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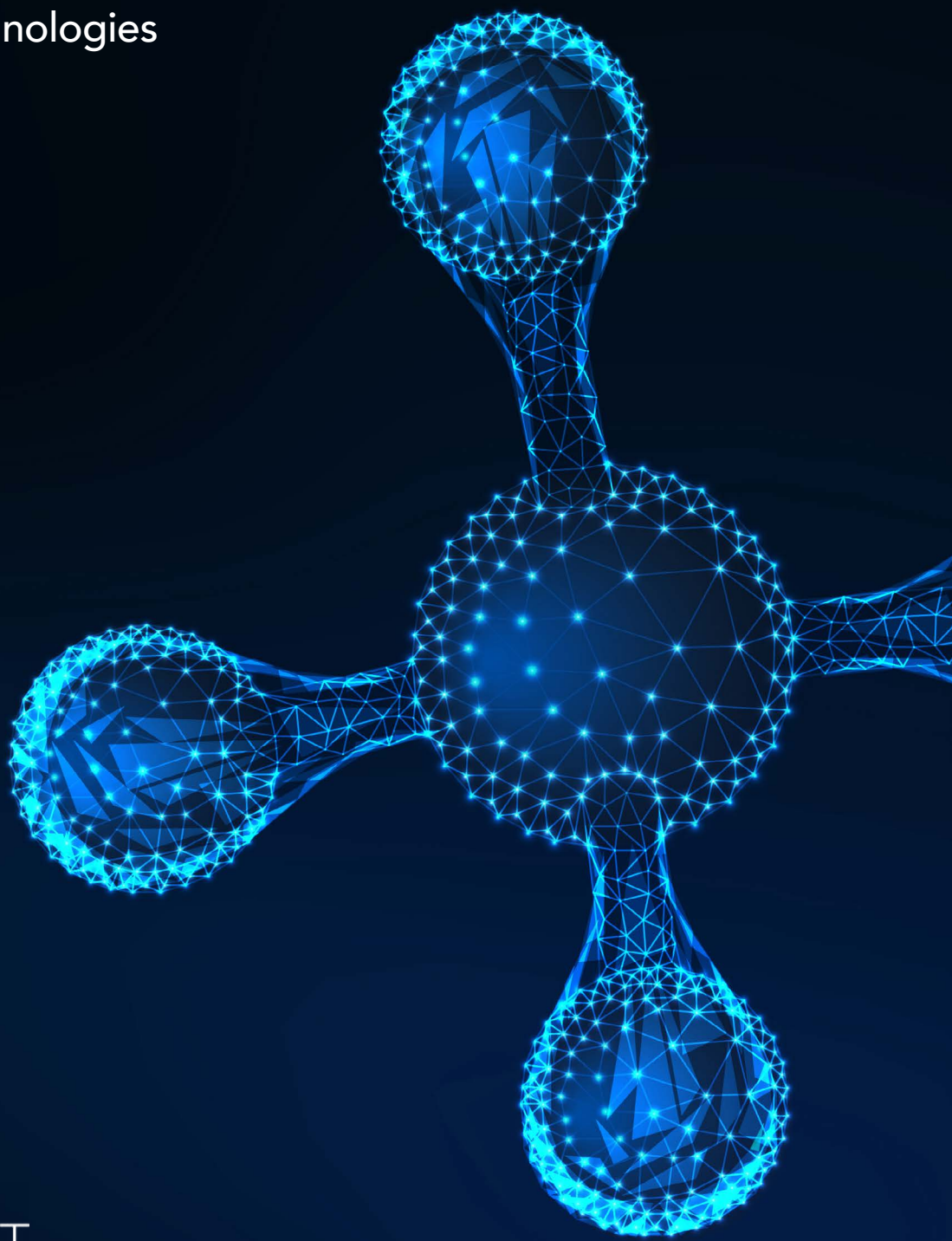
METHANE QUANTIFICATION: TOWARD DIFFERENTIATED GAS

An Assessment of Methane Measurement and Monitoring Technologies



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About COEFFICIENT

COEFFICIENT is a mission-based strategic consultancy focused on advancing public policy and market solutions in the energy and environmental sectors. Located in Washington, D.C., COEFFICIENT is a leader in developing transformational 21st century climate policies that integrate environmental sustainability and corporate governance with digital technology solutions. Learn more at www.co2efficient.com.

Technical Terms Used in Methane Detection and Measurement

The following are common terms you may encounter in discussions regarding methane detection and measurement technologies, including in this report.

ATMOSPHERIC COLUMN: The body of air above a specified area; measurements of methane are often referred to as "column measurements," "column methane," or measurement of the "methane column."

CONSTELLATION: A group of satellites that work together as a system.

GEOLOCATED: Ability to associate a device connected to the internet with a specific geographic location.

GEOREFERENCED: Ability to associate an aerial digital image or video with a specific geographic location on the ground. Also referred to as **geotagged**.

LEAK DETECTION AND REPAIR (LDAR): A set of practices designed to identify methane leaks for repair.

LIGHT DETECTION AND RANGING (LIDAR): A remote sensing method that uses light in the form of a pulsed laser to measure distances to the ground and generate precise, three-dimensional information about features on the ground. Airplanes and helicopters are the most common platforms for acquiring lidar data over broad areas.

MASS SPECTROMETRY: An analytical technique that is used to measure the mass-to-charge ratio of ions.

METHANE EMISSIONS QUANTIFICATION: An emerging set of practices for measuring actual emissions from the source (equipment, well, facility, or site) and calculating those measurements in a way that provides useful information to industry and other stakeholders, including regulators.

MINIMUM DETECTION LEVEL (MDL): Measurement of the mass of emissions over time that can be detected under optimal conditions. MDL is typically expressed in kilograms (kg) or grams (g) per hour (h). A lower MDL represents better detection capabilities.

OPTICAL GAS IMAGING (OGI): A thermal imaging technology that utilizes high sensitivity infrared cameras to detect emissions of industrial gases. OGI cameras are widely used by industry for LDAR activities.

OPTICAL SPECTROMETRY: A technique for measuring the distribution of light across the optical spectrum, from the ultraviolet spectral region to the visible and infrared.

SUPER-EMITTER: A site or piece of equipment that produces a disproportionate share of total emissions. NASA has defined a methane super-emitter as a source that produces more than 10 kilograms of methane per hour.

UNMANNED AERIAL VEHICLE (UAV): An aircraft without any human pilot, crew, or passengers; also called a drone. The Federal Aviation Administration (FAA) uses the term **unmanned aerial system (UAS)** to refer to any system that include a UAV or drone as well as a ground-based controller and/or communication system.

Introduction

The Problem: Accelerating Risk for Natural Gas

The August 2021 report by the UN Intergovernmental Panel on Climate Change (IPCC) included many dire warnings regarding global temperature rise and new policy and actions that should be taken; however, one recommendation that garnered some of the most significant attention was the panel's urgent call for action on methane emissions. The panel identified methane emissions as a fundamental driver of climate change, representing the first time a major climate report has recognized the need to address methane emissions as part of the pathway to limiting global warming.

Even before the report's release, several governments were already accelerating new regulations to tackle methane. An early draft of legislation in Europe states that "the EU will consider enforcing an effective stop of all routine venting and flaring in the EU energy sector by 2025". The actual proposal, released in December 2021, would in fact ban venting and flaring practices except in narrowly defined circumstances. The proposal also would require companies to measure and quantify their asset-level methane emissions at source and carry out comprehensive surveys to detect and repair methane leaks in their operations. With regard to natural gas imports, the proposal will require importers to provide detailed information about methane emissions measurement, reporting, and verification (MRV) and calls for consideration of stronger measures to restrict fossil fuel imports in 2025. (More information about the proposal can be found here.)

In the U.S., the Environmental Protection Agency (EPA) is currently developing new, more ambitious regulation of methane leaks from the oil and gas industry that are expected to be released this fall. Several states, including Colorado and New Mexico are already implementing regulation on methane. The U.S. Congress has flirted with the idea of imposing a fee on methane emissions as soon as 2023, regardless of EPA's action. And, the U.S. Securities and Exchange Commission (SEC) is expected to release a new rulemaking on climate disclosures and ESG risks in 2022, after receiving over 5,500 comments on the topic last year. Environmental groups have called for at least a 50% reduction in U.S. methane emissions by 2030.

With these and other actions, it has become clear that risk for natural gas is accelerating. Nonetheless, with emerging technologies, the oil and gas industry has an opportunity to reimagine the future of natural gas in ways that promote transparency, trust, and transactability in differentiated gas markets.

The Vision: Transparency, Trust, Transactability

The current environment has created a compelling leadership opportunity for the oil and gas sector to get ahead of regulator and investor expectations on methane emissions through quantification and reduction. A small number of companies are already pursuing this opportunity by adopting three principles for methane emissions measurement, monitoring, reporting, and verification, namely: Transparency, Trust, and Transactability.

Transparency begins with a recognition that companies must go beyond leak detection and repair to quantification of methane emissions. This will necessarily involve making accurate, granular measurements and frequent monitoring. To achieve transparency of methane emissions, companies will need to understand the measurement capabilities of various technologies; pilot and deploy technologies to measure emissions; and create a baseline emissions measurement against which to compare future reductions.

Trust involves ensuring that regulators, investors, and other stakeholders have confidence in emissions data and can rely on such data to make policy and investment decisions. This will require verification of emissions data not just by industry or environmental NGOs, but by independent third parties or data platforms. To achieve trust, companies can identify and work with third parties to validate emissions measurements. In addition, all stakeholders will need to come to consensus about standard baseline emissions measurement methodologies (which in the near term could be a "hybrid" of measurements and emissions factors as proposed by the GTI Veritas program) and standards for reporting baseline emissions and regular updates.

Transactability means that customers can buy and sell products based on emissions data, ultimately creating new markets for differentiated gas products. This will require that data is interoperable across multiple systems and the development of standard, secure certification processes for products.

Development of a framework that promotes strong performance metrics for all segments of the gas supply chain and a market for differentiated natural gas must connect the dots between transparency, trust, and transactability. A strong and robust future for natural gas will require high quality data and rigorous MRV to gain credibility in the eyes of NGOs and policymakers. In addition, it will require the integration of methane emissions data with financial performance data that can help provide the currently missing link between ESG reporting and data-driven climate accounting.

We have an opportunity to ensure a strong future for natural gas with real emissions reductions, consumer trust, and new markets for differentiated products. This assessment addresses a critical piece of achieving this future.

How Do We Get There?

Experts have noted that there are at least 600,000 methane leaks in the U.S. today, and even this large number may represent an undercount.[1] Up until recently, most companies have focused on leak detection and repair (LDAR)—an undoubtedly worthy goal, but not one that results in a full picture of a site's emissions.

Quantifying emissions is challenging because there are so many potential point sources—myriad facilities, equipment, and small components of equipment at each site. How can companies measure these potential sources in an accurate, timely, and cost-effective way?

Traditional approaches for LDAR have typically involved optical gas imaging (OGI) cameras that provide a visual of methane leaks at various resolutions and distances. However, the shift from LDAR to measurement will require more sophisticated sensors that do not only detect, but also quantify methane emissions.

Sensor technologies have expanded rapidly in recent years and promise to enable increasingly cost-effective methane solutions. Sensors are generally mounted or integrated with other technologies, and these technologies each have strengths and limitations for measuring methane emissions.

Scope of this Tech Assessment

This assessment reviews leading and emerging technologies that are being deployed with sensors for methane measurement and monitoring, specifically:

[1] Cate Haight, "The Fight Against Methane," *Columbia Energy Exchange podcast*, July 13, 2021, https://www.energypolicy.columbia.edu/fight-against-methane.

1. The measurement capabilities of various technology categories;
2. How specific technologies have been piloted or deployed in the field; and
3. Leading technology initiatives that have integrated multiple technologies, and in some cases, implemented approaches for independent verification of emissions and certification of differentiated gas.

This assessment will describe six technology categories and more than 30 detailed profiles of leading methane emissions technologies.

This assessment also highlights "Technologies in Action"— leading technology initiatives where multiple stakeholders have collaborated to integrate multiple measurement and monitoring technologies in the field and validate the resulting data for use in reporting and certification.

Profiles of Technology Providers and Initiatives

The profiles focus on leading technology solutions and collaborative projects specifically focused on measuring and monitoring methane emissions. Technology solutions typically include a hardware component (sensor and other devices or vehicles) and a software component (data analytics and cloud-based platforms). In many cases, images are gathered by hardware and then analyzed by software to quantify methane.

This set of profiles may not include every possible technology provider, but seeks to assess leading, known, and emerging technologies that may be of interest to oil and gas companies. We reviewed a number of additional companies for which there was a lack of quality information available in the public domain, including: Aerometrix, Luxmux, Modis, Nevada Nano, Oiler, Surface Solutions, Orbital Sidekick, and others. These companies and technologies were excluded from this assessment but may be revisited in a future phase of this project.

The profiles are organized into six technology categories. For each category we have assessed the overall strengths and weaknesses, which reflect industry and stakeholder learnings to date about the most effective ways to deploy technologies from each category.

