Quantum Sensing for Energy Applications: Review and Perspective

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On its revolutionary threshold, quantum sensing is creating potentially transformative opportunities to exploit intricate quantum mechanical phenomena in new ways to make ultrasensitive measurements of multiple parameters. Concurrently, growing interest in quantum sensing has created opportunities for its deployment to improve processes pertaining to energy production, distribution, and consumption. Safe and secure utilization of energy is dependent upon addressing challenges related to material stability and function, secure monitoring of infrastructure, and accuracy in detection and measurement. A summary of well-established and emerging quantum sensing materials and techniques, as well as the corresponding sensing platforms that have been developed for their deployment is provided here. Specifically, the enhancement of existing advanced sensing technologies with quantum methods and materials is focused on, enabling the realization of an unprecedented level of sensitivity, placing an emphasis on relevance to the energy industry. The review concludes with a discussion on high-value applications of quantum sensing to the energy sector, as well as remaining barriers to sensor deployment.

1. Overview

1.1. Basics of Quantum Information Science

Quantum Information Science (QIS) combines the intellectual foundations of quantum mechanical and information science theories, relying upon quantum mechanics and elements of mathematics, computer science, physical sciences, and engineering. Quantum mechanical theory includes a probabilistic description of matter and energy and can be used to naturally explore physical systems that are not well accounted for within the classical regime. Information theory defines information in terms of the entropy of a variable, enabling modern electronics and computing devices to perform more efficiently. A proper blend of these two established theories has appeared as a new paradigm in science and technology and provides the foundation of QIS. Over the last three decades, QIS has become one of the most rapidly growing fields of research in areas such as physics, chemistry, and engineering.

QIS has already exhibited utility in both communication and computation, and applications are expected to increase in areas such as quantum sensing and quantum networking. Studies have been performed in different research institutions worldwide to explore the utility of QIS in areas including high energy physics, nuclear science and energy, economics, communications, and optimization. QIS is expected to be particularly useful for the energy sector: early stage proposals seeking applications are being investigated in research institutions around the globe in areas such as nuclear energy, material sciences, and energy infrastructure optimizations. QIS is typically divided into four main pillars: quantum sensing and metrology, quantum networking, quantum simulations, and quantum computing. In Figure 1, we summarize the possible energy applications of each of the four pillars of QIS.

In the short and intermediate term, quantum sensing has emerged as a potentially impactful and practical pillar of QIS that could have wide-ranging benefits for a range of economic sectors. Quantum sensing defines the measurement of physical quantities using quantum objects, quantum coherences or quantum entanglement to achieve sensitivities beyond classical limit.
Examples of state-of-the-art commercial sensing technologies which utilize quantum mechanical laws to achieve an unprecedented level of accuracy in measurement include navigation,[6] atomic clocks,[13] gravimeters and gradiometers,[14–16] nuclear magnetic and paramagnetic resonances,[17] and electron microscopes.[18] The U.S. National Quantum Initiative Act, which was signed into law in late 2018, instructs three U.S. agencies—the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE)—to work with academic institutions and private industry to catalyze the growth of QIS.[19] According to the NSF, in the next ten years several opportunities will be enabled in quantum sensors for biotechnology and defense, next-generation positioning and navigation, and timing systems useful to military and commerce, while providing new opportunities to address complex problems in material science, chemistry, and physics. These applications have wide-ranging implications in important areas such as energy and security, impacting everyday life.

1.2. Quantum Sensing for Energy Applications

Ever-growing investment into quantum sensing-based research has created opportunities for quantum sensor deployment in a range of energy-relevant applications. Several exciting areas of application include renewable energy, nuclear energy and nuclear waste management, fossil energy, geothermal energy, electricity delivery and reliability, vehicle electrification, and energy efficiency. Common themes can be identified that span many of these various areas of application including:

1) Monitoring of energy infrastructure and advanced manufacturing

Quantum sensing can be used to realize unprecedented combinations of range, resolution, and sensitivity for measurements of critical parameters of interest. Data from sensor devices with high sensitivity and reliability that are capable of detecting early signs of equipment failure can be analyzed using predictive models[20] to obtain insight on future performance and assess operational state of health with a higher degree of confidence. Such enhanced monitoring systems enable condition-based asset maintenance rather than time-based maintenance, thereby lowering the overall cost and minimizing interruptions and failures. Unprecedented performance and cost trade-offs can be potentially achieved, allowing a broader commercial deployment. As one example, entangled photons can be integrated with an optical fiber sensor platform, which can be evaluated for its ability to maintain quantum coherence over application-relevant length scales. While classical sensing platforms are rapidly advancing, quantum technologies ultimately can push their performance beyond classical limits.

2) Electricity delivery transmission, distribution, and storage

Monitoring power losses during energy transmission, storage and distribution, and accurately calculating the techno-economic viability of power utilities requires electrical grids that are integrated with advanced optimization tools. Electrical grids are complex interconnected networks that transmit power from producers to consumers. Existing electrical grids can benefit from integrating “smart grid” technologies, including quantum security, networking, computing, and sensing features.[21] Sensors are often deployed to monitor the performance and integrity of the grid and to analyze parameters such as temperature and strain/stress in overhead power lines, towers, and transformers.[22,23] If quantum sensing materials are developed that can function in extreme environments, they will improve
power grid performance by providing improved sensitivity and/or faster response times when monitoring grid health.

3) Building energy efficiency

Smart buildings, which conserve energy by automating ventilation, heating, lighting, and other energy-consuming systems to minimize waste, can benefit from technology derived from QIS. Energy usage is monitored and optimized using a series of sensors and actuators that track energy consumption throughout the day, enabling demand to be met more efficiently. Opportunities exist for quantum sensors to be integrated into smart buildings and smart grids, and for quantum computing and simulations to solve optimization problems for energy distribution. Together, these steps will ensure that resources are distributed such that energy consumption is minimized.

4) Nuclear energy

Deployment of quantum sensors in nuclear power plants has potential to aid in greater plant efficiency and safety. A recent Nuclear Science Advisory Committee (NSAC) QIS subcommittee’s report on nuclear physics and QIS laid out recommendations for integrating QIS (particularly quantum sensing) for national nuclear security. For example, an atom interferometric quantum sensor could be used for detecting isotopes in nuclear energy plants. Highly sensitive QIS-enhanced devices can not only detect early stages of radiation breaches but also can provide avenues for remote monitoring of safety-related issues in the power plant.

The current status of quantum sensors in the fossil energy domain and perspectives on the potential applications of quantum sensing for subsurface surveying and scanning, natural gas infrastructure, and critical element detections using quantum enhanced sensing technologies are discussed in more detail in the next section.

1.3. Quantum Sensing for Fossil Energy Applications

In Figure 2, we present the Energy Information Administration’s (EIA) projection of world energy growth from 2000 to 2050 for energy consumption by fuel type, and it shows an ever-increasing trend of fossil energy consumption within that time frame, at a similar growth rate as nuclear, renewables, and liquid fuel types. Fossil energy remains the dominant resource for energy usage. The statistics showed that in 2018, global energy consumption grew at a rate of 2.9%, which was the fastest growth since 2010. Global oil consumption grew by 2.2 million barrels per day, and coal consumption doubled its ten years growth rate with a 1.4% increase. On the other hand, carbon emission rose by 2% in the last seven years. According to the recent data for the world’s total primary energy supply, the percentage of the total energy from three major sources coal, oil and natural gases are 27%, 32%, and 22%, respectively, with remaining energy derived mainly from nuclear, biofuels, wind, and solar power. While alternative sources are expected to grow in coming years, fossil fuels are anticipated to be the primary source of global energy for decades to come. Fossil fuel-based electricity generators currently only exhibit efficiencies on the order of ≈30%; and so increasing electricity generation efficiency with fossil energy and allowing for reliable resource recovery, extraction, transport, and utilization are key societal challenges, along with curbing greenhouse gas emissions.

Fossil energy application areas are commonly separated into the following: coal mining and recovery, CO₂ utilization and coal beneficiation, carbon capture and sequestration, upstream oil and gas, midstream oil and gas, downstream oil and gas, electricity generation, and electricity transmission and distribution. The domain of fossil energy production can potentially exploit the opportunities that are offered by quantum technologies to provide higher levels of safety and security.

Specifically, quantum sensors can be used to remotely monitor oil and gas flows with a higher confidence in downstream, midstream, and upstream stage of oil and gas production. The sensitivity of existing distributed sensing systems designed for monitoring gas flows in pipelines and boreholes can be further enhanced by using entangled photons whose polarizations...
encode quantum information. In addition, quantum sensors can be used to scan the subsurface to detect oil, gas, and mineral deposits with higher accuracy than existing technologies. Sensors based on the nitrogen vacancy in nanodiamond are highly sensitive and have potential applications in critical elements detection and recovery (see Section 2.3.2). Detection of low levels of methane from natural gas infrastructure monitoring can enable improved quantification of methane emissions, an important greenhouse gas. The detection of low levels of CO₂ will enable better monitoring, verification and accounting in carbon sequestration applications while also aiding in the early identification of impacts on water quality and wellbore integrity. By integrating concepts of QIS in existing traditional sensing technologies, unprecedented performance and cost trade-offs will be potentially achieved. Table 1 summarizes sensing needs that quantum sensors may address for each fossil energy area.

