

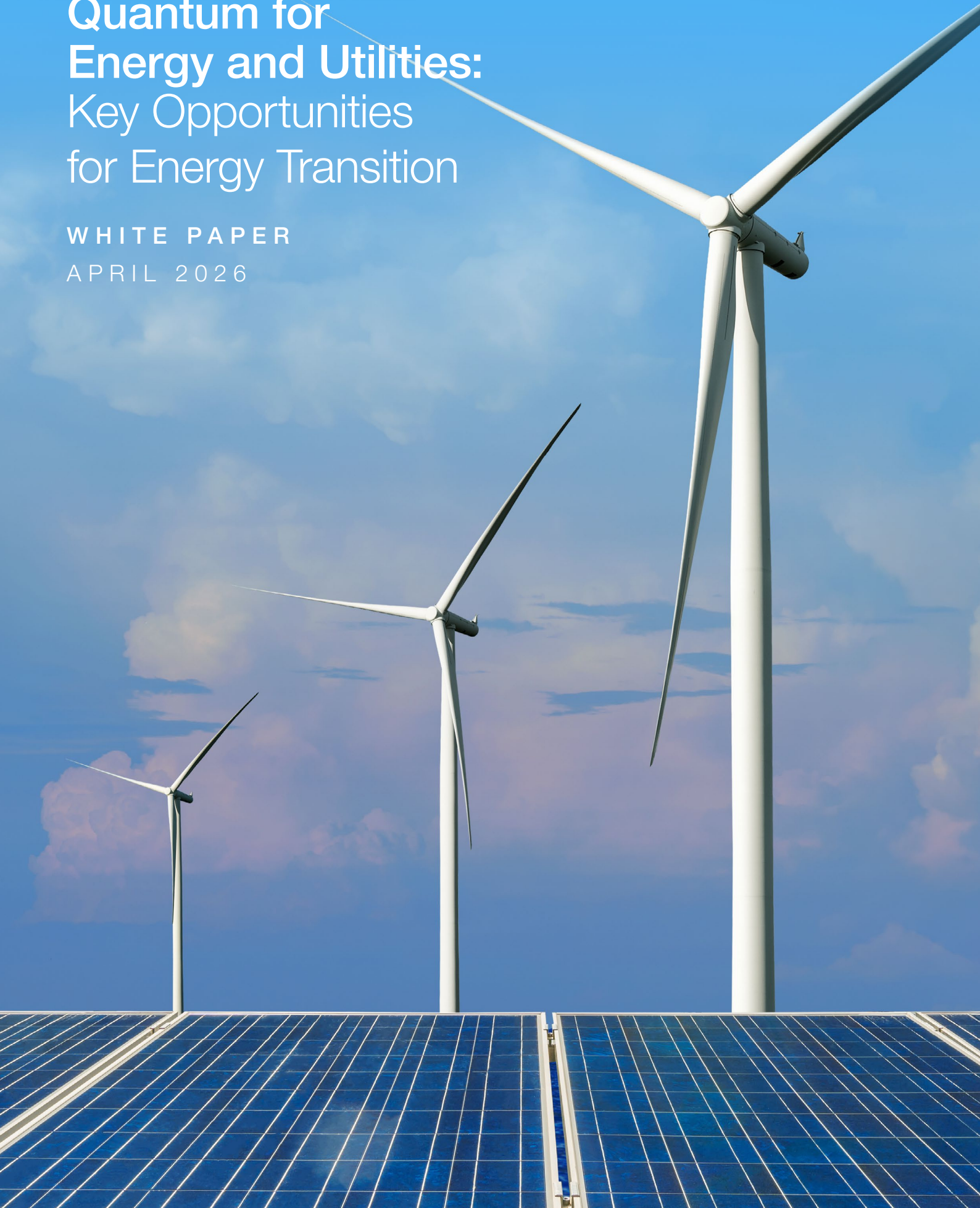
In collaboration
with Aramco



Quantum for Energy and Utilities: Key Opportunities for Energy Transition

WHITE PAPER

APRIL 2026



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Foreword



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The world is facing a tightening “energy trilemma”¹ that requires reducing emissions while keeping energy reliable and affordable, in an environment shaped by geopolitical volatility and persistent uncertainty. Progress on transition indicators has continued, but unevenly and slower than required. Meanwhile, electricity demand is accelerating as economies digitize and artificial intelligence scales up, intensifying pressure on grids and bringing infrastructure upgrades, flexibility and security to the forefront of national agendas.

Against this backdrop, the limits of conventional computation are becoming more visible. Renewable-heavy power systems exhibit non-linear dynamics that are difficult to model with sufficient fidelity. Breakthroughs in batteries, catalysts, carbon capture and storage, and hydrogen rely on molecular interactions that are costly to simulate with classical methods. And across supply chains, trading and network operations, optimization problems grow combinatorially, where incremental improvements in solution quality or time-to-decision can translate into material operational and economic value.

Quantum technologies, including computing, sensing and communication, do not replace existing tools, but they can expand what is tractable. Quantum computing may help explore vast design

and planning spaces and, eventually, improve materials simulation accuracy. Quantum sensing can increase measurement fidelity for subsurface imaging and monitoring. Quantum communication can strengthen critical-infrastructure security when long-lived assets must remain trustworthy for decades.