All profiles are organized in a template, by category and alphabetical within categories. Each profile generally includes information outlined in TABLE 1. A summary of the profiles included in this assessment are listed in TABLE 2.

TABLE 1
Information Provided in Each Profile

Field	Description
NAME(S) AND LOCATION	Name of the company and/or technology and location of headquarters or operations
PARTNERS OR INVESTORS	High-profile organizations involved in funding or piloting/deploying the technology
TECHNOLOGY DESCRIPTION	Description of the technology, its key functionality, and its state of development or deployment
NOTEWORTHY TECHNICAL SPECIFICATIONS	Key technical specs, including minimum detection level (MDL), if available and other relevant performance specifications[2]
NOTEWORTHY DISTINCTIONS	Any additional details that differentiate the technology from others in the category or across categories
RECENT PROJECT(S)	High-profile projects where the technology has been tested or deployed (if any)

[2] Note that in this Tech Assessment, the technical specifications listed are publicly available information and may not have been validated in the field.

TABLE 2
Summary of Profiles

Category	#	Profiles	
SATELLITES	9	• Bluefield • GHGSat • JAXA GOSAT • MERLIN • MethaneSAT	• NASA Geocarb • PRISMA • Satlantis • TROPOMI
AIRCRAFT	4	• Ball Aerospace • Bridger Photonics	• Kairos Aerospace • Scientific Aviation
DRONES	4	• ABB HoverGuard • Baker Hughes LUMEN Sky	• Scientific Aviation • SeekOps
MOBILE (OTHER/CROSS-CUTTING)	5	• Aeris • LaSen • mAIRsure	• Picarro • University of Calgary PoMELO
HANDHELD	3	• Distran • Providence Photonics • Sensia Solutions	
STATIONARY	12	• Baker Hughes LUMEN Terrain • Cleanconnect.ai • Honeywell Rebellion GCI • Kuva Systems • Longpath Technologies • MIRICO	• Sensirion Nubo Sphere • Project Canary • QLM Technology • Quanta3 • Sensia Solutions • Scientific Aviation SOOFIE
TOTAL	**37**		

Satellites

Satellites are typically used for frequent, low-cost measurements over large areas. They are often used to identify super-emitters, monitor facilities over time, and verify other sources of methane estimates or measurements. Several satellites specifically focused on or relevant for methane are already in operation or planned for launch in the next few years. Sensors on satellites measure methane in the total atmospheric column; they are typically not able to identify a specific emissions source.

TABLE 3 highlights the overall strengths and limitations of satellites.

TABLE 3
Satellites: Strengths and Limitations

Strengths	Limitations
• Most satellites are operated by governments and/or nonprofits, and as a result, the data collected is publicly accessible • Satellites are useful for identifying (and/or verifying) large emissions sources, including super-emitters • Satellites enable very wide area surveys • Some satellites make daily observations	• The granularity of data from satellites is relatively low because of their distance from the ground • Satellites are more limited in detecting smaller emissions sources and have limited capabilities for localizing the source of emissions • The timeliness of data availability varies by technology; it is often several days before data is available

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Field	Description
NAME	Bluefield Technologies
HQ/LOCATION	Palo Alto, CA
PARTNERS/INVESTORS	• Ground Squirrel Ventures • Operator Partners, an early-stage venture capital firm • Unshackled Ventures
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Bluefield is a startup developing "CubeSats," backpack-sized microsatellites with optical sensors to detect methane. The company was founded in 2016 and as of 2019 had raised a total of $2.5M. Bluefield plans to build 22 satellites and develop other infrastructure including sensors and an artificial intelligence (AI) platform that would provide monitoring and analytics for methane emissions. The start-up is in a prototype stage and plans its first launch in 2022. Bluefield also has developed a data algorithm and analysis tool called BFX-2 that analyzes data from other satellites.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 70 kg/h (according to the *Carbon Limits* report) The company claims that its satellite will offer 20 m precision (compared to 20 km precision offered by Tropomi)
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	In 2020, Bluefield's BFX-2 tool was used to identify a significant methane leak in Florida.

Field	Description
NAME	GHGSat
HQ/LOCATION	Montreal, Canada
PARTNERS/INVESTORS	• ABB • Chevron • ExxonMobil • Investissement Quebec, a business and financial consultancy for companies in Quebec • Oil and Gas Climate Initiative (OGCI) • Space Capital • Shell • Total
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	GHGSat provides high-resolution remote sensing of GHGs from space. It currently operates three satellites that measure greenhouse gases (including methane): GHGSat-D or Claire (launched in 2016); GHGSat-C1 or Iris (launched in 2020); and Hugo (launched in January 2021). Iris represents the first satellite of a larger "constellation" that will include up to 10 satellites by the end of 2022. GHGSat uses sensors with a resolution 100X higher than any other satellite today. A 2020 paper published by authors from Harvard University states that GHGSat has the highest spatial resolution and spectral resolution of any satellite, so that "to this day GHGSat-D remains the only gas sensing satellite with such high spectral and spatial resolution." It is the leading example of a satellite designed to measure large emission sources from specific point sources.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 1,000 kg/h for Claire; 70-250 kg/h for Iris (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	In February of 2021, GHGSat was able to identify leaks from at least eight natural gas pipelines and unit flares, which if gone undetected would have had the same impact as 250,000 gasoline-powered cars. In October 2020, GHGSat announced that Iris had detected the smallest methane emission to date from space, a controlled release from a facility in Alberta, Canada with an emissions rate of 260 kg/h.
RECENT PROJECT(S)	GHGSat has partnered with Shell, Chevron, and Total Energies SE to track methane emissions from offshore oil and gas platforms in the North Sea and the Gulf of Mexico. GHGSat has also signed an agreement with ABB to deliver the payloads – the component of a satellite responsible for its communication functions – for the satellite companies next three methane satellites. In 2020, ExxonMobil announced it is conducting field trials of eight emerging methane detection technologies, including GHGSat, at nearly 1,000 sites in Texas and New Mexico.

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Field	Description
NAME	NASA Geostationary Carbon Observatory (GeoCarb)
HQ/LOCATION	NASA Jet Propulsion Laboratory, Pasadena, CA
PARTNERS/INVESTORS	• Colorado State University • Lockheed Martin Advanced Technology Center • SES Government Solutions Company, a provider of commercial satellite communication solutions to the U.S. government • University of Oklahoma
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	GeoCarb is a space-based mission for NASA's Earth Science Division that will use a satellite flying in "geostationary orbit" to map daily concentrations of carbon dioxide, methane, and carbon monoxide over North America and South America. The satellite will contain a spectrometer instrument developed by Lockheed Martin and the University of Oklahoma that measures the wavelengths of incoming light to determine the composition of gas. It is expected to launch in summer 2022 and stay in orbit for three years.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 4,000 kg/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	NASA states that GeoCarb will be GeoCarb will be the first U.S. satellite to measure methane near Earth's surface.
RECENT PROJECT(S)	

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Field	Description
NAME	Japan's GOSAT and GOSAT-2 (also called Ibuki and Ibuki-2)
HQ/LOCATION	• Japan Aerospace Exploration Agency (JAXA), Tokyo, Japan • Ministry of the Environment (MOE), Tokyo, Japan • National Institute for Environmental Studies (NIES), Tsukuba, Japan
PARTNERS/INVESTORS	• Mitsubishi Electric Corporation
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	GOSAT was the world's first satellite mission dedicated to GHG monitoring. Its mission is to monitor the global distribution of GHGs, estimate CO2 sources and sinks on a sub-continental scale, and verify GHG emissions reductions The mission also aims to observe methane on the same spatial and temporal scales as CO2 and with an accuracy higher than 2%. The first GOSAT (Ibuki) was launched in 2009; it had a planned operational period of five years but was extended in 2014 and is still operating today. GOSAT-2 (Ibuki-2) was launched in 2018 with improved measurement precision. Japan is currently working with Mitsubishi to develop instruments for the GOSAT-GW (formerly known as GOSAT-3) including a new sensor for more accurate observation of GHG concentrations. The new satellite will also have enhanced geophysical quantity observation for improved water cycle and meteorological monitoring. GOSAT-GW is expected to launch in 2023 or 2024.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 7,100 kg/h for GOSAT; 4,000 kg/h for GOSAT-2 (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	GOSAT measures CO2 and methane from 56,000 locations on the Earth's surface, including the atmosphere over open seas.
RECENT PROJECT(S)	In 2019, the World Meteorological Organization's World Data Centre for Greenhouse Gases began posting GHG data from GOSAT; the data can be accessed here.

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Field	Description
NAME	Methane Remote Sensing Lidar Mission (MERLIN)
HQ/LOCATION	• German Aerospace Center (DLR), Cologne, Germany • National Centre for Space Studies (CNES), Paris, France
PARTNERS/INVESTORS	• Ferdinand-Braun-Institut, a research institute in Berlin • Fraunhofer Institute for Laser Technology, a research institute in Aachen, Germany focused on lasers and optics
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	MERLIN is a satellite under development by German and French space agencies focused on global methane emissions. It is expected to be the first lidar in space for the measurement of GHGs, and is expected to launch in 2024 or 2025 and operate for at least three years. Its Methane Integrated Path Differential Absorption (IPDA) lidar will fire laser beams towards Earth's surface and then analyze the signal bounced back to deduce the amount of methane in the sounded atmospheric column. Germany is developing and building the methane Light Detection and Ranging (LIDAR) instrument, and France is providing the satellite platform and the satellite control center.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	

MethaneSAT™

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Field	Description
NAME	Environmental Defense Fund (EDF)'s MethaneSAT
HQ/LOCATION	Austin, TX
PARTNERS/INVESTORS	• Ball Aerospace • Blue Canyon Technologies • Harvard University • Smithsonian Astrophysical Observatory (SAO) • Rocket Lab, an American aerospace manufacturer and launch service provider that will manage, and operate the Mission Operations and Control Center (MOCC) for MethaneSAT in Auckland, New Zealand • SpaceX • New Zealand Ministry of Business, Innovation, and Employment (MBIE), which includes the New Zealand Space Agency
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	EDF is currently developing MethaneSAT, a satellite focused on providing regular monitoring (intervals under seven days) of approximately 50 major regions accounting for more than 80% of global oil and gas production. The satellite is expected to have the capability to identify the location of methane emissions and quantify the emissions rate. It is expected to cover a 200-kilometer (124-mile) view path, passing over target regions every few days; detect methane concentrations as low as 2 parts per billion (ppb); and focus in on areas as small as 100 m. Data collected will be transmitted back to Earth and processed using an analytical software platform that will make data available in days rather than weeks or months. All data will be available to the public at no cost. MethaneSAT is currently on schedule for a launch window that opens October 1, 2022. In 2021, MethaneSAT announced a contract with SpaceX to deliver its satellite into orbit aboard a Falcon 9 rocket.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 200 kg/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	While other satellites typically either identify emissions across large geographic areas or measure them at predetermined locations, MethaneSAT will do both.
RECENT PROJECT(S)	

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Field	Description
NAME	PRecursore IperSpettrale della Missione Applicativa (PRISMA)
HQ/LOCATION	• Italian Space Agency Fucino Space Centre, Ortucchio, Italy (mission control center) • Italian Space Agency Matera Space Center, Matera, Italy (data acquisition and image data processing)
PARTNERS/INVESTORS	• European Space Agency (ESA) • Leonardo, Italian technology developer for aerospace, defense, and industrial equipment) • OHB-Italia, a major European satellite systems integrator
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	PRISMA is the Italian Space Agency's (ASI) first hyperspectral spacecraft that was launched into orbit in 2019 onboard the VEGA rocket, jointly built by the Italian and European Space Agency (ESA). The satellite contains two instruments, a hyperspectral sensor with a medium-resolution panchromatic camera (sensitive to all colors of light), both of which are intended for environmental monitoring, pollution control, crop classification, and natural resources management. These instruments enable the satellite to distinguish both the characteristics of observed objects and trace the chemical-physical composition of the area under observation. The PRISMA mission was initially conceived by the ASI to test Italian-made hyperspectral space sensor technologies, and not intended for specific applications for methane emissions monitoring. Although PRISMA has the potential to map methane point emissions, the dedicated applications to detect and quantify methane plumes has only been extrapolated through scientific studies thus far. Researchers have studied imagery and datasets (satellite imaging spectroscopy data) derived from the PRISMA satellite to isolate individual sources of methane in the Permian Basin. This data is not publicly available on a database, but users can request data through the PRISMA portal.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Data extrapolated from PRISMA in this study identified methane with emissions rates >500 kg/h
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	In a June 2021 study conducted by researchers from Harvard University, California Institute of Technology, Environmental Defense Fund, and several European academic and research, analysis of imagery from the PRISMA satellite revealed methane hotspots in the Permian Basin.