Table 1. Potential applications of quantum sensing in fossil energy areas.

| Fossil energy area                          | Sensing application                                                                 |
|--------------------------------------------|--------------------------------------------------------------------------------------|
| CO₂ utilization and coal recovery          | Rapid, sensitive detection of CO₂ emission and leaks, graviometers for coal exploration, coal mine safety |
| Upstream oil and gas                       | Quantum gravimeters for the detection of oil/gas deposits                            |
| Midstream oil and gas                      | Monitoring pipeline integrity during transport and storage                            |
| Downstream oil and gas                     | Monitoring CO₂ emission during consumption                                           |
| Carbon capture and storage                 | Rapid, sensitive detection of CO₂ emission and leaks                                |
| Coal mining and recovery                   | Sensing of critical metal elements from coal and coal utilization byproducts, graviometers for coal exploration, coal mine safety |
| Electricity generation and distribution    | Sensors monitoring electromagnetic fields                                             |
| Nuclear physics and energy                 | Monitoring temperature in transformers                                               |
|                                            | Monitoring national nuclear security, superconducting quantum interference devices (SQUIDs) |

Figure 3. General scope of this review: different components of quantum sensing and their relevance to sensing needs within the energy sector.

graviometers and magnetometers have already proven useful for fossil energy in exploring oil and gas resources and subsurface characterization. A brief discussion of commercially available quantum sensing technologies is included, emphasizing that quantum sensors are sufficiently mature to be deployed within the market. The review concludes with an overview of remaining barriers to and challenges for continued quantum sensor deployment and a discussion of future opportunities to introduce quantum technologies into the energy sector. Taken together, this review is intended to familiarize researchers within the energy sector with quantum sensing technologies, while providing experts in quantum sensing an overview of potential areas of need in the energy sector that could benefit from quantum sensors. Figure 3 highlights a general scope of this review.

2. Quantum Sensing

2.1. Overview of Quantum Sensing Principles

Quantum sensing is broadly defined as the use of quantum materials, quantum coherence, and/or quantum entanglement to measure physical quantities (i.e., temperature, electromagnetic fields, strain, etc.) and/or to enhance the sensitivity of classical analytical measurements. Two prominent strategies may be exploited for quantum sensing. The first, photonic quantum sensing, exploits the quantum nature of light for a range of sensing applications, from remote target detection to the readout of optical memory. Nonphotonic quantum sensors, which rely on spin qubits, trapped ions, and other materials with well-defined quantum states have also been developed for applications including magnetometry, thermometry, and others. Both quantum sensor types may also be used to enhance the performance of classical sensor systems with the promise of reduced noise as compared to the so-called "shot limit."

To construct a working quantum sensor with any candidate material, DiVincenzo and Degen outlined a set of three necessary conditions that must be followed: i) The quantum system must have discrete resolvable energy levels (or an ensemble of two-level systems with a lower energy state (0) and an upper energy state (1) that are separated by a finite transition energy; ii) it must be possible to initialize the quantum sensor into a well-known state and to read out its state; iii) the quantum sensor can be coherently manipulated, typically by time-dependent fields.
The interaction with these fields leads to a shift of the quantum sensor’s energy levels or a change in the transition energy gap. Figure 4 shows a summary of publications on the topic of quantum sensors with a focus on materials, sensing, and devices. As one can see, during the past few decades the developments of quantum sensing has increased rapidly.

Table 2 broadly summarizes the different types of quantum sensors with their features, advantages, and challenges. This section will highlight relevant quantum sensing approaches, techniques, and materials with potential for energy-relevant applications.

Quantum sensing[6,16,38,40] deals with the optimal estimation of classical parameters encoded in quantum transformations, offering maximum precision at the fundamental limits. There are many successfully demonstrated applications, from enhancing gravitational wave detectors to precisely determining quantities such as length, speed, and material properties and improving optical resolution of extremely close point-like sources.

Figure 5a summarizes the ten-year forecast of quantum sensor markets by sensor type, while Figure 5b highlights the main current applications of quantum sensors. Although quantum sensing has attracted a great deal of attention, many challenges prevent their practical deployment for industrial applications.[16,49] One prominent barrier at present is the lack of hardware designed for actual sensing in temperatures and conditions that would be encountered during use outside of a controlled laboratory setting. Hardware restrictions often limit the actual sensor performance, creating a gap between theory and actual sensing results.[50] Indeed, quantum sensing is well developed for photonic applications compared to other areas of QIS mainly because quantum optics provides the most mature and convenient setting for implementing quantum metrology without the need for cryogenic operational temperatures or other constrained operational conditions.[36] The loss of quantum coherence, often accelerated by environmental loss and noise, is another barrier to sensor deployment: nonclassical states are essential for quantum metrology because they can increase the signal-to-noise ratios of quantum metrology systems, but are vulnerable to loss.[41] For nonphotonic quantum sensors, material costs, operational temperature requirements, and production challenges also arise, and research toward scalable and robust material fabrication are on-going.[51,52] Thus, widespread use of quantum sensing is limited by both materials science and instrumentation barriers.

### 2.2. Quantum Sensing Techniques and Materials

Sensing materials play an important role in many sensor devices by providing a well-established, sensitive, and reversible response to key parameters of interest and generating a detectable signal (optical, electrical, mass, acoustic, etc.). A promising assortment of sensing materials[6,37] have been developed that use quantum processes to probe environmental properties...

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**Table 2. Different types of quantum sensors.**

| Technology                  | Quantum features                     | Experimental conditions                      | Advantages vs classical systems             | Challenges                               | Refs. |
|-----------------------------|---------------------------------------|---------------------------------------------|--------------------------------------------|------------------------------------------|-------|
| Nonphotonic quantum sensors | Spin qubits, neutral atoms, trapped ions | Multiple parameter measurements             | High sensitivity, low noise               | Decoherence, quantum projection noise      | [6]   |
| Remote target detection     | Quantum illumination, quantum entanglement | Quantum interferometry                      | Enhanced signal to noise ratio            | Very fragile with respect to optical loss | [41]  |
| Quantum radar               | Microwave quantum illumination        | Quantum interferometry                      | Expose stealth targets                    | Lack of photon-microwave converters      | [42]  |
| Quantum spectroscopy        | Quantum entanglement, single photons  | Intensity correlation measurements          | Beyond the shot-noise limit, approaching the ultimate quantum limit | Quantum decoherence                      | [43]  |
| Quantum microscopy          | Quantum entanglement, quantum detection | Microscopy and quantum detection            | Super-resolution beyond the Rayleigh limit | Unknown location of the source centroid   | [44]  |
| Quantum interferometers     | Entangled states, squeezed light       | Smaller-scale interferometers               | Heisenberg scaling                        | Very fragile with respect to optical loss | [45]  |
| Gravitational wave detector | Squeezed light                        | Kilometer-sized interferometers             | Heisenberg scaling                        | Very fragile with respect to optical loss | [46]  |
| Quantum reading of optical classical memory | Quantum channel discrimination | Interferometer and single-photon source | Error-free, faster optical readers and denser memories | Using photon sources and detectors with very high efficiency | [47]  |
including temperature, electric and magnetic fields, pH, thermal conductivity, strain, and force, among others. Here, several prominent classes of materials used in quantum sensing applications are briefly discussed and summarized, including emerging materials such as quantum metal–organic frameworks (MOFs) that may exhibit promise as sensors with further research and development.

Materials suitable for use as quantum sensors must meet the DiVincenzo and Degen criteria described above. In addition, the sensor must be able to selectively interact with variables of interest (i.e., magnetic field, pH, temperature, etc.) in a way that predictably alters the material’s quantum states, such as a shift in their respective energy levels. In tandem, quantum materials may be used to enhance classical sensing performance. This section will introduce general techniques and definitions related to quantum sensor materials, followed by a discussion on specific quantum materials and examples of how they have been deployed for sensing applications.

2.2.1. Sensing Techniques Using Quantum Materials

The initialization, manipulation, and read-out of states for quantum materials may be probed using a variety of optical and magnetic techniques. This enables changes in the read-out to be determined as a function of environmental factors such as electromagnetic field or temperature. The read-outs discussed here include the zero phonon line (ZPL), optically determined magnetic resonance (ODMR), spin relaxation times, optical charge conversion (OCC), and level anticrossings (LACs).

i. Zero phonon lines

Because quantum materials involve a single transition between two distinct, defined energy levels (or quantum states), single photon emission (SPE) may be induced. Here, optical excitation leads to a transition from the ground state to the excited state; during relaxation, single photons are released at a given time (i.e.,
the probability of multiple photons released at a single time is equal to $0$. While a distribution of emission energies may be observed from SPEs due to coupling between electronic and vibrational states, leading to a broadening of the emission spectrum, certain percentage of the emitted photons do not involve vibrational coupling, and their emission is simply equal to the energy gap between the ground and excited energy level. This “zero phonon line” emission band appears as a single narrow emission band in the emission spectra of some quantum materials. 

Sensing using the ZPL operates under the same principle as classical fluorescence-based sensors, in which changes in emission peak energy, intensity, and/or breadth in response to environmental changes may be exploited for sensing applications. However, the intrinsic narrowness of the ZPL provides enhanced sensitivity and reproducibility for probing small changes in environmental variables such as temperature with high spatial resolution.

ii. Optically detected magnetic resonance

Perhaps the most widely used quantum material property for sensing applications is ODMR, which is often observed in diamond nitrogen vacancy centers (NV-) and other materials. The energy diagram of NV- in diamond is shown in Figure 6.