This white paper has been developed through a strategic partnership between the World Economic Forum and Aramco – part of the [industry track](#) of the Forum’s [Quantum Economy Network](#) – and focuses on practical paths rather than hype. It draws on expert input, surveys and early projects to highlight use cases across the energy value chain, from generation to transmission and system security. Turning pilots into routine capability will require investment in skills, better data integration and continued progress in hardware reliability.

We extend our sincere thanks to the experts and organizations across industry, academia, technology providers and policy who contributed time and insight to this paper. We hope it equips energy and utilities industry decision-makers with a practical basis to prioritize credible quantum opportunities, align stakeholders and investments, and build the technical, security and talent foundations needed for responsible integration in the years ahead.

Executive summary

This report offers business leaders a roadmap to move from low-risk, high-value pilots towards scaling-up quantum alongside high-performance computing and AI.

Quantum solutions are emerging for energy and utilities in grid optimization, materials discovery and infrastructure security, with near-term gains using hybrid workflows. Leaders should prioritize high-impact cases, benchmark data and scale up when results outperform classical methods.

Quantum technologies in computing, sensing, communication and cybersecurity are moving from research to early pilots and entering the energy and utilities sector as an additional set of tools for specific, hard problems. They will not replace classical computing, but they may expand what can be explored, simulated and optimized, particularly when used in hybrid workflows that combine quantum methods with established high-performance computing and AI approaches.

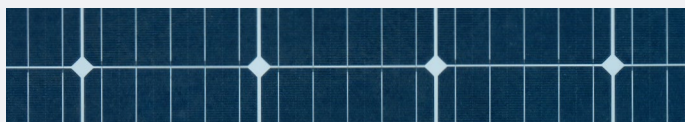
The earliest opportunities are concentrated in hybrid quantum-classical optimization, emerging sensing

applications and post-quantum cybersecurity upgrades. Over the longer horizon, advances in quantum simulation and sensing could unlock higher-fidelity modelling and measurement that support cleaner, more resilient energy systems.