SATLANTIS

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Field	Description
NAME	GEI-SAT Precursor
HQ/LOCATION	Bilbao, Spain (Originally founded in Gainesville, FL)
PARTNERS/INVESTORS	• AXIS-ICO, Spain-based venture fund for start-up technologies • Basque Government and Bizkaia Government • Centre for the Development of Industrial Technology (CDTI), a government agency supporting technology development in Spain • Firefly Aerospace, a Texas-based provider of launch vehicles, spacecraft, and in-space services • Enagas, a Spanish natural gas company • ORZA, Basque pension fund-based investment firm • Sepides, a Spanish state holding company promoting energy entrepreneurship • Science and Innovation Link (SILO), Spanish consulting firm for technology innovation • University of Florida
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	GEI-SAT Precursor is intended to be the first of a constellation of satellites dedicated to methane detection and quantification being developed by the Spanish start-up company Satlantis. The firm develops satellite payload technologies for Earth observation and remote sensing. The GEI-SAT Precursor will employ Satlantis's proprietary iSIM technology, a multispectral binocular imaging camera that allows for concurrent observations in the visible, near-infrared (VNIR) and shortwave-infrared (SWIR) spectral ranges, which in combination, provide more precise geolocation and accurate identification of methane emission sources, according to the company. The technology can be provided in microsatellite and CubeSat formats. The GEI-SAT Precursor is under development and expected to launch in Q3 2023; it will be the company's fifth satellite flight.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	In March 2021, Satlantis closed its second investment round (14 million Euros) headed by Enagás and accompanied by current investors AXIS-ICO and ORZA, among others. In November 2021, CDTI joined the investment round with an additional 3.5 million Euros.
RECENT PROJECT(S)	

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Field	Description
NAME	European Space Agency and Netherlands Space Office Copernicus Sentinel-5 Precursor (S5P) with the TROPOspheric Monitoring Instrument (TROPOMI)
HQ/LOCATION	Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
PARTNERS/INVESTORS	• Airbus Defense and Space • California Institute of Technology • German Aerospace Center (DLR) • Max Planck Institut, a research institute in Munich, Germany • Netherlands Institute for Space Research (SRON) • National Aeronautics and Space Agency (NASA) • Norwegian Institute for Air Research (NILU) • Royal Belgian Institute for Space Aeronomy (BIRA-IASB) • Royal Netherlands Meteorological Institute (KNMI) • S[&]T Corp, a data solutions company in Europe • Science and Technology Facilities Council, a government research agency in the UK • University of Breman, Germany
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	TROPOMI is an advanced multispectral imaging spectrometer that monitors methane and other gases, aiming provide methane column concentrations with high sensitivity to the Earth's surface, good spatiotemporal coverage, and sufficient accuracy to facilitate inverse modeling of sources and sinks. The satellite makes global observations daily, and data is available within a few days. TROPOMI was launched in 2017 with a planned mission of seven years. TROPOMI's data is cross-referenced and validated by NASA with data from JAXA's GOSAT and the ground-based Total Carbon Column Observing Network (TCCON) at the California Institute of Technology. All TROPOMI data can be accessed here. Methane data from the satellite can be accessed here.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 4,200 kg/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	A 2020 study authored by scientists from Environmental Defense Fund (EDF), Harvard University, Georgia Tech, and the Netherlands Institute for Space Research (SRON) quantified methane emissions from the Permian Basin using TROPOMI satellite data.

Aircraft

Manned aircraft, ranging larger multi-engine research planes, to small single-engine general aviation aircraft can fly at different altitudes and have a long range. High altitude flights can target large areas while low altitude flights can detect and measure methane from a point source.

TABLE 4 highlights the overall strengths and limitations of aircraft.

TABLE 4
Aircraft: Strengths and Limitations

Strengths	Limitations
• Aircraft can cover wide areas, often in a single day	• Most data collected by aircraft is proprietary and not accessible to the public • Accuracy can be significantly affected by weather conditions, including clouds and wind speed • Aircraft surveys are typically done bi-annually or quarterly • Aircraft have limited capabilities for localizing the source of emissions

Ball Aerospace

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Field	Description
NAME	Ball Aerospace Methane Monitor
HQ/LOCATION	Boulder, CO
PARTNERS/INVESTORS	• Carina RST • Environmental Defense Fund (MethaneSAT)
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	The Ball Aerospace Methane Monitor uses lidar attached to a fixed-wing aircraft to gather atmospheric column measurements of methane. According to the company, the technology works regardless of cloud conditions and can survey up at least 100 square miles of production sites or approximately 375 miles of transmission pipelines each day. The flight data is geolocated and provided in near real time; some data is processed on board to allow for real-time alerts regarding large emission sources and full results are delivered within 24 hours.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 9-12 kg/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	Ball Aerospace is also developing the spectrometer-based sensing system for MethaneSAT (see profile in the *Satellites* section).
RECENT PROJECT(S)	In 2018, Ball Aerospace announced it would provide its methane monitoring technology and data analytics tools exclusively to Denver-based Carina RST, a company offering methane monitoring as a service to oil and gas producers.

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Field	Description
NAME	Bridger Photonics Gas Mapping Lidar
HQ/LOCATION	Bozeman, MT
PARTNERS/INVESTORS	• ARPA-E • Collaboratory to Advance Methane Science (CAMS), an industry-led research collaboration administered by the Gas Technology Institute • ExxonMobil • Massachusetts Institute of Technology (MIT) • SoCalGas
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Bridger Photonics offers a "Gas Mapping Lidar" technology for aerial surveys of oil and gas infrastructure, including production facilities and other infrastructure. Data and images are captured during the aerial surveys and then processed using proprietary algorithms to quantify emissions and identify the source, down to the equipment level. Bridger Photonics operates across North America in the Permian Basin, Alberta, Eagle Ford Basin, Denver-Julesburg area, and with distribution utilities across the U.S.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Some technical results from the August 2021 CAMS study of Bridger Photonics' Gas Mapping Lidar technology can be found here. The company claims to have achieved an MDL of <3 kg/h in the CAMS study.
NOTEWORTHY DISTINCTIONS	In April 2021, following field trials, ExxonMobil subsidiary XTO Energy selected Bridger Photonics Gas Mapping Lidar for the first application to the EPA Alternate Means of Emissions Limitation (AMEL) under Subpart OOOOa. The AMEL provision allows an entity to petition the EPA to allow an alternative compliance approach to a federal air standard provided that the proposed alternative achieves equivalent or greater emissions reduction relative to the existing standard. Bridger Photonics and MIT were winners of the 2019 R&D100 award for the Gas Mapping Lidar technology. The Gas Mapping Lidar technology was developed with $2.5 million in support from ARPA-E's MONITOR program from 2015 to 2018. The technology was also awarded $4.6 million under ARPA-E's SCALEUP program in 2020.
RECENT PROJECT(S)	In August 2021, SoCalGas signed a $12 million agreement with Bridger Photonics to "detect, localize, and quantify" methane emissions across its distribution area.

KAIROS AEROSPACE

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Field	Description
NAME	Kairos Aerospace LeakSurveyor
HQ/LOCATION	Mountain View, CA
PARTNERS/INVESTORS	• Data Collective Venture Capital (DCVC) • DCP Midstream • Energy Innovation Capital • ExxonMobil • John Crane, an engineering technology firm • Oil and Gas Climate Initiative (OGCI) • Pioneer Natural Resources
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Kairos Aerospace offers a hyperspectral imaging system mounted on a small aircraft called LeakSurveyor. The system uses sensors and an optical camera to map a region. Kairos can survey up to 100 square miles per plane, per day (Kairos uses nine planes, as of February 2021). The technology provides georeferenced methane emissions data, including a digital map or aerial photo of the ground basin or facility tied to geographic coordinates. This digital imagery is combined with real-time optical imagery to identify the source of the emissions and assist in quantification. The technology can be used for upstream, midstream, and downstream oil and gas surveying. Kairos has worked in North America, including in the Permian Basin, Rockies Basins, Midcontinent Basins, and Western Canadian Basins.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 46-52 kg/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	In August 2021, Kairos announced that it had raised an additional $26 million in funding from DCVC, OGCI, and other investors. In 2020, ExxonMobil announced it is conducting field trials of eight emerging methane detection technologies, including Kairos, at nearly 1,000 sites in Texas and New Mexico. In 2020, the Society of Petroleum Engineers published a case study of Kairos Aerospace's work with Pioneer Natural Resources. In 2018, Kairos was selected to participate in EDF's methane detector challenge but was unable to conduct testing due to flooding at its test site that would have severely impacted the capability of its sensor system.
RECENT PROJECT(S)	The company provides data in their technical white paper showing how during 2019 and 2020, they inspected more than 136,000 wells and over 42,000 miles of pipeline in North America, resulting in the elimination of more than 8 billion cubic feet of methane emissions.

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Field	Description
NAME	Scientific Aviation
HQ/LOCATION	Boulder, CO
PARTNERS/INVESTORS	• California Air Resources Board (CARB) • Environmental Defense Fund (EDF) • ExxonMobil • National Oceanic and Atmospheric Administration (NOAA) • United Nations Environment Programme (UNEP) and Climate and Clean Air Coalition (CCAC) • University of Michigan Scientific Aviation is participating in the PermianMap project (see *Technologies in Action* section of this report). ChampionX acquired Scientific Aviation in July 2021.
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Scientific Aviation operates four fixed-wing aircraft that have been specifically configured for atmospheric measurements and emissions quantifications of methane and other greenhouse gases. The company offers measurements to trace methane, and other complementary measurements including wind speed and direction, temperature, humidity, 3-dimensional location, and time. Data are transmitted to an onboard computer system where Scientific Aviation's custom software compiles, stores, and displays the data in real time. All data is also continuously uploaded and stored to the company's cloud-based data repository.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 2-5 kg/h (as provided by the company, according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	Scientific Aviation is partnering with the UNEP/CCAC and EDF to undertake "a first-of-its-kind group of studies that will provide top-down quantification of methane emissions from the energy sector in Europe and North Africa." The initial three projects will be in the Norwegian North Sea, Romania, and Algeria. The public can track the flights for this program here.
RECENT PROJECT(S)	California Air Resources Board (CARB) contracted with Scientific Aviation to conduct airborne methane emissions quantifications at a variety of target sites, including industrial, agricultural, and waste sources. The company made 199 measurements at 114 different target sites between November 2019 and February 2021. Results of the surveys can be found here. In 2020, ExxonMobil announced it is conducting field trials of eight emerging methane detection technologies, including Scientific Aviation aircraft, at nearly 1,000 sites in Texas and New Mexico. In 2016, Scientific Aviation was contracted to collect point source measurements of the Aliso Canyon Gas Leak in Southern California.

Drones

Unmanned aerial vehicles (UAVs) or drones can typically measure methane in three dimensions, including methane concentrations in the vertical atmospheric column within a methane plume. In addition, some can calculate wind speed and direction enabling more data for calculations.

TABLE 5 highlights the overall strengths and limitations of drones.

TABLE 5
Drones: Strengths and Limitations

Strengths	Limitations
• Drones can identify large and small emissions sources • Drones can safely get physically closer to evaluate a potential emissions source compared to larger vehicles • Drones can cover a moderately large area in a short amount of time • Data collected is typically available in real time or near real time	• Most data collected by drones is proprietary and not accessible to the public • Drone surveys are typically done bi-annually or quarterly • Drones are not typically operated autonomously and require personnel to operate, potentially creating safety issues • Drones may be prohibited in certain sensitive or restricted facilities or areas of a site

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Field	Description
NAME	ABB HoverGuard
HQ/LOCATION	Zurich, Switzerland
PARTNERS/INVESTORS	• Anemoment, Colorado-based air monitoring equipment manufacturer • ZICOM Group, Singapore-based engineering and equipment specialist firm
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	ABB, a global technology solutions company, offers four technologies for methane leak detection, including handheld, stationary, and mobile (car-mounted and drone-mounted) technologies[3]. The company's HoverGuard solution is a drone-based solution for detection, monitoring, and quantification of methane and carbon dioxide emissions from natural gas distribution and transmission pipelines, storage facilities, and other sources along the natural gas value chain. The sensor that detects emissions activity uses a patented laser-based technique called cavity-enhanced laser absorption spectroscopy. The UAV from which the technology operates is also retrofitted with a Global Navigation Satellite System (GNSS) that provides data on location, navigation, and timing of emissions, a sonic anemometer provided by Anemoment used to profile wind speed and frequency, and a gas analyzer to measure gas concentrations. The data collected by the drone is connected to a cloud system to relays information on the source location and size of the leak in real time. The patented algorithms in ABB's proprietary software provide estimates of leak origin and emissions volumetric flow rate calculated and other relevant emissions measurements.
NOTEWORTHY TECHNICAL SPECIFICATIONS	HoverGuard can detect leaks 100 m from the source
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	HoverGuard was launched in April 2021, and ZICOM, ABB's partner in the South Asia region for testing its Mobile Gas Leak Detection solutions, noted in a July 2021 article that they are "keen to explore the speed of inspection" of the technology in Bangladesh.

[3] Based on our analysis of publicly available information regarding the various ABB technologies, it is not clear that all are able to measure and quantify emissions. The scale and maturity of ABB's stationary technology (EverGuard) is also unclear. The capabilities of HoverGuard are more clearly delineated, and therefore we have chosen to include a profile for HoverGuard and exclude profiles for the other technologies. Additional ABB technology profiles may be reconsidered in a future phase of this project.