Briefly, optical excitation of NV- centers leads to a transition from the ground state $I_s$ to the triplet excited state $I_s^>$, and relaxation can occur via fluorescence near the ZPL or through an intersystem crossing to $I_s^>$ followed by the emission of a lower energy (near infrared) photon, leading to a ground state preferentially in the $m_s = 0$ spin state. Electrons in the $I_s$, $m_s = \pm 1$ state are more likely to undergo an intersystem crossing than those in the $I_s$, $m_s = 0$ state, and, because spin is preserved during optical excitation, a difference in the luminescence lifetime is observed for electrons excited out of the $I_s = 0$ state versus the $I_s = \pm 1$ state. Pumping the system with microwave (MW) radiation resonant with the ground state triplet spin transition places the system in the degenerate $m_s = \pm 1$ state. However, the presence of a magnetic field lifts the degeneracy of the $m_s = \pm 1$ state, causing Zeeman splitting (Figure 6, inset) and a corresponding decrease in the fluorescence intensity at the resonant frequencies between $m_s = 0$ and $m_s = -1$ and between $m_s = 0$ and $m_s = 1$, due to partial population transfer to “dark” $m_s = \pm 1$ states. The ODMR spectra plots the luminescent intensity as a function of frequency (Figure 7a,b), and the frequency separation between the two spin transitions (where the intensity decreases) can be used to probe parameters such as temperature and magnetic field strength (Figure 7c,d).

iii. Spin relaxation lifetime

Spin relaxation techniques have been used with NV- centers in nanodiamonds to sense the presence of nearby nuclear spins. Here, changes in the quantum material’s longitudinal spin relaxation time $T_1$ are monitored by optically sampling the population difference in the quantum material’s ground state. This difference is determined by random jumps due to a fluctuating magnetic field in the dynamic environment. Changes in initial fluorescence in the pulsed fluorescence measurements are monitored. This enables the detection of the presence of nuclear spins in the vicinity of the quantum material center down to a single atom level. For example, Figure 8 illustrates the detection of magnetic noise from a Gd$^{3+}$ ion near a shallow NV- center.

iv. Optical charge conversion

OCC techniques can be exploited in quantum materials for sensing applications. Here, optical transitions to different vacancy center charge states can be monitored using photoluminescence spectroscopy. Optical pumping promotes excitation to luminescent “bright” charge states, and conversion to non-luminescent “dark” states can then be induced using a second lower-energy pulse. Sufficiently fast detectors can monitor the conversion from “bright” to “dark” states, and the rate of this conversion is highly sensitive to external microwave or radio-frequency electric fields. An example of an OCC set-up and experimental data is shown in Figure 9, where silicon carbide (SiC) is used for electric field detection. Here, the reset illumination is either 365 or 405 nm, with a pump color of 976 nm. Illumination at 365 nm generates electron–hole (e–h) pairs that reset VV to VV0 (bright state) in the steady state, at 405 nm
directly ionizes \( \text{VV}^- \) (dark state) to \( \text{VV}_0 \), and at 976 nm excitation converts \( \text{VV}_0 \) to \( \text{VV}^- \) by direct two-photon ionization or indirectly by one-photon ionization of local traps. In addition, \( \text{VV}_0 \) photoluminescence is provided through excitation at 976 nm. \( \text{VV}(0/-) \) is the transition energy level between the neutral and negatively charged states. \( \text{VB} \) and \( \text{CB} \) are the valence and conduction bands, respectively. An RF electric field (rms amplitude \( E \), frequency \( f_0 \)) is applied across a coplanar capacitor with a 17 \( \mu \)m gap. \( \text{VV}_s \) are created by carbon implantation immediately below the surface. A fast detector with 10 MHz bandwidth (BW) allows for direct detection of a full OCC transient signal in a single measurement. Figure 9b shows an example of data collected using this technique.

v. Level anticrossing spectroscopy

Level anticrossing spectroscopy techniques that require only optical measurements, without the use of an external rf field,
can also be deployed for sensing applications.[77] Here, ground state level anticrossings (GSLACs) between spin states, such as \( m_s = -3/2 \) and \( m_s = 1/2 \) or \( m_s = -1/2 \), give rise to photoluminescence resonance peaks upon magnetic excitation. When an applied magnetic field is in resonance with a given GSLAC, the external magnetic field being sensed will lead to a deviation in the PL intensity, which can be measured using a lock-in in-phase photovoltage.[77] Figure 10 illustrates the level scheme for NV\(^-\) centers in diamond. Here \( m_s \) is the electron spin projection quantum number, \( D_g \) and \( D_e \) are the ground- and excited-state zero-magnetic-field splittings, \( \Omega_{MW} \) is the MW Rabi frequency, \( \gamma_{g}^{\pm} \) and \( \gamma_{g}^{\mp} \) are the relaxation rates from the singlet \( ^1E \) to the triplet ground-state \( ^3A_2 \), and \( \gamma_{e}^{0} \) and \( \gamma_{e}^{\pm} \) are the relaxation rates from the triplet excited state \( ^1E \) to the singlet state \( ^1A_1 \). The GSLAC technique has been used to observe fluctuating magnetic fields at frequencies from 500 kHz to 8 MHz.[78]

2.2.2. Quantum Sensing Materials

i. Atom/ion sensors

One of the more widely explored strategies for quantum sensing relies upon the atomic spins of neutral atoms, electric states and vibrational modes of trapped ions, and Rydberg states in Rydberg atoms, each of which can be initialized and readout using optical techniques.[6] Common neutral atoms are typically alkali metals, such as cesium or rubidium, which can be used as a thermal atomic vapor (typically in a cell with a buffer noble gas, such as argon or neon),[80] or they can be laser cooled in a vacuum chamber.[81] Atomic vapors are best known for their use in atomic clocks[82] and magnetometry,[83] while cold atom sensors are most famously used in commercially available gravitometers (see Section 2.4.1),[84] with applications in inertial sensing as well (e.g., navigation).[85]

A range of trapped ion sensors have been developed, using ions such as \(^{88}\text{Sr}^+\), \(^{171}\text{Yb}^+\), \(^{24}\text{Mg}^+\), and \(^{9}\text{Be}^+\), and have been studied as sensors for applied force,[86] spectroscopy,[87] electric...
and magnetic fields,\[88\] and as atomic clocks.\[89\] Another class of atom-based quantum sensors include Rydberg atoms, which are most frequently used to detect electric fields,\[90\] and in recent years have also been used in the detection of magnetic fields.\[91\] Atom and ion quantum sensors are among the most mature classes of quantum sensors, and are currently available commercially in atomic clocks and gravimeters/gradiometers (Section 2.4). However, barriers including the need for liquid helium temperatures (in the case of cold atoms) and/or vacuum conditions can hinder applications in the harsh environments (e.g., elevated temperature, pressure, corrosive conditions, etc.) that are often encountered for energy applications. Consequently, solid-state qubits have received increasing attention for quantum sensing, and these materials are discussed in subsequent sections.

ii. Carbon nanodiamonds

Carbon nanodiamonds have emerged as an exciting quantum material with demonstrated sensing efficacy in the detection of temperature,\[54–56,71,92\] strain,\[65,66\] pH,\[62,63\] electric,\[93,94\] and magnetic fields,\[60,61\] fields, spin,\[95\] thermal conductivity,\[64\] and the phases of water molecules,\[96\] even under harsh conditions such as high pressure.\[97\] Quantum emission is enabled via defect sites within the nanodiamond; these “color centers” are lattice defects from carbon vacancies and atomic impurities such as nitrogen\[34,74,98\] (NV), silicon\[99,100\] (SiV), tin\[71,101\] (SnV), germanium\[100,102\] (GeV), and other atoms.\[103,104\] Luminescence from single defect sites in nanodiamond can be experimentally observed,\[72\] and changes in luminescent features such as the ZPL energy, width, or amplitude may respond to environmental factors such as temperature, enabling them to act as luminescent sensors.\[55,71\] For example, nanodiamonds (diameter <250 nm) containing SiV centers exhibit a narrow emission band at its ZPL (≈740 nm) upon excitation with a 532 nm laser, with a broader, low-intensity phonon sideband (PSB) peak centered at ≈765 nm. Changing the temperature of the nanodiamond impacts the ZPL amplitude and both the energy and width of the PSB and ZPL emission peaks.\[72\] Consequently, Plakhotnik and co-workers used a multiparametric technique analyzing the SiV nanodiamond ZPL position, width, and amplitude in tandem as a function of temperature, which enabled the detection of temperature changes as low as 0.4 °C within 1 ms.\[72\] Similarly, Akimov’s group used the ZPL position and peak width of GeV-center nanodiamonds to monitor temperature.\[92\] With increasing temperature, a red-shift and broadening of the ZPL peak was observed, which enabled temperature changes as small as 0.1 K to be detected within a range of 150 to 400 K, with the ability to operate over a total range of 4 to 860 K (Figure 11).\[92\] Similar fluorescence-based detection of temperature changes have also been accomplished using NV\[−\]\[105\] and Sn\[71\] centers. The use of high-performance thermometers is particularly useful for fossil energy applications, including monitoring the health of power grids\[23\] (i.e., temperature in transformers\[22\] and transmission lines), oil refining processes, pipeline integrity,\[106,107\] and coal mine safety,\[108\] among others. The widespread deployment of quantum thermometers requires the sensor platform to be made sufficiently economical to compete with existing technologies. Additionally, demonstrated superior sensitivity and the ability to function under harsh conditions (i.e., temperatures >250 °C, high pressure, corrosive environments, etc.) will be crucial for NV\[−\] center-based thermometers to be commercially viable.