Quantum solutions offer high-impact benefits for targeted use cases across energy and utilities. While hardware for sensing, communication and computing continue to mature, applications are gaining traction across four value pillars (see Figure 1):

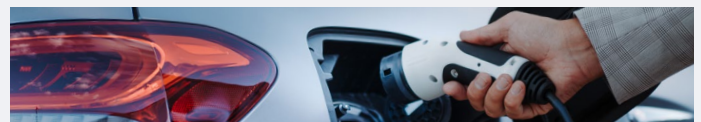
- Transition and materials acceleration
- Operational optimization
- Trusted infrastructure and cyber resilience
- Precision monitoring and sensing

FIGURE 1 Targeted quantum value pillars for energy and utilities



1 Transition and materials acceleration

Complement classical methods to improve materials discovery for batteries, catalysts, carbon capture, hydrogen and solar



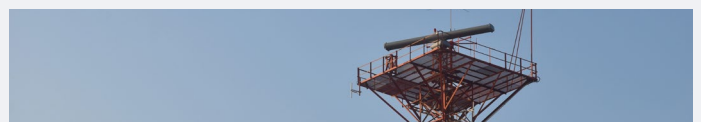
2 Operational optimization

Improve planning and control problems, such as AC optimal power flow, grid resilience and EV smart charging



3 Trusted infrastructure and cyber resilience

Reduce “harvest now, decrypt later” exposure through disciplined post-quantum cryptography migration planning and assessing quantum-secured communication approaches



4 Precision monitoring and sensing

Advance subsurface mapping and non-invasive detection use cases, such as leaks and emissions

Notes: This figure is non-exhaustive.

Source: World Economic Forum’s Quantum for Energy and Utilities Working Group.

To help leaders sequence investment and capability building, this paper presents an organizational roadmap with three horizons:

Within 2 years

Focus on a small set of high-value use cases, run low-risk pilots with measurable success criteria, and build internal literacy and partner ecosystems, while strengthening the security foundation through post-quantum cryptography readiness assessments.

Over 3-5 years

Move from experimentation to institutionalization by embedding quantum into digital, operational technology (OT) and cyber roadmaps, expanding

scaling-up mechanisms and collaboration frameworks, and rolling out post-quantum cryptography (PQC) and quantum key distribution (QKD).

Beyond 5 years

Treat quantum as part of the permanent compute and security stack alongside high-performance computing (HPC) and artificial intelligence (AI), sustaining continuous innovation pipelines and coordinating across the sector so that standards, procurement and regulation keep pace with technical capability. Organizations that start now, with disciplined measurement and strong collaboration, will be best placed to turn early pilots into scalable operational capability.

1

Introduction

Quantum technologies are emerging as complementary tools for energy and utilities, offering potential improvements in efficiency, measurement sensitivity and data security.

Quantum technologies are gradually moving from research and experimental study to early-stage deployment, presenting new opportunities for efficiency and reliability improvements in the energy and utilities sector. While many capabilities remain at a developmental stage, early findings indicate that these tools can complement existing digital systems and support more informed decision-making in complex energy environments.

Quantum technologies comprise three broad areas as follows:

Quantum computing may help with optimization and simulation tasks that strain classical methods, potentially improving grid planning, asset scheduling and materials research. Real-world impact will depend on continued advances in hardware and software, but over time quantum algorithms could enable more accurate modelling and smoother renewable integration.

Quantum sensing can boost measurement sensitivity and data quality in certain operations. By detecting subtle magnetic or gravitational variations, it may improve subsurface characterization, anomaly detection and monitoring of storage or transmission assets, supporting more predictive maintenance and safer performance. Broad deployment, however, still requires validation in real conditions.

Quantum communication, including quantum key distribution (QKD), can add protection for critical data flows as networks become more connected. It will not replace today's security stack soon, but it can strengthen layered defences and help prepare for future cryptographic risks. For further technical insights, refer to resources on the World Economic Forum's Quantum Economy Network, such as: [quantum fundamentals](#), [quantum economy](#) and [quantum security](#).

1.1 Methodology

This white paper was developed to combine breadth of perspectives with depth of analysis, drawing on workshops, surveys and expert interviews to test assumptions, challenge early hypotheses and ground recommendations in evidence (see Figure 2).

FIGURE 2 Methodology



Note: The percentage values in the community insight figures (blue bar graphs) indicate the percentages of participants who have selected a particular option.

