel cells during low-load phases (taxiing and cruising) and combustion turbines during high-load phases (takeoff), achieving a peak power demand of 16.2 MW.

In the aircraft's prototype, LH_2 is stored in two symmetrically placed tanks near the centerline, connected to power components through counterflow pipe-in-pipe heat exchangers. These exchangers utilize supercritical helium or water as working fluids to cool systems operating between 20 K and over 300 K. Hydrogen absorbs heat before entering the fuel cells and turbines, enabling efficient energy transfer and system cooling.

Pressure Regulation and System Optimization

The study employs a novel pressure regulation strategy to maintain tank pressure slightly above the combined pressure drops across the heat exchangers and the optimal 1.3 bar fuel cell operating pressure, eliminating the need for cryogenic pumps.

Pressure is managed using hydrogen gas charging from compressed cylinders and vapor venting, with sensors providing real-time feedback to ensure stability during various flight phases.

The tanks feature an elliptical shell with half-ellipsoid end caps to optimize volume, wall thickness, and insulation, enhancing the gravimetric index (fuel mass vs. system mass). Aluminum alloy 2219 was selected for its strength and cryogenic performance, while closed-cell rigid polyurethane foam minimizes heat ingress during a 120-minute ground hold.

Heat exchangers were sized using thermal-fluid models based on temperature-dependent properties, cooling loads, and pressure constraints. System-level optimization considered vent pressures and component masses to maximize efficiency, addressing key challenges in hydrogen storage, thermal regulation, and safe delivery for zero-emission flight.

Optimized Performance: Fuel Efficiency and Thermal Regulation

The optimization showed that the maximum overall gravimetric index of approximately 0.62 was achieved at a vent pressure of 1.63 bar, slightly above the optimal pressure for the tank alone (1.36 bar). This shift highlights the importance of system-level integration, as lower tank pressures necessitated larger, heavier heat exchangers, ultimately reducing efficiency.

The system's mass breakdown indicated that LH_2 fuel accounted for 54.7% of the total system mass, followed by tank walls at 25.4%, insulation at 3.2%, heat exchangers and their insulation at 3.4%, working fluids at 1.4%, and cryogenic fans and pumps at 11.9%. Tank wall and insulation thicknesses were optimized to fit within the aircraft's fuselage constraints.

Heat exchanger designs were tailored to specific component requirements, with inner pipe diameters ranging from 3.3 cm for initial hydrogen warming to over 7 cm for fuel cells operating near 333 K. Pressure drops across exchangers were controlled to maintain tank pressure during peak flow at takeoff. The system incorporated commercially available cryofans and pumps to drive working fluids efficiently with minimal added mass.

Tank pressure regulation simulations confirmed the system's ability to manage tank pressure dynamically through gas charging and vapor venting during all flight phases, including a 40-minute taxi-out and rapid power ramp-up scenarios. Due to lower ambient temperatures, heat leakage rates decreased at cruising altitude, and vented hydrogen vapor was proposed to be redirected to fuel cells, minimizing fuel losses.

Applications in Next-Generation Aerospace Technology

The integrated LH2 storage and thermal management system significantly advances aviation. It enables efficient hydrogen storage and thermal control, supporting the development of hybrid-electric aircraft that meet environmental standards without compromising performance or safety.

Using LH2 as fuel and coolant simplifies design and weight considerations. Modular heat exchanger loops with dedicated working fluids allow for independent thermal regulation of components, addressing compatibility and thermal shock concerns.

Initially developed for regional aircraft, the system demonstrates scalability for long-range operations and facilitates integration across various aircraft configurations. Beyond aviation, this technology has potential applications in maritime and heavy-duty transport sectors.

Toward Zero-Emission Aviation

This research marks a significant step toward zero-emission aviation by integrating LH2 storage, thermal management, and transfer control. It demonstrates a scalable solution for hybrid-electric aircraft by optimizing hydrogen's dual role as a propellant and coolant. The findings highlight the significance of system-level optimization in regulating hydrogen flow, laying the groundwork for sustainable aircraft design and clean aviation technologies.

Future work should enhance heat exchanger efficiency, particularly for cooling fuel cell stacks that generate substantial heat. Refining thermal management and optimizing system architecture, including fuel storage, transfer mechanisms, and superconducting components, will further improve the feasibility of hydrogen-powered aviation. These advancements are essential for developing commercially viable zero-emission air transport.

Source:

Virdi, P, S., & *et al*. Liquid hydrogen storage, thermal management, and transfer-control system for integrated zero emission aviation (IZEA). *Applied Energy*, *126054* (**2025**). DOI: 10.1016/j.apenergy.2025.126054,
https://www.sciencedirect.com/science/article/pii/S0306261925007846