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Field	Description
NAME	LUMEN Sky
HQ/LOCATION	Houston, TX
PARTNERS/INVESTORS	• Oklahoma State University • Shell
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	LUMEN Sky is an aerial, drone-based system for methane monitoring. It is part of an integrated LUMEN system that also includes LUMEN Terrain, a ground-based, stationary, continuous monitoring device. These technologies are operated by Avitas, a Baker Hughes venture. LUMEN Sky gathers data and images that are then processed to identify, localize, and quantify methane emissions. According to the company, surveys may be conducted quarterly or every other month to optimize data collection and actionable results.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 61 g/h (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	Since 2018, Shell has used LUMEN Sky in the Permian Basin, conducting over 500 test flights.

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Field	Description
NAME	Scientific Aviation
HQ/LOCATION	Boulder, CO
PARTNERS/INVESTORS	• ConocoPhillips • Environmental Defense Fund (EDF) • Neptune Energy • Texo DSI, UK-based drone platform provider Scientific Aviation was acquired by ChampionX in July 2021
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Scientific Aviation offers quadcopter and hexacopter platforms for drone-based aerial surveys. The drones are equipped with sensors to analyze methane/ethane from point sources as well as wind, temperature, relative humidity, and pressure. The drones are controlled remotely using an app, and data and images are available in real-time. Scientific Aviation also uses a proprietary software platform to process data.
NOTEWORTHY TECHNICAL SPECIFICATIONS	• MDL: 10 g/h (according to the *Carbon Limits* report) • Accuracy: 20-50% (according to "field experience from an independent party" as reported in the *Carbon Limits* report) • Detection distance: 1-20 m (according to the *Carbon Limits* report)
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	In 2021, Scientific Aviation's drone technology was deployed in the North Sea with Texo DSI for a methane quantification study on an offshore gas production facility operated by Neptune Energy, a UK-based oil and gas production company. In 2019, Scientific Aviation partnered with ConocoPhillips on drone field-testing at the Eagle Ford site in Texas.

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Field	Description
NAME	SeekOps
HQ/LOCATION	Austin, TX
PARTNERS/INVESTORS	• BP • Caterpillar Venture Capital • Environmental Defense Fund (EDF) • Equinor and Equinor Technology Ventures • ExxonMobil • FlyLogix • Harbour Energy, a UK-based oil and gas company • Neptune Energy • OGCI Climate Investments • Schlumberger • Shell • Sky-Futures, a global drone inspection and survey provider • Total
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	SeekOps offers the drone-agnostic SeekIR sensor, which uses laser absorption spectrometry to measure in-plume concentrations. The technology is capable of detecting, localizing and quantitating methane emissions using SeekOps' proprietary machine learning algorithms and data analytics.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: 22 g/h
NOTEWORTHY DISTINCTIONS	In July 2021, SeekOps closed $14 million in new funding from Schlumberger, Equinor Ventures, OGCI Climate Investments, and Caterpillar Venture Capital. According to the *Carbon Limits* report, SeekOps' results from the EDF methane detector challenge show that SeekOps detected 100% of leaks in all leak classes and did not have any false positive detection. However, the uncertainty of the quantification was higher than the technical specifications and may have a bias towards overestimation.
RECENT PROJECT(S)	In 2020, ExxonMobil announced it is conducting field trials of eight emerging methane detection technologies, including SeekOps, at nearly 1,000 sites in Texas and New Mexico. In 2020, SeekOps and FlyLogix achieved a significant milestone in field testing of offshore production in the North Sea; the technologies demonstrated measurement of an emissions rate of <2.5 kg/h, lower than the stretch goal of 3 kg/h for the project. The project is supported by bp, Total, Equinor, Harbour Energy, and Shell.

Mobile Technologies (Other/Cross-Cutting)

Many sensors can be used in a variety of mobile applications, including specific aerial applications described above, as well as with ground-based vehicles (cars, trucks, vans). Ground-based mobile surveys are typically limited by available roads downwind from the site or source of methane. Operators also highlight potential safety issues from driving vehicles around sites.

TABLE 6 highlights the overall strengths and limitations of sensors attached to ground vehicles. However, note that the sensors described in this section may also be attached to other types of vehicles.

TABLE 6
Ground Vehicles: Strengths and Limitations

Strengths	Limitations
• Ground vehicles can identify smaller emissions sources • Ground vehicles can cover a moderately large area in a short amount of time • Data collected is typically available in real time or near real time	• Most data collected by ground vehicles is proprietary and not accessible to the public • Ground vehicles may require multiple passes over an area to achieve the same coverage as an aircraft or satellite, or even a drone • Ground vehicles require a driver, potentially creating safety issues • Ground vehicles may be prohibited in certain sensitive or restricted facilities or areas of a site

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Field	Description
NAME	Aeris Technologies MIRA
HQ/LOCATION	Hayward, CA
PARTNERS/INVESTORS	• ARPA-E Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) program • Los Alamos National Laboratory • Rice University • Southern Cross, a provider of field services to utilities
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Aeris Technologies offers a series of middle infrared (MIRA) gas analyzers with tunable diode laser spectrometers combined with miniaturized electronics for detection of methane and other gases. The company offers four versions of its technology: Pico (for mobile applications in the field); Ultra (for temperature-controlled mobile or stationary applications); Strato (designed for UAV applications); and Responder (designed for any vehicle). Data is GPS enabled and available in real time through a data file continuously updated for mapping in Google Earth. According to a 2020 analysis by the group Carbon Limits, Aeris sensors only deliver concentration data, and their ability to quantify emissions "depends on method of use."
NOTEWORTHY TECHNICAL SPECIFICATIONS	The company notes that it achieves a level of sensitivity (<1ppb/s sensitivity for methane and ethane) that discriminates between methane/ethane and biogenic sources such as landfill gas, cattle operations, swamp gas, sewer gas, and permafrost. The company claims this capability "eliminates" false positives.
NOTEWORTHY DISTINCTIONS	In 2018, Aeris was one of eleven companies invited to participate in the controlled testing phase of the Mobile Monitoring Challenge, sponsored by Stanford University's Natural Gas Initiative (NGI) and the Environmental Defense Fund (EDF).
RECENT PROJECT(S)	In 2021, the company announced a partnership with Southern Cross to provide advanced detection and emissions reduction solutions to utilities in North America. Between 2015 and 2018, Aeris received $2.5 million in funding from the ARPA-E MONITOR program to develop a complete methane leak detection system that allows for highly sensitive, accurate methane detection at natural gas systems.

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Field	Description
NAME	LaSen
HQ/LOCATION	Las Cruces, NM
PARTNERS/INVESTORS	• British Columbia Oil and Gas Commission • Colorado State University (CSU) Methane Emissions Technology Evaluation Center (METEC) • U.S. Department of Energy (DOE) LaSen also notes that they "partner with" (which may mean they are a member of) the following associations: American Gas Association, Global Methane Initiative, Interstate Natural Gas Association of America, and several regional and state gas trade associations.
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	LaSen offers two technologies for methane detection and quantification: a laser-based Differential Absorption Lidar (DIAL) chemical sensor technology called Airborne LiDAR Pipeline Inspection System (ALPIS) deployed using a helicopter; and a drone-based Tunable Diode Laser Absorption Spectrometer (TDLAS) tuned to specifically absorb methane with an optical gas imaging (OGI) camera and GPS receiver. LaSen operates its own fleet of helicopters and drones to conduct surveys. Data is accessed through LaSen's proprietary dashboard in near real time.
NOTEWORTHY TECHNICAL SPECIFICATIONS	The company claims "98% accuracy is not limited by clouds, wind, or time of day." LaSen's helicopters can cover survey up to 300 miles per day.
NOTEWORTHY DISTINCTIONS	LaSen received support from DOE's advanced manufacturing program to support development of the ALPIS system. LaSen's website notes that its drone-mounted solution complies with EPA's OOOOa inspection requirements for upstream assets.
RECENT PROJECT(S)	Between 2017 and 2019, LaSen's helicopter-mounted LIDAR system was deployed by the British Columbia Oil and Gas Commission to conduct aerial surveys of 98 gas wells near Alberta, Canada. The survey aided in leak identification over large sections of pipeline assets and the Commission "intends to continue the aerial inspection program annually, focusing on different areas throughout northeastern British Columbia." In 2018, LaSen's Differential Absorption LIDAR (DIAL) airborne sensor unit mounted under their helicopter was one of the twelve technologies tested at the CSU METEC facility.

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Field	Description
NAME	mAIRsure
HQ/LOCATION	Jackson, WY
PARTNERS/INVESTORS	• Colorado State University (CSU) Methane Emissions Technology Evaluation Center (METEC) • Colorado Office of Economic Development and International Trade • ExxonMobil • U.S. Department of Agriculture
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	mAIRsure is an early-stage company that offers a system of mobile sensors that can be mounted on various vehicles, including trucks and UAVs, and cloud-based analytics for methane monitoring at oil and gas operations. Its solutions can geolocate point sources of methane including wells and tanks, as well as tailing ponds and open face mines. The company refers to its solution as "sensors as a service." The company evolved from research by Colorado State University and Cornell University in the areas of laser sensing, turbulent plume dispersion, and integrated cloud-based analytics. The company has published several academic papers regarding its technology and collaborations with EPA and a Google Street View car, among others, which can be accessed here. mAIRsure's system has also been independently validated by CSU METEC. See mAIRsure's 2021 presentation to EPA here.
NOTEWORTHY TECHNICAL SPECIFICATIONS	• Detection threshold as low as 3 scfh • Accuracy +/- 20%
NOTEWORTHY DISTINCTIONS	In 2016, mAIRsure was one of twelve companies invited to participate in the annual Oil & Gas Cleantech Challenge, sponsored by The Colorado Cleantech Industries Association (CCIA). According to mAIRsure, their sensors have been deployed on over 300,000 pickup trucks.
RECENT PROJECT(S)	In 2020, ExxonMobil announced it is conducting field trials of eight emerging methane detection technologies, including truck-mounted sensors from mAIRsure, at nearly 1,000 sites in Texas and New Mexico.

PICARRO

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Field	Description
NAME	Picarro
HQ/LOCATION	Santa Clara, CA
PARTNERS/INVESTORS	• CleanAir Engineering, a provider of technical products and services for sustainability and resource management • Italgas, the largest gas distributor in Italy • National Aeronautics and Space Administration (NASA) • National Oceanic and Atmospheric Administration's (NOAA) • Pacific Gas & Electric (PG&E) • Southern Cross, a provider of field services to utilities • University of Wyoming
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Picarro provides solutions to measure greenhouse gas (GHG) concentrations, trace gases, and stable isotopes across several industries. Picarro's gas analyzers use a patented Cavity Ring-Down Spectroscopy (CRDS) that can determine the presence and concentration of methane in the atmosphere. The Picarro CRDS can be mounted to any vehicle to collect methane plume data. That data is sent to Picarro's cloud-based platform, where analytics software transforms the data into actionable results that clients can access in real time. Picarro also measures atmospheric and meteorological conditions and integrates this data to improve accuracy. The company says that its technology can "virtually eliminate" false positives caused by non-natural gas sources of methane.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	In 2012, PG&E became the first utility to use Picarro's methane detection technology. In 2016, the utility announced it had completed its 1 millionth inspection using the technology. Picarro's instruments have been used by NASA to calibrate the Japanese GOSAT satellite.
RECENT PROJECT(S)	In September 2021, Picarro partnered with CleanAir Engineering to quantify upstream and midstream natural gas operator emissions in the Marcellus Shale region. The companies claim that the results will help clients "meet environmental, social, and governance (ESG) targets." Picarro's Cavity Ring Down Laser Spectroscope (CRDS) instrument has been used as part of Scientific Aviation's aerial surveys and the University of Wyoming's ground vehicle surveys in the PermianMAP project. The University of Wyoming has also used Picarro's CRDS is their study quantifying emissions from orphaned coalbed methane wells in the Powder River Basin. The results of the study, published in 2021, can be found here. Since 2017, Picarro has worked with Italgas to improve leak surveillance and enhance analysis of emissions. In 2021, Italgas became the largest user of Picarro's natural gas management solutions, with 20 Picarro-equipped vehicles and an additional 80 other mobile units.

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Field	Description
NAME	Portable Methane Leak Observatory (PoMELO)
HQ/LOCATION	Calgary, Canada
PARTNERS/INVESTORS	• Colorado State University (CSU) Methane Emissions Technology Evaluation Center (METEC) • Emissions Reduction Alberta • Stanford University/Environmental Defense Fund (EDF) Mobile Monitoring Challenge
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	The Portable Methane Leak Observatory (PoMELO) is a University of Calgary project to build a methane sensing system for the upstream oil and gas industry and serve as a research platform to advance mobile pollution monitoring. The system consists of a methane sensor, a Global Navigation Satellite System (GNSS) that provides data on location, and an anemometer to measure wind speed and direction. The system is vehicle-based and includes a roof-mounted, open-path laser absorption sensor connected to a data analytics platform. The project also includes a variant called "Padmapper" which is focused on increasing the efficiency and efficacy of surveys on upstream oil and gas pads.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	In 2019, developers of the PoMELO mobile methane detection system presented their technology at the Stanford/EDF Mobile Monitoring Challenge and published their results here.
RECENT PROJECT(S)	In 2020, the University of Calgary published an summary and detailed paper from a single-blind detection experiment at the CSU METEC facility, highlighting the ability of the Padmapper system to detect small emissions sources in a mock facility. In June 2020, the PoMELO technology won a $1.6 million grant from the Emissions Reduction Alberta Natural Gas Challenge for a full-scale field pilot.