1.2 What is pushing quantum technology adoption in energy and utilities?

Several market signals are accelerating quantum-readiness efforts in energy and utilities, and they are concrete rather than speculative. The US Department of Energy has warned that, under certain capacity retirement and load growth scenarios, blackout risk could rise sharply by 2030, while outages already cost US businesses about \$150 billion annually. At the same time, cybersecurity threats are intensifying: industry threat intelligence reports indicate that 70% of 2024 attacks involved critical infrastructure, underscoring the need for long-lived protections across grid and operational technology systems.

The most immediate quantum-linked step is the transition to post-quantum cryptography, as the US National Institute of Standards and Technology (NIST) finalizes standards and migration guidance. Given long asset lifecycles, the “harvest now, decrypt later” risk² makes early planning essential. Rapid digitization also adds complexity, with global smart meter deployments projected to exceed 3 billion by 2030. This expands forecasting and

optimization workloads, such as weather-dependent renewable load balancing, and motivates tightly scoped quantum or hybrid pilots benchmarked against classical high-performance computing.^{3,4}

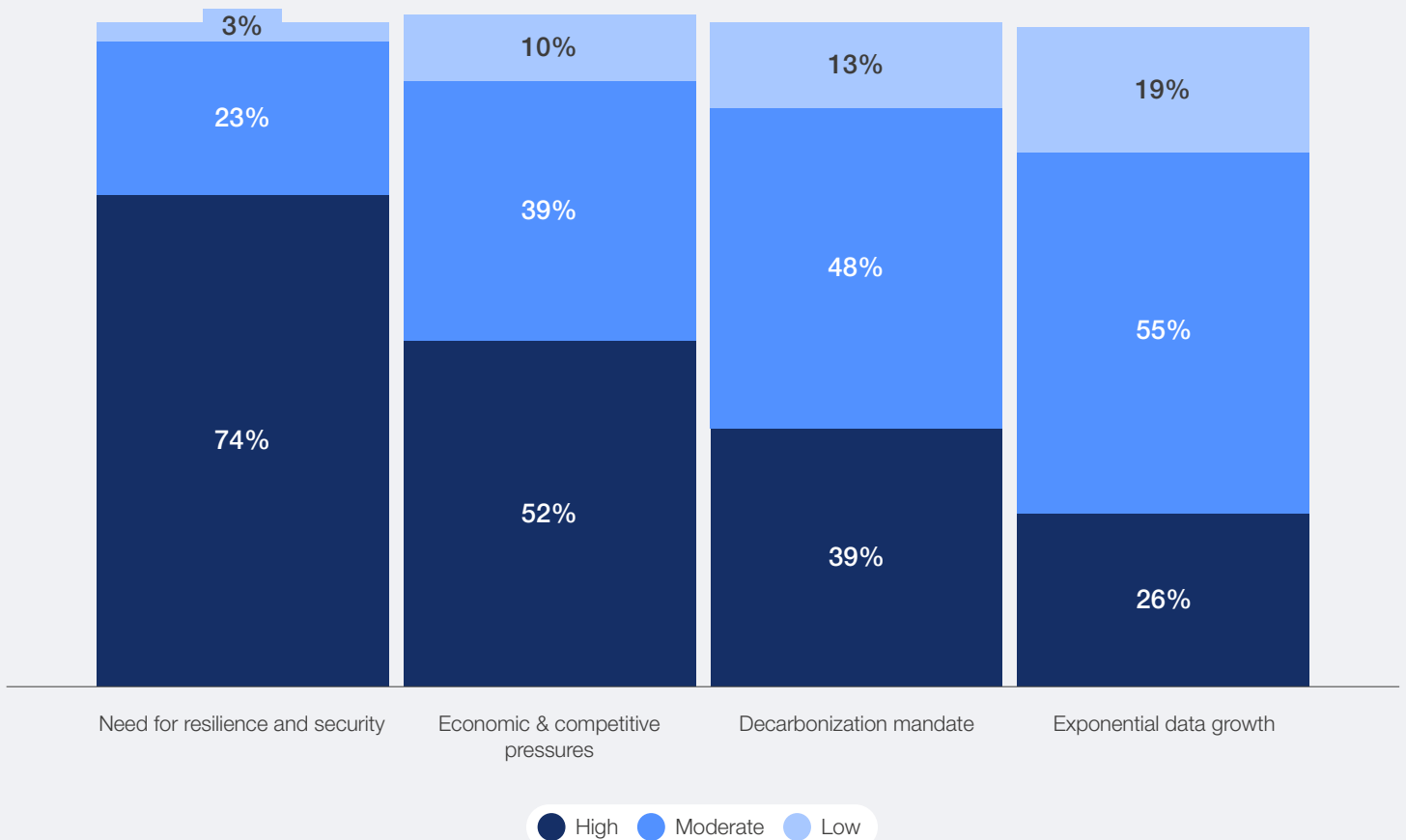


Community insights for drivers of technology adoption

Quantum adoption in energy and utilities is primarily driven by resilience and security imperatives, with economic and competitive pressure as a secondary accelerator. Decarbonization and increasing data volumes are also recognized as important factors.

Beyond these key drivers, the community highlights sovereignty concerns, safety and risk modelling, optimization of resource demand, and mastering the complexity of future energy systems and quantum simulation for battery chemistry as emerging key factors for future quantum adoption.

FIGURE 3 Key factors driving quantum technology adoption



Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.

1.3 When will quantum applications materialize in energy and utilities?

Quantum applications are expected to emerge unevenly and in three waves across the energy value chain:

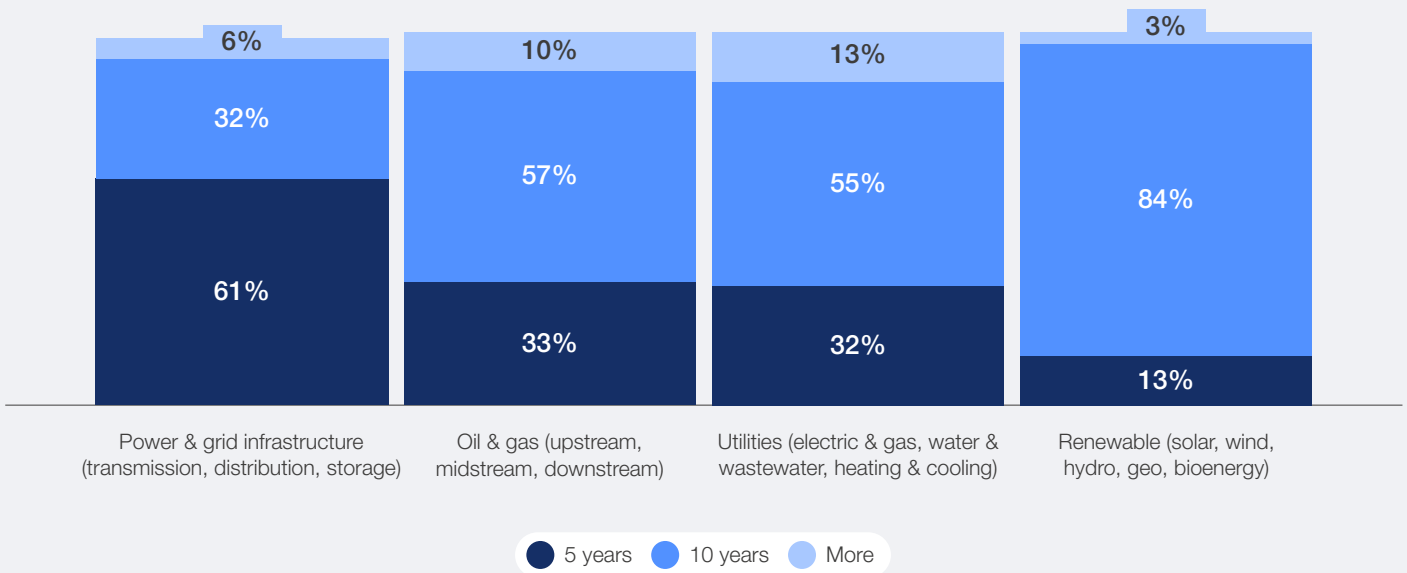
- Near-term decision optimization in operations and markets.
- Mid-term system planning and control, as grids and variable generation scale up.
- Longer-horizon R&D, once fully fault-tolerant machines arrive.