In the case of the negatively charged NV\[−\] centers and the more recently characterized SiV\[+\] centers,\[109\] the diamond’s fluorescence intensity is also sensitive to microwave radiation, providing an additional sensing mechanism via ODMR experiments (vide supra).\[34\] While NV\[0\] and NV\[−\] centers are known, their optical and magnetic activities are poorly understood\[34,110\] and studies on these centers have thus been limited.\[111\] Consequently, quantum sensing experiments typically use only the NV\[−\] center. The sensitivity of the ODMR peak separation as a function of magnetic field strength has made NV\[−\] centers obvious candidates for use in magnetometry\[112,113,114\] applications. A simple example of this phenomena is shown in Figure 12, in which the frequency separating two spin transitions in a single NV\[−\] center increases as a function of increasing magnetic field, demonstrating how NV\[−\] can be utilized to determine the strength of an external magnetic field with high spatial resolution (angstrom scale).\[112\] The ODMR readout of magnetic fields has also been extended for more advanced applications including time-resolved magnetometry,\[61\] nuclear magnetic resonance spectroscopy techniques,\[34,115\] detection of electronic and nuclear spins,\[116\] and magnetic imaging.\[112,117\]

The diamond NV center consists of a nitrogen atom neighboring a vacancy and three carbon atoms. The symmetry of the defect is C3\[h\] containing A1, A2, and E irreducible representations. The
Hamiltonian of the NV center can be described as \[ H = \frac{\hbar}{4} \left( S_z^2 - \frac{2}{3} \right) + \gamma B \cdot S + \epsilon_z E_z \left( S_z^2 - \frac{2}{3} \right) \]
\[ + \epsilon_x \left( E_x (S_z S_x + S_y S_z) + E_y (S_y^2 + S_z^2) \right) \] (1)

The first term is the zero field splitting parameter, where the different factors arise from nonvanishing $S_z$, $S$ commutator, $D = 2.87$ GHz, the second term is the magnetic component, where $B$ is the vector magnetic field, and the third term describes the electric field component, where $E$ denotes an electric field and $\epsilon$ denotes a coupling constant. The zero field splitting term $D$ is sensitive to strain, pressure, and temperature.\[14\] Because each component of the Hamiltonian is sensitive to different parameters, it is possible to extend the sensing efficacy of NV− centers beyond magnetic sensing, particularly in the presence of weak external magnetic fields or if the experiment is designed to cancel the effects of external magnetic fields,\[66\] because the Zeeman effect is significantly stronger than other splitting effects (such as the Stark effect, vide infra) in the ground state.\[14,93,94\] Of course, this responsiveness to other parameters poses significant cross-sensitivity challenges because multiple variables may influence the sensor response, and additional research is needed to isolate variables of interest before NV− systems may be deployed in complex environments.

Several strategies may be employed to mitigate or insulate the NV center from magnetic fields, enabling the ODMR technique to be applied to detect other experimental variables of interest.\[118\] One method involves the alignment of an external magnetic field in the nonaxial plane ($B_z = 0$), leading to the observation of only the central hyperfine transition in the ODMR spectrum, which is susceptible to splitting with electric field and strain.\[93\] Once the magnetic field is mitigated, shifts in the NV− ground triplet-state spin sub-levels resulting from an external electric field can be monitored in the ODMR spectrum due to the Stark effect, enabling electric field detection.\[93,94\] It must be emphasized that electric field sensing using this technique may only occur when the internal electric or strain fields are significantly stronger than the magnetic field along the NV− axes.\[14\] Hence, careful alignment of the external magnetic field to the nonaxial plane is critical for isolating the electric field variable, and the use of a magnetically shielded experimental design may further improve the use of NV− centers in electrometer and strain sensing applications.\[93\] ODMR can also be used to provide a read-out of lattice strain. For example, cantilever-based experiments have been used to apply longitudinal and axial strain on NV− nanodiamonds, producing both a shift in the frequency of the zero-field ODMR line and splitting.\[65,66,119\] Because lattice strain can also be thermally induced, external temperature may also be probed with high spatial resolution by monitoring the frequency of the NV− ODMR spectra as a function of temperature following strain-induced hyperfine splitting.\[54\] It has also been demonstrated that the frequency of the ODMR splitting parameter ($D$) will linearly shift to higher frequencies with increasing pressure, with a corresponding blue shift in the ZPL; hence, NV− nanodiamonds represent a versatile material for pressure sensing using optical techniques.\[120\] Thus, although the NV− system is versatile, a key barrier to the development of practical NV− sensors is that multiple variables can simultaneously influence the ODMR response, and additional strategies are needed to develop sensors that will only respond to single variables of interest.

In addition to ODMR, an emerging method for all-optical sensing using diamond is spin relaxometry. In the presence of nearby magnetic molecules such as Mn$^{2+}$, O$_2$, and Gd$^{3+}$, the longitudinal relaxation rate $R_1$ increases and the longitudinal relaxation time $T_1$ decreases, enabling NV− nanodiamonds to be deployed as ion and molecule sensors (see, for instance, Figure 8).\[63,75,76\] Subsequent works have placed Gd$^{3+}$ near the NV− center for relaxometry-based sensing of pH and redox potential. Here, pH or redox-active polymers were used to selectively and reversibly release Gd$^{3+}$ from the nanodiamond surface into solution (i.e., via redox-induced disulfide cleaving) as a function of pH or redox potential, leading to a response in $T_1$.\[63\] The Brownian motion of a Gd$^{3+}$ complex in solutions of different viscosities was also monitored by probing the $T_1$ of the nanodiamond NV− center.\[121\]

Another NV center approach gaining the momentum is NV center NMR spectroscopy, which allows discrimination of atomic species at the nanoscale level. The basic notion is that the application of short pulses allows one to set up a frequency-dependent effective proton field in the vicinity of the NV center. Several methods such as pulse-echo and dynamic decoupling have been demonstrated for NMR sensing.\[122,123\] Examples of the methods used for ODMR, spin relaxometry, and NMR are shown in Figure 13. Both bulk diamond and nanodiamond NMR find applications in various areas of applied research.\[124\] Research is on-going to discover and characterize new color centers\[104\] and to integrate well-studied systems such as NV nanodiamonds into devices\[125,126\] relevant for sensing applications, including portable systems\[50,52,114,127\] which represent exciting next steps in the integration of this quantum material into practical technologies.

### iii. Silicon carbide

Color centers in SiC have emerged as intriguing quantum materials that exhibit similar properties to nanodiamonds.
There are over 200 polytypes of SiC with a wide array of reported color centers, producing a rich space of potential properties.\cite{37,53} In particular, 6H-SiC and 4H-SiC, the most commonly studied SiC polytopes, exhibit near-infrared emission that minimizes absorbance from optical fibers, facilitating integration into optical devices for sensing applications.\cite{53,130} Consequently, SiC-based quantum sensors have been explored for measuring magnetic fields\cite{131,132}, temperature (10–310 K),\cite{133} strain,\cite{134} and electric fields,\cite{57,58} among others. The silicon monovacancy (V$_{Si}^-$) and divacancy (V$_{Si,Si}$, with missing adjacent Si and C atoms) are the two most well-studied SiC centers for quantum applications.\cite{37,98} The neutral divacancy V$_{Si,Si}^0$ has a spin quantum number of 1 (S = 1), with optical properties that are similar to NV$^-$ vacancies in diamond. The negatively charged silicon monovacancy V$_{Si}^-$ has a S = 3/2 system, leading to differences in electronic structure relative to V$_{Si}^0$ (Figure 14).\cite{98,130,135} Both centers exhibit ODMR (with vacancy-dependent differences in ODMR features) that can be exploited for sensing applications. Additionally, unlike the NV$^-$ center in diamond, V$_{Si}^-$ spins exist only in one orientation, which simplifies interpretations of magnetic resonance transitions.\cite{136} The ODMR method has specifically been used for magnetometry,\cite{53,99,77} thermometry,\cite{53,137} strain characterization,\cite{131,138,139} and electrometry,\cite{139} using similar techniques to those described above for NV$^-$ diamond centers.

Like the NV$^-$ centers, because SiC is responsive to a multitude of variables, care must be taken during experimental set-ups to isolate variables of interest. In addition to strategies discussed in the nanodiamond section (vide supra), one possible advantage in SiC is the multitude of addressable high spin centers that may exist in a single SiC crystal. It has been shown that certain centers exhibit low sensitivities to temperature, for example, rendering them excellent candidates for magnetometry applications, whereas other centers are highly sensitive to temperature changes and are less sensitive to magnetic fields, making these centers preferable for thermometry applications.\cite{53} The ability to selectively engineer specific color centers for specific sensing targets would represent a critical step in advancing the viability of ODMR-based quantum sensors. Continued research and development of SiC centers that are sensitive to only one variable are therefore crucial.

OCC can also be exploited for sensing applications (see Section 3.2) using SiC. For example, Figure 9 demonstrates a set-up in which the OCC is used to image acoustic waves on piezoelectric surface-acoustic wave (SAW) devices.\cite{57} OCC has also been used for strain sensing applications.\cite{134} A recent update has improved the sensitivity of this technique by applying a reference electric field during the measurement.\cite{58} This high spin V$_{Si}^-$ center can be further exploited for the detection of magnetic field, temperature, and strain using level anticrossing spectroscopy techniques (see Section 3.2 and Figure 10).\cite{77} For example, Figure 15 illustrates the sensitivity of the V$_{Si}^-$ PL to temperature.\cite{77} This technique has also been exploited for both magnetometry\cite{77,140} and thermometry\cite{133} applications.

SiC is quickly emerging as a versatile material for quantum sensing applications, with advantageous properties including optical fiber-relevant emission wavelengths, processability, and
the ability to operate at room temperature in ambient conditions. Research focused on integrating SiC color centers into devices,[125,141] improved material processing,[129,132] and the discovery of new optically active vacancy centers[106,142] should further expand the utility of SiC centers in energy-based sensing applications.

iv. Rare earth ion-doped solids

The line-like emission bands from lanthanide ion f-orbitals, which are shielded from the environment by their outermost filled s and p orbitals, have long been valued in luminescent applications such as biological imaging, lighting displays, and sensing.[143] Their narrow emission bands and high degree of shielding has led to recent exploration of lanthanide ions doped into solid crystals for quantum applications, and while these transitions are parity forbidden in free space, they become weakly allowed when dispersed in a crystal field, particularly at cryogenic temperatures.[198,144] Despite their relatively weak emission,[198] the long nuclear spin relaxation and coherence times of rare earth ions,[198] coupled with relatively facile synthetic strategies,[144] have spurred significant interest in developing rare earth-based quantum materials. While not extensively evaluated for sensing applications, a range of rare earth-ion doped solids have been produced, including europium and erbium-doped yttrium oxide,[145] europium-doped yttrium silicate (Y2SiO5),[146] samarium nickelate,[147,148] cerium,[149] and praseodymium[150,151]-doped yttrium aluminum garnet (YAG), thulium-doped lithium niobite,[152] and others.[144]

Similar to color centers in diamond and silicon carbide, rare earth-doped solids can exhibit ODMR (Figure 16), suggesting potential utility in sensing applications. Optical readouts of individual REEs have been demonstrated in Ce(III)−,[149] Pr(III),[150] and Tb(III)-doped YAG,[153] Nd(III)-doped niobium,[154] Eu(III)-,[155] and Yb(III)-doped Y2SiO5[156] among others. Quantum sensing of external magnetic fields has been demonstrated for 151Eu3+ doped into Y2SiO5,[146] and the sensitivity of optically measured level anticrossings to external magnetic fields has been studied in holmium(III)-doped 7LiF5Y[157] providing early promise.