Handheld Technologies

Handheld technologies, primarily optical gas imaging cameras, can survey individual equipment and components for methane emissions and allow identification of very small emissions sources. However, handheld technologies require close access to equipment and components and can be very time consuming. A single component may require measurement from multiple angles to classify with high accuracy. OGI cameras are approved for surveys required under the EPA OOOOa regulation and are the standard way that oil and gas operators have conducted annual methane LDAR programs. Handheld technologies here typically process images and data collected using proprietary algorithms and models to more precisely quantify emissions.

TABLE 7 highlights the overall strengths and limitations of handheld technologies.

TABLE 7
Handheld Technologies: Strengths and Limitations

Strengths	Limitations
• Handheld technology is highly portable and can be deployed in many locations • Handheld technology allows closer proximity to identify the source of small leaks • Data collected is typically available in real time or near real time	• Most data collected by handheld technologies is proprietary and not accessible to the public • Handheld technology is very limited in its ability to cover larger areas at a fast pace • Safety hazards may increase in close proximity to a methane emissions source • Handheld technologies may have limited ability to quantify large emissions sources

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Field	Description
NAME	Distran Ultra Pro
HQ/LOCATION	Zurich, Switzerland
PARTNERS/INVESTORS	The company notes that the technology has been used by major industrials including Total and Shell SpaceX has deployed the technology at the International Space Station, but not for methane detection
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Distran's Ultra Pro is a handheld ultrasound imaging camera that uses 124 ultrasound microphones to detect the specific sounds that pressurized gas leaks emit and identify the position of the sound source. The technology can quantify the leak rate (in liters per hour or in cubic feet per minute) in real time. An operator can use Distran's Audalytics software or other software to create a report from the data that is collected. Watch a brief (20-second) demonstration of the technology here.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Minimum detection threshold of 2 L/h at 30 cm (in a quiet environment) and 10 L/h at 30 cm (in an industrial environment) Working distance from 0.3 m to 100 m.
NOTEWORTHY DISTINCTIONS	In 2021, the Distran Ultra Pro became the first ATEX certified ultrasound camera. (The ATEX Directive is a safety certification in the EU.) Renamed the Ultra Pro X, the new version has been specifically designed for use within potentially explosive atmospheres for the oil and gas, chemistry, and power plant industries. In 2020, the Distran Ultra Pro was included in SpaceX's 21st Commercial Resupply Services mission (CRS-21) to the International Space Station f(ISS) for use in detecting air leaks at the ISS. Over time, air leaks require re-pressurization of the ISS atmosphere.
RECENT PROJECT(S)	

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Field	Description
NAME	Providence Photonics
HQ/LOCATION	Baton Rouge, LA
PARTNERS/INVESTORS	• Teledyne FLIR
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Providence Photonics has developed two Quantitative Optical Gas Imaging (qOGI) technologies: Q100 and QL320 that are intended to be add-ons to existing Teledyne FLIR infrared cameras (specifically the GF320 and GFx320 models). The Q100 was released in 2016 and requires a synchronization procedure for calibration with the device and a specific camera. The QL320 does not require this synchronization procedure. The devices work by measuring the 2D size of an emitted gas plume, estimates the volume of the plume in space, and models how fast the plume is dispersing into the atmosphere. Data from the devices can be accessed in real time.
NOTEWORTHY TECHNICAL SPECIFICATIONS	According to a recent study by the European Oil Company Organization for Environment, Health and Safety (CONCAWE), Providence Photonics' qOGI technologies have a 6% error rate on average, compared to the 31% error rate of a traditional detection technology.
NOTEWORTHY DISTINCTIONS	This technology could represent a simple add-on for measuring emissions; the use of FLIR OGI cameras for leak detection and repair is quite common across the oil and gas industry and the Providence technology may represent one simple and cost-effective approach for transitioning from LDAR to measurement.
RECENT PROJECT(S)	

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Field	Description
NAME	Sensia Solutions
HQ/LOCATION	Madrid, Spain
PARTNERS/INVESTORS	• European Commission (see Sensia Solutions profile under Stationary Technologies)
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Sensia Solutions provides infrared imaging technologies for a variety of gases, including methane detection and quantification. The company offers two models of handheld optical gas imaging (OGI) cameras for methane detection: Caroline Y and Mileva 33. According to an analysis by Colorado State University, these cameras (specifically the Mileva) only offer methane detection, not quantification. However, the company notes that many of its cameras (including the Caroline and Mileva) can be paired with its "Redlook" advanced image processing software to quantify the mass flow rate and gas concentration. The Redlook platform also offers a variety of advanced, real-time monitoring features.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Minimum Detectable Leak Rate (MLDR) of 0.35 g/h (Mileva 33) and 1.4 g/h (Caroline Y)
NOTEWORTHY DISTINCTIONS	In October 2021, Sensia Solutions received Spain's CincoDias prize for innovation in the category of business-university collaboration, related to its work with the Carlos III University in Madrid.
RECENT PROJECT(S)	

Stationary Technologies

Fixed sensors that continuously monitor methane emissions are fundamental to measurement and quantification of methane, including calculating an emissions baseline, reducing emissions compared to that baseline, and differentiating and certifying Responsibly Sourced Gas (RSG). The number and placement of sensors necessary to optimize detection and quantification at a site is typically developed according to a proprietary model and varies by site.

TABLE 8 highlights the overall strengths and limitations of stationary technologies.

TABLE 8
Stationary Technologies: Strengths and Limitations

Strengths	Limitations
• Stationary technologies offer continuous 24/7 measurement and monitoring • Data collected is typically available in real time or near real time • Stationary technologies can detect large and small emissions, depending on the position and maximum distance they are able to cover • Stationary technologies are generally autonomous and do not require human intervention	• Most data collected by stationary technologies is proprietary and not accessible to the public • Stationary technologies may have limited functionality based on where they are located or positioned; the optimal number of stationary sensors may vary by site and facility

Field	Description
NAME	LUMEN Terrain
HQ/LOCATION	Houston, TX
PARTNERS/INVESTORS	• Northeast Natural Energy • Oklahoma State University • Roeslein Alternative Energy
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	LUMEN Terrain is a ground-based, stationary, continuous monitoring device for methane emissions. It is part of an integrated LUMEN system that also includes LUMEN Sky, an aerial, drone-based methane monitoring sensor. These technologies are operated by Avitas, a Baker Hughes venture. LUMEN Terrain is solar-powered and capable of streaming data from sensors to a cloud-based software dashboard in real time. The information collected from the sensors is wirelessly streamed to a cloud platform. LUMEN Terrain provides methane concentration data, as well as the location and rate of the leak.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	In June 2021, Roeslein Alternative Energy announced that it would deploy LUMEN Terrain at 22 biogas lagoons in Missouri. Results from the project can be found here. In April 2021, Northeast Natural Energy, a West Virginia-based oil and gas company, announced it would deploy LUMEN Terrain as part of an effort to seek independent certifications of natural gas production under the MiQ methane standard and under the Equitable Origin EO100TM Standard for Responsible Energy Development.

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Field	Description
NAME	CleanConnect.ai
HQ/LOCATION	Berthoud, CO
PARTNERS/INVESTORS	• Sixgill, an artificial intelligence solutions provider based in Israel
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	CleanConnect.ai offers a system of EPA-certified OGI cameras and AI software to autonomously and continuously detect and quantify methane leaks, called the Autonomous 365 Suite. Cameras are mounted in a fixed location to provide a view of a facility and provide images, leak rate, equipment causing the leak, and GPS location, among other data.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	CleanConnect.ai offers monitoring as a service, thereby reducing the capital expenditure required by an operator.
RECENT PROJECT(S)	At the August 2021 EPA workshop, the company highlighted results from several unnamed, upstream "early adopters" of their technology. The company has also noted that Jonah Energy and Occidental Petroleum mentioned their technology at the workshop. The presentation can be found here.

Honeywell

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Field	Description
NAME	Honeywell Rebellion Gas Cloud Imaging (GCI) and Mini GCI
HQ/LOCATION	Houston, TX
PARTNERS/INVESTORS	
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	In 2019, Honeywell acquired Rebellion Photonics, a Houston-based provider of visual gas monitoring solutions. The company's Gas Cloud Imaging (GCI) and Mini GCI technologies use hyperspectral imaging to capture infrared spectrum and video to continuously monitor, quantify, and display gas leaks in real time. The standard GCI is designed for large sites and has a range up to. 1,700 m; the Mini GCI designed for congested areas and small sites and has a range up to 100 m. Both provide methane concentration and leak size and location data. Honeywell also offers a propriety AI-driven software platform, Spectra, to manage data analytics and display real-time video footage.
NOTEWORTHY TECHNICAL SPECIFICATIONS	False alarm rate <1%
NOTEWORTHY DISTINCTIONS	According to the company, Honeywell's gas cloud imaging system has been deployed by more than 25 energy and chemicals customers globally.
RECENT PROJECT(S)	

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Field	Description
NAME	Kuva Systems (formerly known as MultiSensor Scientific)
HQ/LOCATION	Cambridge, MA
PARTNERS/INVESTORS	• Carbon Management Canada Research Institutes • Cenovus Energy • Clean Energy Venture Group • Dräger Safety AG & Company, a global medical and safety technology provider • Emissions Reduction Alberta • Launchpad Venture Group • Microsoft • NAL Resources, a private oil and gas company in Canada • Texas Tech University (TTU)
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Kuva Systems is an industrial IoT platform providing an automated, image-based, continuous methane monitoring and quantification solution. Kuva's infrared imaging system automatically detects and measures emissions in real time and provides operators with an annotated video clip of the leak. Kuva's cameras provide an adjustable 360-degree field of view and captured images are first qualified by the Kuva Cloud to eliminate false-positives and then quantified for display in a data dashboard.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: <0.02 kg/h in a lab test and 1-10 kg/h in the TTU field test (with no false positives), as noted by the company in their EPA workshop presentation Range: 50 m
NOTEWORTHY DISTINCTIONS	Kuva Systems is part of the Microsoft for Startups program; Microsoft Azure IoT platform "provides scalability, configurability, digital twin as well as industrial grade security and encryption" for Kuva imaging cameras and the Kuva Cloud.
RECENT PROJECT(S)	In September 2020, Kuva Systems announced it would begin field installations at up to 100 sites in Alberta, Canada and additional field testing in Texas. In June 2020, Kuva's monitoring technology won a $1.6 million grant from the Emissions Reduction Alberta Natural Gas Challenge to demonstrate an automated fixed camera system and relocatable camera system along with partners Cenovus Energy, NAL Resources, and CMC Research Institutes. Kuva has field tested its technology at the Texas Tech University (TTU) Oilfield Technology Center using over 100 blinded tank releases over a 6-week period.

LONGPATH TECHNOLOGIES

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Field	Description
NAME	LongPath Technologies
HQ/LOCATION	Boulder, CO
PARTNERS/INVESTORS	• Advanced Research Projects Agency-Energy (ARPA-E) • Colorado State University Methane Emissions Technology Evaluation Center (METEC) • National Institute of Standards and Technology (NIST) • National Oceanic and Atmospheric Administration (NOAA) • University of Colorado, Boulder
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	LongPath Technologies has developed a stationary laser sensor technology and software to monitor oil and gas leaks over long distances (>2.5 miles). The company describes the technology as a "radar for methane;" it deploys a single, centralized laser sensor that sends invisible, eye-safe beams across a region to detect, locate, and size methane leaks among dense oil and gas infrastructure. In addition, the company offers a cloud-based data collection and reporting system within 30 minutes after detection (near real-time). LongPath received approximately $2 million from ARPA-E in 2015 under the MONITOR program and $5 million in 2021 under the agency's SCALE-UP program to support commercialization.
NOTEWORTHY TECHNICAL SPECIFICATIONS	In a test conducted by the Methane Emissions Technology Evaluation Center (METEC) at Colorado State University, LongPath quantified >90% of leaks (out of more than 30 leak scenarios) down to less than 10 scfh (approximately 0.2 Mcfd or 0.2 kg/h) from a distance of nearly 1 mile.
NOTEWORTHY DISTINCTIONS	The inventors of LongPath's core technology—laser-based precision spectroscopy including the optical frequency comb technique—won the Nobel Prize in Physics in 2005; LongPath has been working with the technology for almost a decade.
RECENT PROJECT(S)	According to the company, the technology has been piloted with four companies in Colorado, California, and Canada and is currently deployed commercially in New Mexico, Texas, and Oklahoma, covering 180 wells over a 30 square mile area.