Figure 16. ODMR signal of a single Ce3+ ion (in YAG) as the frequency of microwaves (MW) is swept across the spin resonance. Inset shows level structure of the ground-state and the optically excited spin doublets. The red line is the Lorentzian fit to the observed signal. Measurements were conducted at ≈3.5 K. Reproduced with permission.[149] Copyright 2014, Springer Nature.
that rare earth ion-doped solids may have utility as quantum sensors. 

v. Perovskites

Perovskite materials of the general formula ABO$_3$, where A and B are metal atoms, are commonly used in a variety of classical sensing applications. An interesting subclass of perovskites (such as metal nickelates) have unfilled d-orbitals in which a single electron influences the behavior of surrounding electrons. These strongly correlated quantum materials exhibit unique, complex properties that have utility for sensing applications, particularly in harsh conditions. Sensing using these perovskites involves manipulating the material’s electronic orbitals under applied bias, which can be explained by semiclassical theory. For example, biomolecules and electric fields can be detected by exploiting the strongly correlated electronic system of samarium nickelate (SNO). Under negative bias in the presence of protons, hydrogen intercalates into the SNO lattice. This work was extended to biological systems, where SNO was functionalized with a glucose oxidase enzyme. In the presence of glucose concentrations as low as $5 \times 10^{-16}$ M, a spontaneous proton transfer in the presence of the enzyme took place, again increasing the resistivity of the HSNO.

vi. Quantum dots

Single photon emission has been reported for atomically thin transition metal dichalcogenides (TMDCs, e.g. MoSe$_2$), 2D materials including hexagonal boron nitride (hBN), colloidal quantum dots (such as ZnS and InP/ZnSe), and stacked, semiconductor quantum dots such as InAs. While a variety of “quantum dots” with high-performance emission properties have been developed, for QIS applications the quantum dots must exhibit the controlled emission of a single photon per light pulse, produce photons in an indistinguishable quantum state, and emit with high efficiency. While single photon emission has been achieved with multiple quantum dot systems, epitaxially grown quantum dots such as InAs in GaAs have, to date, been the most widely used for single photon applications. A lattice-mismatch strain-driven approach is used to spontaneously form monodisperse islands with quantum confinement in three dimensions, yielding single photon emission within the telecom band. Together, single photon emitting-quantum dots represent another emerging quantum material with potential for sensing applications. Similar to the rare earth-doped solids (vide supra), reports of quantum sensors based on quantum dots are limited. However, room temperature ODMR has been observed for boron vacancy sites in hBN with $S = 1$ spin, indicating that these materials may be deployed as optical sensors analogous to color centers in SiC and diamond. Additionally, it has been demonstrated that the emission properties of hBN are sensitive to external magnetic fields, further reinforcing the promise of hBN as quantum magnetometers. Further, the hBN single-photon emission is sensitive to both external electric fields and strain from acoustic waves, suggesting that this material may be suited for electrometry and strain sensing applications.

In addition to hBN, a mechanical motion sensor based on InAs quantum dot single-photon emission has been developed. Here, charged InAs quantum dots are coupled to a mechanical resonator, such as a tuning fork. In the presence of a magnetic field, the InAs emission bands shift in response to strain induced by vibrations from the mechanical resonator. In addition to mechanical force, shifts in the InAs optical features in response to an AC field have been reported as well as Zeeman effect splitting in response to an external magnetic field. Greater control over the ability to both manipulate and monitor the quantum states of InAs quantum dots should therefore yield a new sensing platform for magnetometry and electrometry.

Figure 17. a) Schematic illustrating electronic field sensing using the strongly correlated quantum perovskite SmNiO$_3$ (SNO). Schematics of the electronic structure of Ni 3d orbitals in b) hydrogenated and c) pristine SNO. The electrons become localized in HSNO owing to the strong Coulomb repulsion in doubly occupied $e_g$ orbitals above the $t_{2g}$ orbitals. $U$ represents the on-site electron-electron correlation. d) The experimentally observed change in the electrical resistance ($\Delta R$) for bias potentials from 0.5 V to 5 mV, with error bars representing standard deviations. The dashed line is a linear extrapolation estimate of the resistance change beyond the experimentally measured window. This measurement range spans the bioelectric potentials generated by different maritime vessels and several marine animals, as marked. UUV denotes an underwater unmanned vehicle. Reproduced with permission. Copyright 2019, Springer Nature.

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2.2.3. Emerging Quantum Material Platforms

While most quantum sensing studies have predominantly relied on vacancy sites in diamond and SiC, new material platforms are emerging that, once fully developed, may show utility for quantum sensing in energy-relevant applications. Qubits, including quantum dots,[174] nuclear spins,[175] and electronic spins,[176] have been studied in silicon matrices, which are used extensively in the production of electronics. However, the quantum properties of these materials have only been characterized at temperatures of ≈4 K or lower. Single photon emission has recently been characterized in carbon nanotubes, which are already frequently used in imaging and sensing applications and have telecommunications-relevant near-infrared emission properties.[125,177] The integration of qubits into MOFs is also a promising avenue for spatially controlling the arrangement of qubit arrays. MOFs are highly organized, porous, crystalline structures comprised of metal cluster centers connected by organic molecular linkers, and have been extensively used for sensing applications.[178] The integration of qubits into the MOF structure may pave the way for the quantum sensing of analytes taken into the MOF pores, thereby enhancing existing MOF-based sensing technologies.[182] Several MOFs to date have been designed with highly ordered qubit arrays based on cobalt (II),[183] copper (II),[182,184] and vandyl[185] spins, representing an intriguing class of next-generation quantum materials (Figure 19). Beyond the development of new quantum materials, another emerging area of research couples quantum emitters with plasmonic materials (e.g., quantum plasmonic sensing), which promises significant improvement in measurement sensitivity.[186] Further advances in the development of both quantum sensing materials and strategies are anticipated to expand the accessibility and efficacy of quantum sensing technologies for energy-relevant applications.

2.2.4. Summary of Quantum Sensing Materials and Potential Energy Applications

The quantum materials described here can be envisioned for fossil energy applications, including the continuous measurement of variables such as pressure, temperature, and pH/corrosion around energy infrastructure (e.g., pipelines, storage areas, wells, etc.). Summary in Table 3 highlights the readout techniques, materials, and sensing targets of different quantum sensing techniques and materials, showing the exciting potential of quantum material-based sensors. For example, corrosion in oil and gas pipelines causes billions of dollars in losses annually, and is also a safety and environmental hazard.[187] Among many potential readouts, quantum sensors for pH and/or ions can provide an indirect early sign of corrosion, enabling corrective action to be taken prior to infrastructure degradation.[187] Electromagnetic sensors have also been employed to monitor corrosion within pipelines.[187] Highly sensitive electric and magnetic field sensing can be achieved using a wide range of quantum materials and techniques, creating a strategy for potential sensor development in this area. As discussed in Section 2.2.2 (ii), temperature sensors are used to monitor the performance of transformers and powerlines, as well as explosion risks in coal mines and oil processing facilities, which are all essential considerations for fossil energy.

The detection of magnetic ions may also be useful for monitoring corrosion in real-time and in the sensing of critical metals such as rare earth elements (REEs), which are found in coal, fly ash, and acid mine drainage.[181] Commercially available quantum gravimeters and atomic clocks are already being used for oil and gas exploration, as discussed in Section 2.4.
Table 3. Techniques and potential sensing targets using quantum materials.

| Technique          | Material                                      | Sensing targets                                      | Possible fossil energy applications                               | Refs.          |
|--------------------|-----------------------------------------------|------------------------------------------------------|------------------------------------------------------------------|----------------|
| ZPL                | Diamond vacancy centers, hexagonal boron nitride | Temperature, electric field                           | Pipeline integrity, temperature in transformers and power plants, powerline safety | [71,72,92,170] |
| ODMR               | Diamond vacancy centers, SiC vacancy centers, rare earth doped solids | Temperature, magnetic field, electric field, strain, pressure | Pipeline integrity, temperature in transformers and power plants, powerline safety | [53,54,93,112,139] |
| Spin relaxometry   | Diamond vacancy centers                         | pH, redox potential, magnetic ions, motion           | Corrosion monitoring, valuable ion recovery                      | [63, 75, 121]  |
| OCC                | SiC vacancy centers                              | Strain, acoustic waves                                | Pipeline integrity                                              | [57,58,134]    |
| LAC                | SiC vacancy centers                              | Magnetic field, strain, temperature                   | Temperature in transformers and power plants, pipeline integrity | [77,133,140]    |
| Gradiometers,      | Cold atoms                                      | Gravity, inertia, velocity                            | Oil and gas exploration                                         | [84]           |
| gravimeters        | Atomic vapors, trapped ions                     | Time                                                 | Oil and gas exploration                                         | [82]           |

The integration of quantum materials into sensing-relevant platforms and devices (discussed in the next section) represents an exciting new frontier in the development of high-performance field-deployable sensors for energy applications and beyond.

### 2.3. Quantum Photonics Sensing Devices and Platforms

#### 2.3.1. Quantum Photonics Platform

The quantum photonics field, while sharing similarities with electron-based quantum physics, has unique features arising from the photon nature of light. These features offer new and exciting avenues for manipulating fundamental physical processes such as photon absorption and emission. The electromagnetic wave itself is not a quantum wave since the quantum wave must be complex. However, representing the field in the second quantized notation as

\[
E(k) = C(k) \cdot g(r) \cdot (a_k + a_k^\dagger)
\]  

where the \(a_k\) (creation) and \(a_k^\dagger\) (annihilation) operators are complex quantities allow us to access a vast array of nonlinear and light–matter coupled Hamiltonian treatments. As an example, the Jaynes–Cummings Hamiltonian

\[
H = H_{atom} + H_{field} + H_{inter} \\
= \frac{1}{2} \hbar \omega \sigma^+ \sigma^- + \hbar \omega a_k^\dagger a_k - \sum_k \hbar g (a_k \sigma^+ + h.c.)
\]

where \(\sigma^+\) and \(\sigma^-\) are raising and lowering operators leads to nontrivial light–matter coupling directly manifested via observed Rabi oscillations.

Several methods for manipulating solid-state emission have emerged over the years. Each of these approaches has different critical properties, such as achievable enhancement, outcoupling efficiency, collection efficiency, and ease of fabrication, which can complement each other in the future for integrated quantum computing and sensing platforms.

One appealing platform for quantum sensing and computing is a photonic crystal. This device class mimics the solid-state system; however, unlike atomic crystals, the unit cells can be tailored according to specifications for optimized performance in desired applications. Specifically, the classical Bloch equation adopted for magnetic fields, \(H_k(t) = e^{i\omega t} \psi_k(t)\), leads to a reciprocal space and the appearance of the bandgap at the unit cell boundaries. A number of geometries can be realized such as simple dielectric layered structures for 1D crystals,\(^1\) periodic rods or hole arrays for 2D geometries (\(\text{Figure 20}\)),\(^2\) and inverse opal and Yablonovite for 3D realizations.\(^3\)

The most attractive feature of photonic crystal devices is the ability to engineer the photonic bandgap, which physically implies the prohibition of light propagation for a specific band of frequencies. In this way, 2D and 3D cavities with a very high-quality factor (Q) can be designed and optimized for a particular color center spectrum. Furthermore, a localized defect state with emission frequency within a bandgap can be created in the photonic crystal lattice. The combined effects of high Q and mode...
localization result in a large emission rate enhancement via the Purcell effect, 

Several photonic crystal structures utilizing diamond color centers have been developed.\(^{192}\) Very high quality factor ($Q \approx 10^5$) diamond cavities optimized using a reactive ion etching (RIE) plasma process have been demonstrated.\(^{192}\) Additionally, a pathway to fabricating high $Q$ cavities using monolithic diamond has gained significant research attention.\(^{193}\) Alternatively, scanning of the cavity position relative to the emitter allows for evanescent coupling of the NV center to the photonic crystal.\(^{194}\) Enhancement of emission by photonic crystal defect design and mode volume reduction has also been proposed.\(^{195}\) Further, efficient integration with external waveguides as well as as NV center coupling via photonic crystal waveguides has been realized,\(^{196}\) and path entanglement using photonic crystal waveguide cavities in a diamond Si vacancy system has been demonstrated.\(^{197}\)

Another avenue for integrated sensing modalities is through the use of solid dielectric high $Q$ cavities. Several methods relying on whispering gallery modes such as spherical, ring and disk resonators as well as Mie nanoparticle resonators have been developed in the past decade.\(^{256-259}\) The cavities allow for the creation of the dressed states $\Psi = |\psi; n\rangle$, coupled matter $|\psi\rangle$ and photon number $|n\rangle$ states with highly attractive properties for quantum applications. Their interaction causes energy level splitting, defined as vacuum Rabi splitting

$$E_n^\pm = (n + 1/2) \hbar \omega \pm 2 \sqrt{n} \hbar g_0$$ \hspace{1cm} (4)

One of the most attractive applications of these states is the potential to use them as single-photon controlled gates, which are required for quantum computing. Photonic cavities allow the direct achievement of strong coupling in the quantum electrodynamics (QED) regime, but ensuring high $Q$ confinement, particularly at optical frequencies, is a major engineering challenge.

In the context of diamond photonics, NV center QED Rabi frequency splitting has been demonstrated using silica microsphere resonators with diamond nanocrystals (Figure 22).\(^{198}\) In a separate work, microdisk resonators were shown to exhibit QED path interference effects with diamond crystals placed on the surface of the cavity.\(^{199}\) In the microwave domain, Kubo et al.\(^{200}\) have experimentally shown hybrid NV center/Josephson junction superconducting cavity quantum circuits that take advantage of the long coherence time of solid state qubits.

Another manifestation of strong photon-matter interactions, electromagnetically induced transparency (EIT), has shown great promise for applications in quantum sciences. Here, quantum eigenstates of a multilevel solid-state system ($\Lambda$ system) under destructive interference of an external field collapse onto the state with zero amplitude for one of the states of the

Figure 21. Diamond photonic crystal cavities: a) Narrowband transmission of transverse magnetic (TM) and transverse electric (TE) cavity modes. Reproduced with permission.\(^{192}\) Copyright 2014, Springer Nature. b) Energy density for fundamental photonic crystal cavity mode in cross section and c) in plane. Reproduced with permission.\(^{193}\) Copyright 2010, American Chemical Society. d) Monocrystalline diamond photonic crystal cavity. Reproduced with permission.\(^{194}\) Copyright 2012, American Physical Society.
bare system. Hence, the quantum mechanical interactions and the corresponding absorption associated with this state can be canceled. For example, all-optical field sensing using EIT states in diamond has been demonstrated.[201]

2.3.2. Platforms for Engineering of Local Spontaneous Emission

Spontaneous emission, while deceptively simple and commonplace, is an intrinsically quantum process. Viewed from the Weisskopf–Wigner theory using the interaction Hamiltonian, spontaneous emission leads to an exponential decay between the ground and excited state. The possibility of having cascaded and coupled superradiant emission makes the physics behind it even more nontrivial.[202] Modification of the local density of states of spontaneous emission is a promising route to access and engineer this phenomenon.

Hyperbolic metamaterials (HMM) offer a new and exciting way for manipulating nanoscale emission.[203] In these structures, emission enhancement comes from a divergence of dispersion relation at selected k vector directions. These types of materials can be described by the anisotropic effective permittivity and permeability parameters \( \varepsilon_\parallel \) and \( \varepsilon_\perp \). The dispersion relation takes a form of

\[
\frac{k_\parallel^2 + k_\perp^2}{\varepsilon_\parallel} + \frac{k_\perp^2}{\varepsilon_\perp} = \left( \frac{\omega}{c} \right)^2
\]

and diverges when \( \varepsilon_\parallel \) and \( \varepsilon_\perp \) are of the opposite sign. Most commonly the sign reversal can be achieved using metal/dielectric layered materials or structures with metal rods embedded in the dielectric matrix (Figure 23).

The concept of emission from dipole surface emitters using the HMM concept has been shown.[205] Additionally, enhanced emission from nanodiamonds has been demonstrated in semi-infinite HMM slabs.[204] An 80-fold enhancement of the emission rate on the surface of HMM structures has been observed.[206] Furthermore, HMM permits the realization of super-resolution imaging as the dispersion relation yields a nonvanishing tangential component of the wave vector at the near field focus.[207]

Plasmonics, combined matter-photon electromagnetic modes, over the past few decades have found numerous applications in applied science.[208] Primarily applicable to the visible and infrared parts of the energy spectrum, plasmonics is fundamentally linked to metal-dielectric interface interactions. More specifically, the difference in sign between dielectric/metal permittivity leads to a resonant condition where the local electric field is amplified, yielding an enhancement of a variety of physical processes, such as spontaneous emission. Additionally, this creates a condition for confined plasmon polariton waves propagating along metal dielectric interfaces. In relation to quantum science, both local plasmons and plasmon polaritons have shown promise as effective mediums for enhancing, manipulating and modifying light.[208]
Particularly, enhanced coupling of radiative emission to plasmonic nanowires has been demonstrated both for quantum dots and nanodiamonds (Figure 24). In a separate work, manipulation of free space light propagation through plasmonic arrays has been shown. Further, plasmon-enhanced quantum sensing beyond the classical limit has been experimentally observed. Remote entanglement of quantum emitters mediated by surface plasmon polaritons has additionally been shown and quadrature squeezing of the plasmon modes using an external electron paramagnetic resonance (EPR) source has been demonstrated.

Another intriguing avenue for quantum sensing and single photon emission would be the engineering of density of states in the deep nearfield of a quantum emitter. The singularity of dipole emission offers the potential for drastic manipulations of spontaneous emission which can be made extremely sensitive to minute perturbations of the local environment. Figure 25 illustrates an example of the perturbation of an electric dipole emitter near field geometry used to enhance sensitivity to local permittivity changes.

2.4. Existing Commercial Quantum Sensors and Applications

2.4.1. Gradiometers

Gradiometers are among the most mature quantum technologies currently available for energy-based applications. Semiclassical/quantum microgravity sensors are being developed at lab scales and are being commercialized by companies that deliver unprecedented levels of measurement, reliability, and accuracy for underground survey applications. Opportunities can also be realized by using atom interferometry in gravity survey applications. This type of sensor is a highly sensitive quantum gravimeter capable of detecting gravitational fields through the material’s density contrast (Figure 26). It is portable for outdoor usage, and has an increased sensitivity level enabling higher resolution of either smaller or deeper features compared to existing instruments, such as Scintrex CG-5 or CG-6 gravimeters. In geophysical surveying for mineral and petroleum exploration, most of the currently available sensors severely suffer from unwanted spatially and temporally varying noises that obscure signals from the target of interest. Boddice et al. analyzed data from commercially available instruments based on cold atom quantum technology in a gradiometer configuration and compared that with measurements obtained using classical gravimeters. They found that quantum gravimeters were 1.5 to 2 times more effective than classical gravimeters in the ability to detect small buried features, and that quantum gravimeters could measure at greater depths.