MIRICO

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Field	Description
NAME	MIRICO
HQ/LOCATION	Oxford, UK
PARTNERS/INVESTORS	• Foresight Williams Technology EIS Fund, a UK-based investment fund supporting disruptive technology • Longwall Ventures • Shell • Rutherford Appleton Laboratory, a government research agency in the UK • Science and Technology Facilities Council, a government agency in the UK
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	MIRICO offers laser dispersion spectroscopy technologies that delivers continuous monitoring of methane and other gases in real-time. The MIRICO ORION CH4 can be deployed for continuous or intermittent monitoring of oil and gas facilities, landfills, and agricultural operations. The MIRICO CLOUD, released in 2021, enables real-time visualization of data collected from the ORION, enabling quantification and comparisons with historical data. MIRICO acquired Sedolabs, a cloud-based emissions analytics platform in 2020.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Detection limit of 50 ppb methane over 100m in 1s Measurement range of 50m to 400 m
NOTEWORTHY DISTINCTIONS	In 2020, MIRICO won 3rd prize in the Green Future Enterprise Competition run by GDRF, a major gas utility in France.
RECENT PROJECT(S)	In 2017, MIRICO collaborated with Shell's atmospheric science and modelling experts to combine MIRICO's monitoring technology with Shell's proprietary plume modelling software. The findings of the collaboration were published here.

PROJECT CANARY

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Field	Description
NAME	Project Canary, Canary Model S and Canary Model X
HQ/LOCATION	Denver, CO
PARTNERS/INVESTORS	• Chisholm Energy Holdings, a New Mexico-based natural gas producer • Colorado State University Methane Emissions Technology Evaluation Center (METEC) • IES/Trustwell (see Technologies in Action section of this report) • Lunar Outpost, a company developing air quality and environmental monitoring systems for the lunar surface and Earth • NextDecade Corp, an LNG developer • PureWest Energy, a Wyoming-based natural gas producer • Tallgrass Energy, a Kansas-based pipeline operator In 2020, Project Canary acquired Troposphere Monitoring, a developer of hydrocarbon emissions sensor technology.
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Project Canary is focused on continuous monitoring technology that address a broad array of environmental data (air, water, land, and community) relevant to ESG reporting and certification of Responsibly Sourced Gas (RSG). The Canary Model S is a continuous solar-powered air quality and meteorological monitoring system. Data is transmitted in real-time to a Canary Cloud data platform. The Canary Model X offers higher precision, sensitivity, accuracy, and measurement frequency; the fidelity of its data collection is consistent with what is typically required to certify RSG.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Results from Project Canary's August 2021 testing at METEC can be found here. The test results show that Project Canary can quantify total site methane emissions with a ~100% leak detection rate and a cumulative calculation error of 6%.
NOTEWORTHY DISTINCTIONS	Project Canary is actively engaged in building relationships with state and Federal lawmakers, which may increase their influence on future policy and regulation.
RECENT PROJECT(S)	Project Canary has worked with a number of smaller gas producers to quantify, verify, and certify emissions, including Chisholm Energy Holdings, NextDecade Corp, PureWest Energy, and Tallgrass Energy.

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Field	Description
NAME	QLM Technology
HQ/LOCATION	Bristol, UK
PARTNERS/INVESTORS	• Bristol Equity Club, a technology accelerator • Britbots Seed Fund, a technology accelerator • ChampionX • Development Bank of Wales • Green Angel Syndicate, angel investment firm in the UK • Enterprise 100 Syndicate, a private angel investment group in the UK • Inzpire, a UK-based supplier of advanced defense training, technical services, and military mission systems • Newable Venture Fund, venture capital firm in the UK • SPLICE Project, a consortium effort supporting progress toward commercial readiness of QLM's technology which includes about a dozen research partners, including several universities as well as BP, and National Grid • University of Bristol
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	QLM Technology has developed the Quantum Gas Camera, a Tunable Diode Lidar (TDLidar) gas sensor that combines multiple technologies and can be used in stationary, mobile, drone, and handheld applications. The initial version of the Quantum Gas Camera is intended to be mounted on a pole or tripod mount, with optical zoom and versatile tilt/pan features to measure methane emissions from a fixed location over a long range. The company is also developing a second version of its camera for handheld or drone-mounted applications; QLM is testing this version of its technology as part of an unmanned aircraft system with its partner Inzpire.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Range: 200 m; the company claims that it can cover an entire facility with one camera Additional technical specifications provided by the company can be found here.
NOTEWORTHY DISTINCTIONS	In April 2021, QLM announced it had raised 3.1 million GBP from a consortium of UK-based investors and Texas-based oilfield technology provider, ChampionX. In April 2021, QLM was named one of twelve Bloomberg New Energy Finance (BNEF) Pioneers, a group of "early-stage companies that are pursuing exciting and important low-carbon opportunities."
RECENT PROJECT(S)	In December 2021, QLM completed its first successful trial of the Quantum Gas Camera at a National Grid Gas site as part of the SPLICE Project. Results from a 2020 trial with the National Physical Library, the UK's national measurements standards laboratory can be found here.

Quanta3

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Field	Description
NAME	Quanta3
HQ/LOCATION	Longmont, CO
PARTNERS/INVESTORS	• Environmental Defense Fund (EDF) • Equinor • Shell • Statoil Quanta3 is also participating in Project Astra, whose partners include: AT&T, Chevron, the Collaboratory to Advance Methane Science (CAMS), EDF, ExxonMobil, Microsoft, Pioneer Natural Resources, and Schlumberger
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Quanta3 offers a laser-based stationary sensor that provides continuous monitoring and quantification of methane emissions, including leak location and baseline and history. The sensors are solar powered, operate autonomously, and are not expected to require maintenance for 1-2 years. The sensors transmit data to the cloud and enable access to the data in real time.
NOTEWORTHY TECHNICAL SPECIFICATIONS	
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	Quanta3 is one of seven continuous monitoring companies participating in Project Astra, which plans to establish a pilot sensor network that will leverage advances in methane-sensing technologies, data sharing, and data analytics to provide near continuous methane monitoring for a region encompassing approximately 50 km2 in the Permian Basin of West Texas. Quanta3's sensors operated in the field from October 2020 to June 2021. The best-performing sensors will then be considered for use in the next phase of the project, scheduled to launch in late 2021. In early 2017, Statoil (now Equinor) became the first operator to pilot Quanta3's technology in Texas as a part of EDF's Methane Detectors Challenge. Later that year, Shell also piloted the technology in Alberta, Canada as part of the challenge. The Methane Detectors Challenge, launched in 2014, is a collaboration between EDF oil and gas companies, and US-based technology developers.

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Field	Description
NAME	Systematic Observations of Facility Intermittent Emissions (SOOFIE)
HQ/LOCATION	Boulder, CO
PARTNERS/INVESTORS	Scientific Aviation was acquired by ChampionX in July 2021 Project Falcon partners include Chevron, ConocoPhillips, Devon Energy, ExxonMobil, Pioneer Natural Resources, Shell, and TRP Energy Scientific Aviation is also participating in Project Astra, whose partners include AT&T, Chevron, the Collaboratory to Advance Methane Science (CAMS), EDF, ExxonMobil, Microsoft, Pioneer Natural Resources, and Schlumberger
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	SOOFIE is a fixed sensor technology offered by Scientific Aviation to provide continuous monitoring and quantification of methane emissions. The sensors are solar powered and provide enough battery backup to survive one week of overcast weather. Data measurements are transmitted to cloud-based servers for analysis. accessed through the SOOFIE data dashboard. The SOOFIE system is also integrated with Google Earth to localize and visualize the methane leak locations.
NOTEWORTHY TECHNICAL SPECIFICATIONS	Scientific Aviation's Dashboard User Guide provides more detailed information on the kinds of data offered through the system.
NOTEWORTHY DISTINCTIONS	
RECENT PROJECT(S)	In early 2021, Scientific Aviation announced the launch of Project Falcon, a six-month joint industry study that aims to determine the best way to deploy the company's continuous methane monitoring technology. Under the project, Chevron, ConocoPhillips, Devon Energy, ExxonMobil, Pioneer Natural Resources, Shell, and TRP Energy will test SOOFIE in Colorado, New Mexico, and Texas. Scientific Aviation is one of seven continuous monitoring companies participating in Project Astra, which plans to establish a pilot sensor network that will leverage advances in methane-sensing technologies, data sharing, and data analytics to provide near continuous methane monitoring for a region encompassing approximately 50 km2 in the Permian Basin of West Texas. Quanta3's sensors operated in the field from October 2020 to June 2021. The best-performing sensors will then be considered for use in the next phase of the project, scheduled to launch in late 2021.

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Field	Description
NAME	Sensia Solutions
HQ/LOCATION	Madrid, Spain
PARTNERS/INVESTORS	• European Commission
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	In 2021, Sensia Solutions announced the integration of its optical gas imaging with a new "Methane Laser" (based on Tunable Diode Laser Absorption Spectroscopy), resulting in a stationary, continuous monitoring technology for methane (Caroline FYL) that is integrated with Sensia's software analytics platform, Redlook. Sometimes referred to as Build-in Redlook the two technologies in the system validate or "doublecheck" the results, and the company claims to achieve "virtually zero false alarms." The fixed monitoring devices are solar powered, autonomous, and allow for real-time monitoring. A brochure about Redlook, including the monitoring system and associated software platform can be downloaded here.
NOTEWORTHY TECHNICAL SPECIFICATIONS	• MDL: 80-100 g/h at 35 m and 200-350 g/h at 50 m • False positives rate: 1 alarm per month
NOTEWORTHY DISTINCTIONS	In October 2021, Sensia Solutions received Spain's CincoDias prize for innovation in the category of business-university collaboration, related to its work with the Carlos III University in Madrid
RECENT PROJECT(S)	In 2018, Sensia tested its prototype fixed monitoring system at oil and gas sites across Europe as part of the European Commission-funded Horizon 2020 program GaSeS project.

SENSIRION
THE SENSOR COMPANY

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Field	Description
NAME	Sensirion Nubo Sphere
HQ/LOCATION	Zurich, Switzerland
PARTNERS/INVESTORS	• Colorado State University (CSU) Methane Emissions Technology Evaluation Center (METEC)
TECHNOLOGY DESCRIPTION (WHAT IS IT?)	Sensirion is a Switzerland-based manufacturer of digital sensors and systems for air quality and environmental monitoring solutions. In September 2021, the company announced Nubo Sphere, a stationary methane leak detection system that provides real-time, continuous methane concentration data as well as meteorological data including wind speed and direction, temperature, humidity, and barometric pressure. Data is uploaded to a proprietary "Nubo Cloud," which also monitors the health of connected sensors and the overall system for maintenance or repair issues. The company notes that its system is "future-proofed" because sensor cartridges can be easily changed or updated without upgrades to the overall system.
NOTEWORTHY TECHNICAL SPECIFICATIONS	MDL: <1 kg/h, according to the company's video at the EPA workshop virtual vendor hall.
NOTEWORTHY DISTINCTIONS	In May 2021, Sensirion acquired Swiss company IRsweep, a provider of optical sensing solutions relevant to methane detection.
RECENT PROJECT(S)	Sensirion has tested Nubo Sphere at the CSU METEC test site and has other field tests planned, according to its video at the EPA workshop virtual vendor hall.

Technologies in Action

Carbon Mapper

Carbon Mapper is a non-profit that aims to advance climate action by integrating advanced methane detection technologies with real-time tracking and data analytics. The NGO has public-private partnerships consisting of a broad-based coalition of industry, government, academic institutions, and philanthropic organizations, which are working to leverage their resources and expertise to fund, design, build, and promote satellite and remote-sensing technologies for methane emissions. The project technology will also look at several other environmental indicators, including CO2.