2.4.2. Quantum Light Detection and Ranging (LiDAR)

Quantum LiDAR is another technique undergoing commercial development for fossil energy applications, including oil discovery, gas leak detection, and carbon emissions studies. During LiDAR operation, pulsed light is sent toward a target, and some portion of the impinging light is scattered back to the LiDAR detector. By recording the time between the laser pulse and detection across an array of detector pixels, it is possible to determine the distance the scattered light has travelled, enabling 3D mapping of the terrain. In quantum LiDAR, information is obtained by the detection of single photons (as opposed to conventional LiDAR, which requires detection of multiple photons), which allows for efficient, rapid 3D mapping with higher resolution relative to conventional techniques. Companies including SigmaSpace, Quantum Light Metrology, and ID Quantique, among others, have developed commercially available high-resolution, single photon LiDAR sources for terrestrial mapping applications and the detection of small gas molecules, even in harsh environments such as sub-sea.

2.4.3. Chip Scale Atomic Clock

Oil and gas exploration in harsh environments may also benefit from highly accurate atomic clocks, which measure time using the frequencies of well-defined atomic transitions in elements such as cesium or rubidium. Atomic clocks can be made sufficiently small for integration into devices (volumes as low as 16 cm$^3$ with power consumption less than 120 mW), dubbed “chip scale atomic clocks” (CSACs), and are
used in a range of applications, from oil exploration to national defense.\cite{Microsemi2021} For example, the company Microsemi has developed CSACs for underwater oil exploration using a technique known as ocean bottom seismometry (OBS). Here, underwater mapping is achieved by placing sensors onto the ocean floor. Sound waves are then sent from an above-water ship at various angles and the seismic activity resulting from these waves is detected by the sensors, which time stamp the seismic response. With highly accurate timekeeping, a 3D map of the underwater area may be obtained from the sensors recovered from the ocean floor. As a consequence, CSACs have emerged as an exciting commercial quantum sensor for oil and gas exploration.\cite{Microsemi2021}

2.4.4. Photosynthetically Active Radiation Sensors

PAR sensors are a relatively mature quantum technology that measure the photon flux density in the visible light range (400–700 nm) suitable for photosynthesis, typically using a silicon photodiode detector (Figure 28b).\cite{Li-COR2021} Several companies, including Li-COR, Skye Instruments, and Apogee Instruments manufacture commercially available PAR sensors. PAR sensors have been used in multiple bio-based CO₂ mitigation studies, which is a topic of significant interest to the fossil energy industry as companies try to monitor and mitigate greenhouse gas release.\cite{Li-COR2021}

2.5. Quantum Enhanced Sensing Modalities for Fossil Energy Applications

Fossil energy applications are characterized by several constraints, including the requirement for distributed/remote measurements and harsh operating conditions. Particularly
appealing for distributed quantum sensing applications are sensors based on the Hong–Ou–Mandel effect, since they can be readily integrated into an optical fiber platform. Additionally, the medium in the gap of the Hong–Ou–Mandel beamsplitter can be designed to be sensitive to a wide array of external physical and chemical stimuli that yield corresponding refractive index change. Due to the requirement of the beam splitter to produce a unitary transformation, two photons simultaneously incident on the beam splitter inputs can only result in bunched photon outputs, i.e.

$$|1, 1\rangle_{cd} \rightarrow \frac{|2, 0\rangle_{cd} - |0, 2\rangle_{cd}}{\sqrt{2}}$$

with $|1, 1\rangle_{cd}$ states effectively canceling at the output. This phenomenon has recently led to the development of a range of fiber optic and integrated sensing device platforms.\[^{230}\] The Hong–Ou–Mandel sensor readout method via coincident photon detection provides superior noise immunity, which is important in harsh environment sensing conditions. Separately, sensors based on nanodiamond fiber-optic integration have been developed and can be deployed in a range of sensing modalities.\[^{231}\] Magnetic field sensing for subsurface applications as well as in-situ remote NMR are attractive possibilities for this type of sensor. Quantum sensors based on squeezed/nonclassical light for noise reduction also carry great potential to benefit the fossil energy industry, permitting sensing beyond classically imposed limits.\[^{232}\]

Conventional sensing techniques may similarly be enhanced by quantum processes and/or materials, and there is potential to deploy quantum-enhanced classical sensing techniques for fossil energy-relevant applications. One emerging area of interest is to use quantum states of light to improve the sensitivity of plasmonic sensors, dubbed “quantum-enhanced plasmonic sensing” (see Section 2.3.2).\[^{233}\] Plasmonic sensors have been developed for fossil energy-relevant applications to sense gasses,\[^{234}\] temperature,\[^{235}\] and pH\[^{236}\] under harsh conditions. The use of quantum-enhanced plasmonic sensing techniques is a path toward improving the performance of these existing sensors. Similarly, the sensitivity of Fabry-Perot interferometers, which have been used to sense a range of parameters including temperatures, gases, pressure, and others can be enhanced using squeezed vacuum states.\[^{238}\] The performance of conventional LiDAR,\[^{239}\] which is used in oil and gas discovery and for monitoring pipeline integrity (Section 2.4.1), may also be enhanced.
3. Further Opportunities and Challenges of QIS in Energy Applications

3.1. Global Quantum Initiatives: New Opportunities

A number of research centers and their physics, chemistry, engineering, and material sciences departments around the world are broadly pursuing QIS as a major research and development direction. This has significantly increased outcomes in the field and has also elicited, at a policy level, the continuous distribution of financial support to achieve realistic goals for implementing QIS successfully in high-priority areas like security and safety, which should support future innovations in QIS, and, by extension, the development of viable quantum sensors.

In September 2018, the U.S. National Science and Technology Council (NSTC) issued The National Strategic Overview for Quantum Information Science that identified six main policy opportunities:[240] i) choose a science-first approach to QIS, ii) create a quantum-smart workforce for tomorrow, iii) deepen engagement with the quantum industry, iv) provide critical infrastructure, v) maintain national security and economic growth, and iv) increase international cooperation. A budget of $1.3B was announced for 2019–2023 to initiate and strengthen research addressing these opportunities. The UK National Quantum Technology Programme (NQTP) has taken a step toward developing that nation’s capabilities for establishing a new sector in future QIS technologies.[241,242] The UK government formed four multi-institutional, multi-investigator, challenge-led, and focused research programs, or “Hubs,” comprised of academics, industries and government partners, investing £385M. This effort identified a span of four areas in which quantum capabilities could potentially impart a significant impact: imaging, ultraprecise sensors, secure communications, and new quantum concepts for computers.[241] In 2018, the European Union (EU) announced a ten-year flagship-scale program combining education, science, engineering, and innovation across several EU member states to explore the potential of quantum technologies.[243] This initiative has an investment of €1.3B over ten years and has identified four main pillars: communication, sensors, simulation, and computers. Germany has invested €650M from 2018 to 2022 to stimulate quantum technology development and commercialization on top of the flagship-scale program. China has generated more than $987M in research funding from central and local governments over the past ten years.[244] In 2016, China launched the “Quantum Control and Quantum Information” National Key Research and Development (RandD) project, and within the past three years it invested $337M. Similarly, Japan launched a new initiative in 2018 called Q-LEAP with an initial funding of ¥200M.[245] This initiative focused on developing three pillars—quantum simulation and computation, quantum sensing, and ultrashort pulse lasers—over ten years. Canada[246] and Australia[247] are also creating similar initiatives on QIS with an investment of $1B by Canada in quantum research.

In addition to these examples, government-level interest in QIS in other countries, such as Russia and India, is growing and significant effort has been devoted toward bringing quantum stakeholders, companies, and academia together along this line. These efforts are creating new frontiers in QIS and are making an impact on sensor, computer science, cryptography, and communication technologies. Taken together, these efforts in conjunction with industrial investments will provide physical and human capital for continued growth in the research, development, and deployment of quantum sensing technologies globally.

3.2. Future Directions for Quantum Sensors and Sensing Materials

As outlined in this review, QIS is poised to have transformative impacts within the energy sector, and near-term effects are anticipated with further developments in quantum sensing. Indeed, as outlined in Section 2.3, several mature quantum commercial sensors are already in use for fossil energy applications, and this trend is anticipated to continue. Specifically, quantum LiDAR is sufficiently developed to be deployed for monitoring gas leaks along pipelines, a key aspect of energy security. Quantum LiDAR has additional utility in fossil energy applications including monitoring greenhouse gas emissions and even oil and gas discovery.[221,222] Similarly, commercially available quantum gravimeters are available for both petroleum and mineral resource exploration in the field, and may also be useful for monitoring mining integrity.[16,220] Finally, highly sensitive chip-scale atomic clocks (CSACs) are well-suited for underwater terrain mapping, which opens up avenues for deep-sea oil and gas exploration.[226] Several of these technologies have recently been discussed in the National Energy Technology Laboratory’s Fossil Energy Quantum Information Science and Technology (NETL FE QIST) Workshop report for short-term areas in which QIS will impact fossil energy.[248] Continued reduction in equipment costs and improvements in sensitivity should lead to the expanded use of existing quantum sensing technologies for fossil energy applications.[248]

In the more immediate future (three to ten years), the NETL FE QIST report[248] anticipates the integration of quantum materials and techniques with existing fiber optic sensor platforms, which are widely used for monitoring parameters such as strain and temperature in power plants, reactors, pipelines, transformers, and other energy infrastructure.[22,249] Operation under harsh conditions (temperatures > 250 °C, pressures that are several orders of magnitude higher than atmospheric pressure, etc.) are often required in such applications.[240] Quantum sensing materials including NV− centers in nanodiamonds or SiC may be integrated with optical sensing platforms (particularly optical fibers) for deployment to sense physical parameters including temperature and strain to monitor infrastructure health, or in waste streams to aid in the recovery of critical elements. As current sensor technology approaches the fundamental limitations of classical physics, target areas in which QIS may improve the signal-to-noise ratio of existing fiber optic sensors include: 1) improved laser performance, 2) improved efficiency in optical detectors, 3) optimization of optical fiber sensors, and 4) advances in data collection.[248]

As with any emerging technology, a key challenge is to translate quantum technology from a well-controlled research lab into more complex environmental systems, where a variety of factors may hamper sensor performance. As outlined in Section 2.2.2, while quantum materials such as NV centers and SiC show promise sensing a multitude of important variables...
(i.e., magnetic fields, strain, temperature, electric fields, etc.), the ability to practically isolate individual variables of interest is critical and remains a challenge for these materials, since they may be influenced by multiple variables simultaneously.\(^{[31]}\) Another key step for sensor commercialization is the integration of quantum materials into rugged packaging capable of deployment in “real-world” systems. This is particularly true for energy applications, where harsh conditions such as elevated temperatures, high pressures, and high acidity are often encountered. Similarly, advances are needed in the material science front to enable the mass production of high-performance quantum materials at the lowest possible cost. Finally, continued integration of quantum materials with existing sensor platforms such as optical fibers will accelerate the development of commercial sensing products. The use of quantum processes to enhance the performance of classical sensors for operation in harsh conditions represents another important opportunity for research and development. Future horizons of quantum innovation can be broadly split into the categories of material science and device integration.