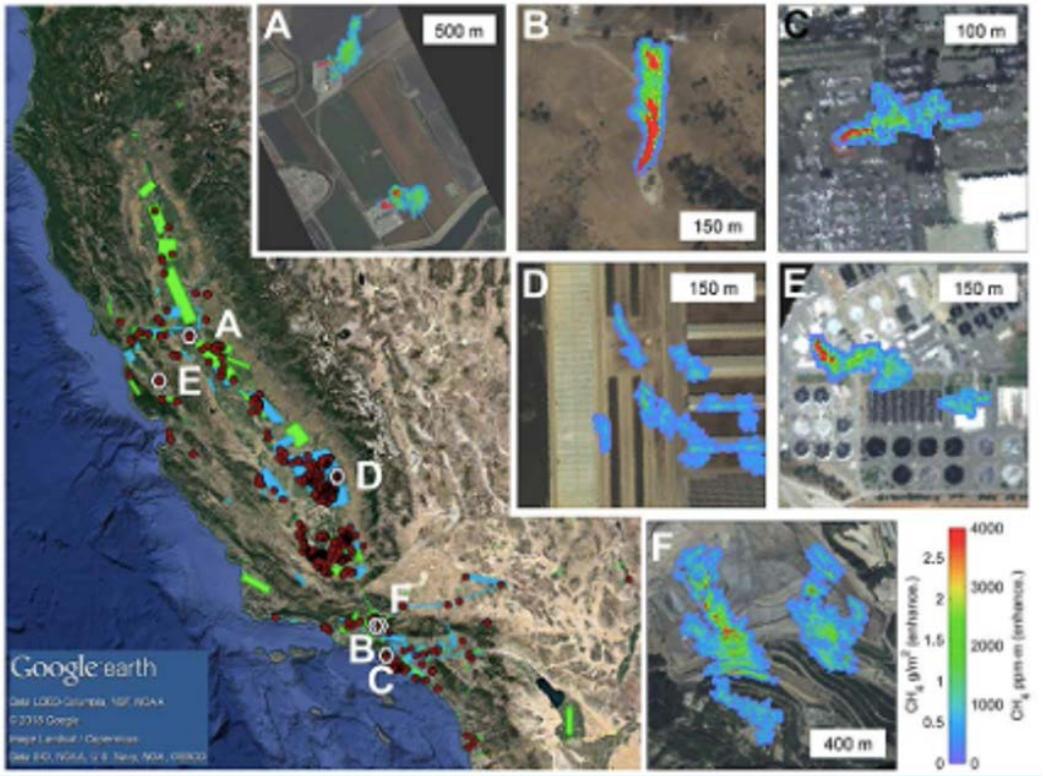

IMAGE 1
Carbon Mapper

Currently, Carbon Mapper is using aircraft equipped with high resolution hyperspectral imaging camera to collect data on super emitters in the Permian basin; the group's longer-term plan is to develop and launch a constellation of satellites for measuring and tracking methane and other greenhouse gases. Carbon Mapper's key partners are NASA's Jet Propulsion Lab (JPL), Planet, California Air Resources Board (CARB), High Tide Foundation, The University of Arizona and Arizona State University, Rocky Mountain Institute (RMI), and Bloomberg Philanthropies. The organization's stated mission is to pinpoint, quantify, and track methane and CO2 emissions at a facility level using satellite data that they will collect from Carbon Mapper satellites built by partners such as NASA JPL and Planet, while offering fast methane leak detection services to operators and regulators, and delivering independent data to help certify methane intensity for oil and gas supply chains. In addition, they will make this data available publicly available through its global open data portal called Methane Source Finder, to increase accessibility, transparency and understanding of the received data. Carbon Mapper will also offer technical support for end-users to enhance the impact of data. This public portal, built in partnership with California's Air Resources Board, will make the data available to industry, private citizens, government, and other sectors.

Carbon Mapper's first two satellite launches are planned for 2023, with additional satellites to be added starting in 2025.

Climate Action Engine

Climate Action Engine (CAE) is an emissions data and analytics platform that visualizes methane emissions from oil and gas industry operations in West Texas' Permian Basin and helps users assess climate risk.

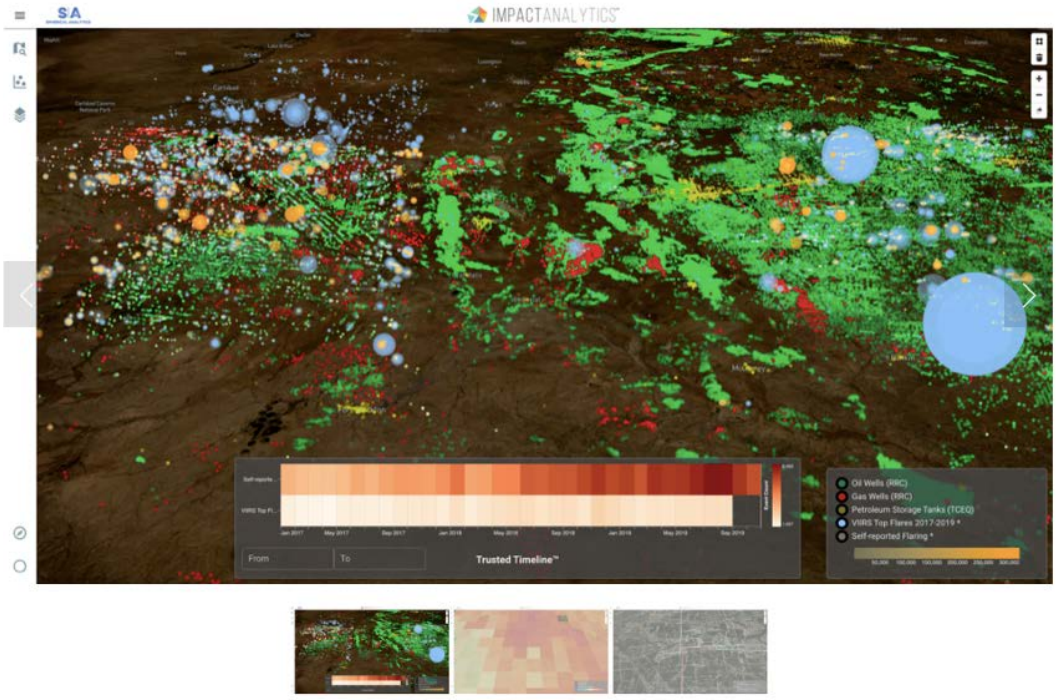

IMAGE 2
Climate Action Engine

The platform integrates publicly available data from aerial sensors and satellites (currently NOAA VIIRS and Europe's TROPOMI) with information about oil and gas industry sites and facilities to produce a more comprehensive picture of emissions and their sources. Users may also upload their own data to the platform.

CAE generates "asset-grade" data (AGD), which is data embedded with proof, immutability, and auditability and can help investors quantify and contextualize ESG factors against more tangible commercial/corporate/business priorities.

CAE is a partnership between RMI (formerly the Rocky Mountain Institute) and Spherical Analytics. The platform has been piloted by major energy companies including Shell, Exxon, and Chevron, and Shell has estimated an 80% reduction in flaring at their Permian Basin operations since they adopted the platform in 2017. CAE enables users to report emissions data in accordance with various standard protocols including the Taskforce on Climate-related Financial Disclosures (TCFD), Sustainability Accounting Standards Board (SASB), Global Reporting Initiative (GRI), and the Climate Disclosure Project (CDP).

See a video demonstration of the platform here.

Flaring Monitor

Flaring Monitor is a first-of-its kind project that tracks company-level flaring in the largest U.S. oil and gas basins, including North Dakota and the Permian Basin. The project uses images from the company Planet and NASA satellite sensor readings of heat signatures from natural gas flares to estimate CO2 and methane emissions in real-time. Flaring Monitor is open source, meaning that it makes its data, code, algorithms, and the resulting datasets available to the public through the platform GitHub.

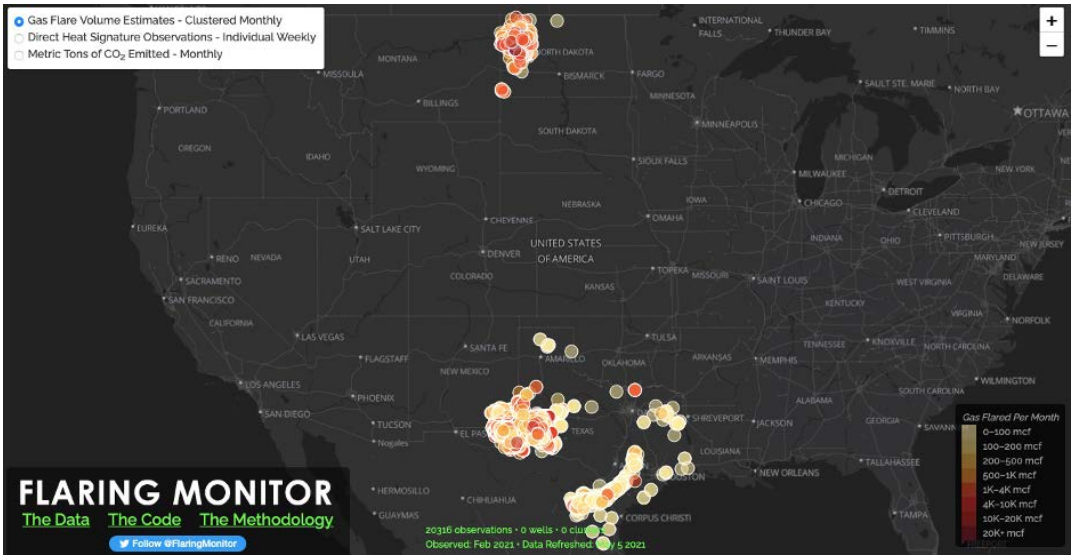

IMAGE 3
Flaring Monitor

Flaring Monitor allows users to compare a company's self-reported data (provided to regulatory agencies) against objective satellite measurements. The platform also allows comparison of flaring associated with different companies. In May 2021, Flaring Monitor noted that its data shows that Shell is "doing better on flaring" than other large energy companies.

For additional information, see Flaring Monitor's white paper here.

IES and Project Canary

In 2020, Project Canary, a provider of stationary technologies for continuous monitoring of methane emissions merged with Independent Energy Standards (IES), a provider of analytics for the oil and gas industry and developer of the "TrustWell" rating and certification system for Responsibly Sourced Gas (RSG). The combined company provides a comprehensive solution for oil and gas sector companies seeking to measure, monitor, verify, and report accurate, timely information about methane emissions and access the growing market for differentiated gas.

IMAGE 4
IES and Project Canary

Project Canary's technology measures environmental data including emissions information in near real-time and stores the data on its cloud-based platform. The data is then integrated with the TrustWell verified attribute programs to create a rating (Rated, Silver, Gold, and Platinum). Each verified attribute program assesses four factors at a facility: 1) the inherent risk of operations; 2) control measures; 3) performance with regard to specific events; and 4) continuous improvement in risk reduction and operations. Each of these factors has multiple components that make up the rating.

Low-Methane is the first of the verified attribute programs to be implemented; the three additional programs are: Freshwater Friendly, Safe Operator, and Chemical Steward. In March 2020, Jonah Energy was the first company to receive a TrustWell Gold rating under the Low-Methane Verified Attribute program.

See the TrustWell report on Jonah Energy's Responsibly Sourced Gas here.

Jonah Energy and OGMP

In 2020, Jonah Energy became the first U.S. company to join the Oil and Gas Methane Partnership (OGMP), a program sponsored by the United Nations Environment Programme and the Climate and Clean Air Coalition. Membership in the group requires a commitment to three specific actions:

IMAGE 5
Jonah Energy and OGMP

- Surveying facilities for nine core sources that make up the majority of methane emissions in typical upstream operations
- Evaluating cost-effective technology options to address uncontrolled sources
- Reporting progress on surveys, project evaluations, and project implementation in a transparent, credible manner that demonstrates results

OGMP is a broad multi-national and multi-stakeholder partnership working on methane emissions measurement and reporting protocols that will enable companies to demonstrate real emission reductions. In 2020, OGMP published its 2.0 Framework, which establishes a "gold standard" for credibility and trust in reporting and reducing methane emissions.

In July 2021 (less than a year after joining), Jonah Energy announced was on track to be the first company to achieve this "gold standard" under the framework. To achieve this, the company is implementing a variety of technologies, including stationary measurement devices, drone-based sensors, aerial laser scanning, and satellite-based asset-wide measurement, that overall enable verified emissions measurement at both the site level and at the source.

See the OGMP 2.0 Framework here. Read the detailed OGMP technical guidance documents here.

PermianMAP

The Permian Methane Analysis Project (PermianMAP) is a pilot project that combines established data collection methods with emerging measurement and monitoring technologies to quantify and report on oil and gas methane emissions in the Permian Basin. It is led by the Environmental Defense Fund (EDF) with technical support from several research and technology partners.

The project focuses on a subsection of the Permian Basin, specifically a 10,000 square-kilometer grid in the Delaware Basin that contains 10% (11,000) of the region's active wells and produces 40% of its oil and gas. More than 100 companies including both oil majors and small independents operate there.

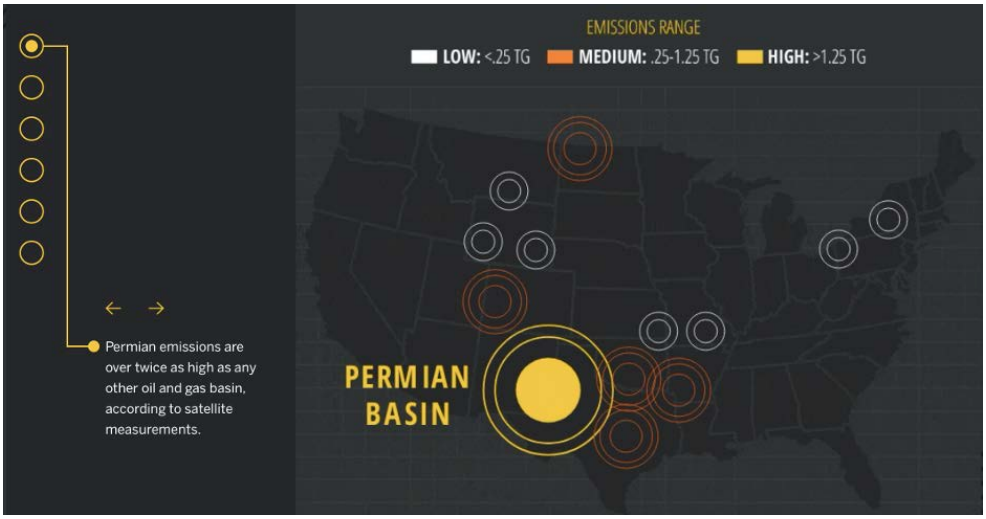

IMAGE 6
PermianMAP

Methane emissions measurements are taken in four ways:

- By Scientific Aviation aircraft that conducted three surveys of the area over 100 days
- By Leak Surveys, Inc. helicopters equipped with an infrared camera to detect flares
- By stationary sensors installed at five towers across the study area that measure methane concentrations continuously (24/7) and are analyzed using a Penn State University model to determine the area's total methane emissions on a quarterly basis
- By the University of Wyoming mobile methane detection van equipped with an infrared camera that can identify the sources (specific locations and equipment) of methane emissions

Data measurements are then cross-referenced with data from the TROPOMI satellite to estimate total methane emissions and then reviewed and verified by an independent scientific advisory panel made up of academics from the U.S. and Canada. Once verified, all data will be made available to the public on the PermanMAP website. Data is also shared directly with companies responsible for the emissions.