In terms of materials science innovations, the development of silicon has been considered to replace conventional superconducting qubits, which would put quantum technologies a step closer to mass deployment via integration with conventional CMOS processes.\(^{[290]}\) In this direction, silicon quantum dots have been gaining significant research attention as potential spin-cavity QED coupled devices similar to transmon qubits.\(^{[251]}\) Alternatively, 2D materials such as hexagonal boron nitride\(^{[252]}\) present unique advantages from the point of deterministic positioning of quantum emitters. Indeed, the atomic crystal lattice can, in theory, be accessed to induce spatially localized perturbation during growth and nucleation.\(^{[253]}\) Apart from color centers in diamond and silicon carbide, rare-earth ions have been gaining momentum as potential bulk quantum solid-state centers. Recently both optical emission and spin manipulation of a single Yb\(^{3+}\) ion have been demonstrated in photonic crystal cavities.\(^{[254]}\) Although performed at cryogenic temperatures, this study represents an important proof of principle for rare-earth ions. Another emerging sensing platform could exploit topological photonic states, which are the surface states arising at the interface between two media with a different Chern number that occur, for instance, for materials with a broken time reversal symmetry.\(^{[255]}\) These types of states can be used to transmit quantum information and sensor signals over significant distances, such as in energy infrastructure, without suffering scattering losses due to material and surface imperfections. Topological designs using magneto-optic photonic crystals and coupled resonators have been experimentally demonstrated.\(^{[256]}\) Currently, this is an active field of research with many emerging approaches realizing topological photonic states immune to scattering.

An alternative quantum photonic subfield, cavity QED, carries great potential for future novel quantum phenomenon. By analogy with the Hong–Ou–Mandel effect, nonclassical cavity interactions with the environment can lead to new physics and applications that are highly applicable for energy purposes. As an example, the appearance of localized topological edge states in an array of coupled photonic resonators with interacting photon pairs has recently been reported,\(^{[257]}\) as well as quantum gates developed using hybrid cavity/photon and NV centers.\(^{[258]}\) The multiparticle entanglement required for scalable quantum computing can also be readily produced with cavity–QED interactions.\(^{[259]}\) Expanding the number of available materials and platforms for quantum sensing will facilitate the rational design of sensor technologies tailored to the specific environmental conditions encountered in energy-based sensing applications.

In addition to these emerging sensing materials and techniques, the integration of quantum technologies with nuclear magnetic resonance (NMR) techniques represents another emerging area of innovation. Solid-state NMR has developed into a formidable technique for in-situ catalysis research, providing a wealth of information about catalytically active sites, reacting molecules, and their interactions.\(^{[260]}\) The hyperpolarization of nuclear spins in NMR spectroscopy holds great promise for ultrasensitive NMR testing, which would require only minimal sample amounts and would enable measurements to be performed even in poor contrast environments.\(^{[261]}\) NV center hyperpolarization has received significant research attention.\(^{[262]}\) Indeed, normally nuclear spins are very weakly polarized, which determines the limit of detection of conventional NMR techniques. Converting controllable electronic spin polarization from the NV center to surrounding external nuclear spins can dramatically enhance NMR spectroscopy performance.\(^{[263]}\) Improved NMR sensitivity would, of course, have broad applications across many scientific disciplines and economic sectors, including fossil energy. A range of NMR techniques are extensively used for characterizing liquid fuels,\(^{[264]}\) oil and gas exploration,\(^{[265]}\) studying carbon capture and carbon storage materials and mechanisms,\(^{[266]}\) and monitoring and analyzing catalytic conversions of carbon dioxide,\(^{[267]}\) to name just a few important applications. Thus, the development of enhanced NMR techniques would have extraordinary benefits for carbon dioxide mitigation studies and resource discovery and characterization. Continued exploration of quantum technologies with NMR-based platforms, in tandem with on-going efforts to develop field-deployable instruments,\(^{[268]}\) is therefore a desirable direction of next-generation quantum sensor development.

### 3.3. Quantum Sensor Networking for Fossil Energy Applications

With the advent of QIS, quantum networking opportunities for safe and secure energy production, processing and delivery will surpass the opportunities offered by existing networking systems. These opportunities include:

- **(a) Assessing actual data on global CO\(_2\) emission**
- **(b) Fossil energy infrastructure automation**
  - Oil, gas, and electricity infrastructure build-out and planning\(^{[269]}\)
  - Operational optimization of interdependent infrastructure
  - Modernization of the grid with “quantum grid,” building, transportation infrastructure and operation to support advanced energy supply
- **(c) Quantum key distribution for security and reliability of energy delivery**

As a long-term opportunity, quantum networking can be used to assess global CO\(_2\) emissions. Sources of CO\(_2\) emission such as
coal-fired power plants, industries, ships, and vehicles fitted with quantum technologies can be connected to a complex communication network fed into powerful quantum processing units to monitor the level of CO₂ emissions from individual sources. A complex network of quantum machines can be used to model CO₂ emission from different sources across the globe, monitor the emission, and mitigate emissions in targeted areas using machine learning and artificial intelligence that can be significantly enhanced by quantum computing. In 2014, NASA first launched its orbiting carbon observatory-2 (OCO-2) to monitor CO₂ emission in the Earth’s atmosphere with a resolution of 1–3 km. This was a computationally breathtaking problem, as achieving such a resolution scale required accurate and detailed models of landscapes and high CO₂ emissions zones on the Earth’s surface. With the advent of quantum computing, the landscape could be divided into cells, and each cell could be equipped with CO₂ monitoring quantum technology, which could eventually be linked to the orbiter to assess overall global CO₂ emission levels.

Quantum sensor networks require distributed nodes with discrete-variable and continuous-variable multipartite entangled states and complex sensing protocols. Quantum sensor networks exploit correlations between individual quantum sensors to enhance the sensing performance of the system for global parameters measurements as well as simultaneous multi-parameter measurements. An entangled quantum sensor network can enhance measurement sensitivities and the precision of multiple spatially distributed parameters. As demonstrated in Figure 29, quantum sensing and quantum networking can be integrated into both traditional and novel approaches to distributed optical fiber sensing to achieve unprecedented levels of performance and cost trade-offs, allowing for broader commercial deployment of distributed optical fiber sensing technologies for natural gas pipeline applications. Entangled light distributed to remote locations via an installed fiber network can enable an increase in precision when estimating system parameters such as temperature, pressure, pipe corrosion, and gas concentrations. Through integration of quantum devices with advanced data analytics methodologies, the resiliency, reliability, security, and integrity of the wellbore for carbon storage and other subsurface applications can be improved.

4. Conclusions

The discovery, production, transportation, and consumption of energy impacts nearly every aspect of society, and an attempt to meet the world’s ever-evolving energy needs has driven unprecedented level of technological innovations. Hence, the energy sector will likely be among the first beneficiaries of the impending “quantum revolution,” as emerging QIS-enhanced technologies may be applied to ensure the safe, secure, and efficient use of energy resources. Indeed, quantum technologies such as quantum gravimeters, LiDAR and atomic clocks are already commercially available and in use for gas and oil exploration. Yet, a need still exists for advanced sensing instrumentation to ensure reliable, secure, and environmentally sustainable energy production and consumption.
responsible fossil energy production and recovery through improved real-time monitoring of subsurface processes and the environment. Identifying high-resolution measurement and monitoring tools that are economical and portable are additional major needs in sustainable fossil energy development. Quantum sensing has the ability to facilitate resource discovery, monitor infrastructure integrity, and aid in greenhouse gas mitigation, which are all key concerns to the energy industry.

The potentially unprecedented sensitivity that may be obtained from various quantum sensor platforms may be deployed to quickly detect failings in a natural gas pipeline, for instance, preventing harmful gas leaks, or to monitor temperature in transformers to ensure their proper operation. Quantum sensing materials such as nanodiamonds can be used with optical fiber sensor platforms to obtain lower detection limits than the current state-of-the-art. In addition, optical fiber sensor interrogation methodologies may be provided with new tools for optimizing the performance of subsurface or natural gas pipeline sensing applications where multiple-km range is desired with sub-m spatial resolution.

While progress in QIS continues, several challenges exist for its implementation in energy technologies. Specifically, innovations in material science are needed to enable mass production of quantum materials, to develop materials sufficiently robust to function under “real-world” environmental conditions, and that can be integrated into practical platforms for commercialization and deployment. In addition, a gap exists between the capability of current QIS stakeholders and the needs to be addressed in the energy sectors. Enhanced collaborations between researchers working in QIS and energy communities will help in addressing specific needs in the energy sector using emerging quantum technologies. Hence, advances in QIS and energy sector performance are inextricably linked, where the multitude of potential benefits to the energy sector from QIS will help drive additional QIS-related research.

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Conflict of Interest

The authors declare no conflict of interest.

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