To date, the project has revealed that the rate of methane leaks in the Permian Basin are three times higher than the national average. The project has found that 11% of flares were either unlit (releasing un-combusted methane) or inefficient (burning only part of the gas and releasing the rest).

See the project's full methodology here. See the data dashboard here.

Snapshot of Criteria Used in Ratings

COEFFICIENT developed 14 criteria for assessing the 3Ts (Transparency, Trust, and Transactability). These criteria were defined primarily to apply to broad-based initiatives that addressed a combination of methane measurement, monitoring, reporting, and verification activities, including but not primarily technology initiatives.

TABLE 9 describes our current criteria and definitions. The criteria, which were designed to begin an introductory dialogue around the policy and market opportunities of these technologies, were validated with a small group of key stakeholders and may continue to evolve in future phases of this project.

TABLE 9
Criteria for Use in Ratings

3Ts Category	Criteria	Definition
Transparency	Access to data or system	Does the technology use an open-source approach or is it only offered as a proprietary product or subscription? Does it make data collected available to the public?
Transparency	Accuracy of Inputs	Does the technology provide accurate data? Is it affected by weather or other sensitivities? Does it result in a significant number of false positives?
Transparency	Granularity of Inputs	Does the technology provide granular data? What is its Minimum Detection Level (MDL) or resolution for images? Does it identify the specific source of methane?
Transparency	Monitoring Frequency	What is the frequency of data collection?
Transparency	Timeliness	How soon after data collection is the data available to access?
Transparency	Area	How much area can the technology cover over a specific survey or timeframe?
Transparency	Support for Advanced Technologies, Digital MRV	Does the technology enable quantification and interoperability, not just LDAR? Does it include data analytics software or platform for understanding the data collected?
Trust	Verification Practices/ Mechanisms	Does the technology provider allow for independent validation of the data collected? Does it verify the data through an integrated third-party verification tool/ process/mechanism?
Trust	Quantity of Participants	How many partner organizations are funding, supporting, piloting, or adopting the technology?
Trust	Quality of Participants	Are the partner organizations well-known, credible, and diverse?
Trust	Policy Engagement	Does the technology intersect with policy or regulation? Have policymakers or regulators integrated features of the technology into law?
Trust	Maturity and Scale	Is the technology still under development, already demonstrated, or commercial? Is the technology easy and cost effective to scale?
Transactability	Certification of natural gas products	Does the technology enable certification of low-emission natural gas that can be bought/sold/traded in a market?
Transactability	Enables Meaningful Investor Analysis/ Assessment	Does the technology enable contextualization of methane emissions data in a way that can be understood and shared across the corporate ESG and financial communities? Does it have the capability to align with standard or emerging reporting methodologies used by investors and financial markets?

Key Takeaways from Preliminary Ratings (Version 1.0)

COEFFICIENT developed a set of preliminary ratings of the technologies profiled in this report. These ratings are based on the information we have been able to collect and our evaluations of how well each technology addresses the 3Ts criteria; they are intended to help inform stakeholders about the general strengths and limitations of various technologies in a policy context and indicate how different technologies can complement each other. We believe any of the technologies profiled and rated have the potential to be valuable solutions for different contexts; the intention of the ratings is not to provide a full technical evaluation of the specifics of each technology or to exclude any technology from consideration as a methane measurement solution, but to start a dialogue about the potential of these technologies to work collectively to provide a more transparent, trustworthy and transactable energy future.

Ratings were assessed on a 1-5 scale, with 1 being the lowest and 5 being the highest. Ratings were assigned based on known information; where not enough publicly available information was found on specific criteria, no rating was made. All but three of the profiles were rated on at least ten criteria, and most were rated on between 11 and 13 criteria. New or additional information about any technology may impact the rating. Ratings are likely to evolve as additional information becomes available in future phases of this project.

The following are key conclusions from these preliminary ratings:

- Almost all companies/technologies have the *capability* to quantify methane emissions and integrate with Digital MRV systems. However, our sense is that the technologies are *not actually implemented* in this way by most oil and gas operators; instead, many operators are focused on regulatory compliance under EPA OOOOa rather than taking the next steps toward measurement and quantification.
- Most companies/technologies are offered as a product or service to customers, and except for some satellite technologies, the data collected is housed in proprietary systems and not made public. Without new standards, this may create interoperability barriers to wider deployment and integration with new regulation.
- Timeliness (how quickly data is available) is a strength of most companies/technologies; most offer access to data in real time or near real time.
- Very few companies/technologies are focused on key criteria for trust and transactability, specifically: verification activities; integration with emerging policy and regulation; certification activities; or investor activities. As such, most profiles receive ratings of 1 on these criteria.
- Many companies/technologies received a rating of 3 on maturity/scale, indicating that they are currently or have been piloted in the field with oil and gas operators, but testing and improvements are ongoing, and the technologies may not yet be ready for wide-scale commercial deployment.
- The overall top-rated profiles are: MethaneSAT (satellite); TROPOMI (satellite); Picarro (mobile- other/cross-cutting); Baker Hughes LUMEN Terrain (stationary); and Project Canary (stationary). These generally received higher ratings not necessarily because of better technical specifications but rather because they were some of the very few companies/technologies that are addressing verification and certification activities. Each of these received an overall rating between 3 and 4. All other profiles received overall ratings between 2 and 3. The average rating across all profiles was 2.43.
- For additional details regarding how ratings were defined and calculated in this report, and for recommendations on how to evolve these criteria in future phases of this project, please contact COEFFICIENT.

Emerging Issues for Consideration

Interoperability and the Future of Digital MRV

An emerging issue that oil and gas companies should build awareness around is interoperability. Interoperability is essentially an issue of integration. Data that meets high standards of transparency, trust, and transactability will also need to be used across different platforms and programs.

However, currently standards are lacking to enable interoperability. Different formats and processing techniques, varying definitions for metadata, and varying granularity all create barriers to sharing data across platforms. In addition, costs associated with creating interoperable systems and legitimate concerns about privacy and confidentiality often block progress.

Although seemingly arcane, interoperability must be addressed to fully realize the potential of the 3Ts (Transparency, Trust, and Transactability). Industry and policymakers may consider a role for the National Institute of Standards and Technology (NIST), which has a long and respected history of working with diverse stakeholders to establish technical standards.

In the early 2000s, concepts for a "smart grid" began to emerge, but there were no standards for power plants, meters, buildings, vehicles, and other devices and systems to communicate with the grid. Without standards, smart grid technologies were at risk of becoming prematurely obsolete or being implemented without necessary security features.

In 2007, Congress directed NIST to coordinate development of a framework and standards to achieve interoperability of smart grid devices and systems. In 2010, NIST published a "Framework and Roadmap for Smart Grid Interoperability," including a "reference model"—a tool for defining and developing architectures for systems and subsystems within the smart grid and ensuring interoperability and cybersecurity.

Today, the NIST Smart Grid Interoperability Panel (SGIP) maintains a catalog of standards and provides an open process for stakeholders to interact and accelerate standards harmonization and advance the interoperability of smart grid devices and systems. As of December 2020, 88 million smart meters have been deployed in the U.S., representing 57% of all electric meters. NIST may be well-positioned to play a similar role in data interoperability for methane emissions.

Transactability and the Role of Environmental Attributes in Certification of RSG

A durable framework to achieve methane emission reduction requires transparency, trust, and transactability. Fast-advancing technologies (as discussed in this assessment) are increasingly enabling the transparency of emissions data. In addition, efforts are ongoing to increase trust by reconciling the differences between top-down and bottom-up emissions calculations and developing standardized reporting methodologies.

However, achieving transactability of responsibly sourced gas (RSG) products will require additional tools to 1) independently verify the environmental attributes of the product and 2) enable secure transactions between producers and customers.

Similar challenges existed two decades ago as renewable electricity production began to rise and power producers sought to attract (or respond to demand from) customers for clean or "green" energy. In response, Renewable Energy Credits (RECs) were created to track renewable electricity from the point of generation to the consumer. Today, a REC represents one megawatt-hour (MWh) of electricity generated from a renewable energy resource that can be bought and sold in the open market.

In the U.S., RECs grew as states passed renewable portfolio standards (RPSs) and have also been also used in the voluntary market, where customers buy renewables to meet sustainability goals. RECs are tracked by regional digital tracking systems that facilitate the creation, management, and retirement of RECs and ensure that each REC is assigned a unique serial number and counted only once. Auditing of RECs is done by independent third-party organizations or certified internal auditors.

How might the REC model apply to RSG? Environmental attributes for RSG are more complex than for renewable power, and challenges remain around establishing 1) consistent definitions for attributes, 2) standardized measurement protocols, and 3) interoperability among trading platforms and registries. However, several initiatives are emerging to apply the lessons of RECs to these challenges.

One company exploring this opportunity is Xpansiv. Xpansiv operates multiple registries that allow producers and customers to track, measure, and transact commodity products based on environmental or other derived attributes. In October 2021, Xpansiv and S&P Global Platts launched a new benchmark for methane performance in natural gas production based on methane intensity and other measurable, differentiating attributes, including well location and production type. Producers that meet the benchmark receive a digital Methane Performance Certificate (MPC) representing one (1) MMBtu of gas; MPCs are embedded with a blockchain-based system of record-tracking. Buyers and sellers can also access Xpansiv's digital inventory of third-party verified asset information to understand and track attributes including other certifications such as those offered by Equitable Origin (EO) and Independent Energy Standards (IES). In these ways, Xpansiv is offering a digital view inside each MMBtu of a gas, creating as they call it, "Digital Natural Gas."

In encouraging the growth of the marketability of differentiated gas products beyond paper contracts and bilateral transactions, the market requires a suite of technologies to build the digital infrastructure to support diverse types of transactions. Digital solutions can be employed to create verified systems to validate the environmental attributes of differentiated gas and facilitate transparent transactions. Like the renewable power sector, the oil and gas industry has an opportunity to adapt digital frameworks to achieve the sector's objectives and mandates for emissions reduction.

Conclusions and Recommendations

The following are key conclusions from this assessment and recommendations for industry and policymakers.

- Many oil and gas operators today have not yet moved from a mindset of leak detection to a **mindset of measurement and quantification**. In large part, this is because regulation has not required them to do so. However, as measurement technologies continue to improve and mature, both investors and regulators are likely to demand more on measurement and quantification. There is an opportunity for industry to get ahead of this trend by moving toward measurement and quantification now.
- Very few companies/technologies profiled in this assessment are focused on key criteria for **trust and transactability**, specifically: verification activities; integration with emerging policy and regulation; certification activities; or investor activities. These criteria are absolutely critical to addressing growing pressure from investors and to building markets for Responsibly Sourced Gas (RSG).
- Measurement and monitoring **technologies have advanced significantly** in recent years and will likely continue to evolve as industry and other stakeholders learn more about their performance in the field under various scenarios and conditions. Industry and its partners should **engage directly with policymakers to share data and outcomes** that can help inform and ensure effective policy and regulation.
- Policymakers and regulators have an opportunity to enable more **transparent methane emissions reporting** and ensure **real emissions reductions** in the near term and long term by using this assessment and other resources to understand the strengths and limitations of advanced measurement and monitoring technologies and how these technologies are being demonstrated and assessed in the field. Policymakers should consider **establishing protocols for assessing the performance** of emerging measurement and monitoring technologies to better ensure their effective deployment.
- Policymakers and regulators will also need to better understand how data collected using these technologies can be used to **calculate a company's total emissions**. Efforts are underway by the Gas Technology Institute and others to **develop methodologies** for integrating and reconciling top-down and bottom-up measurements of methane emissions, and policymakers should also consider a government role in establishing or verifying such methodologies.
- Companies should consider the formation of a **buyer's consortium** for customers interested in RSG procurement. Such a consortium could help support policymaker outreach and education and accelerate the deployment of measurement and verification technologies necessary to certify RSG and enable new markets.

Additional Resources

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