Community insights for technology application timeline

Quantum impact is expected within 10 years across most energy segments, with grid infrastructure leading near-term adoption. Phased but uneven deployment maturity is expected across all sub-sectors. The power and grid sub-sector shows the strongest five year outlook, while renewables are expected to be longer-term. Moderate acceleration is expected in oil and gas and utilities.

FIGURE 4 Timeline for quantum application across energy and utilities sector



Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.



1.4 Quantum solutions across the energy and utilities value chain

The energy and utilities industry is undergoing multiple transformations, including decarbonization of generation and a digital revolution in infrastructure. In addition, demand for resilience and security is increasing across the whole value chain.

Chapters 2, 3 and 4 of this white paper analyse quantum solutions – in the form of quantum computing, quantum sensing and quantum

security and communication – across the following three sectors (see Table 1):




- Energy (generation and supply)
- Power and grid infrastructure
- Utilities (public services and critical infrastructure)

TABLE 1 Quantum opportunities by subsector

Energy (generation and supply)	Quantum computing	Quantum sensing	Quantum security and communication
 Fossil fuels <ul style="list-style-type: none"> → Oil and gas → Coal 	<ul style="list-style-type: none"> → Optimize refinery processes to reduce energy intensity → Reservoir modelling and seismic imaging with higher accuracy 	<ul style="list-style-type: none"> → Subsurface mapping for hydrocarbon reservoirs → Leak detection in pipelines and methane monitoring 	<ul style="list-style-type: none"> → Secure SCADA* systems and pipelines from cyberattacks
 Renewable <ul style="list-style-type: none"> → Solar → Wind → Hydro 	<ul style="list-style-type: none"> → Materials discovery for more efficient solar PV and wind turbine composites → Grid optimization for variable renewable integration 	<ul style="list-style-type: none"> → Wind resource measurement with ultra-precise sensors → Geothermal subsurface heat-flow mapping 	<ul style="list-style-type: none"> → Secure decentralized solar and wind farms connected via smart grids
 Nuclear <ul style="list-style-type: none"> → Fission → Future tech 	<ul style="list-style-type: none"> → Reactor design simulations → Materials discovery for radiation-resistant components 	<ul style="list-style-type: none"> → Radiation detection with extreme precision 	<ul style="list-style-type: none"> → Quantum-safe encryption of nuclear facility operations and data
Power and grid infrastructure	Quantum computing	Quantum sensing	Quantum security and communication
 Transmission <ul style="list-style-type: none"> → High-voltage network → Cross-border interconnectors 	<ul style="list-style-type: none"> → Large-scale optimization of high-voltage grid flows → Cross-border power trading optimization 	<ul style="list-style-type: none"> → Detect faults and line stress in real time 	<ul style="list-style-type: none"> → Quantum key distribution (QKD) for ultra-secure grid communication
 Distribution <ul style="list-style-type: none"> → Local grid → Smart grid 	<ul style="list-style-type: none"> → Local optimization of distributed energy resources (DERs) → EV charging scheduling at grid scale 	<ul style="list-style-type: none"> → Detect anomalies in local distribution networks 	<ul style="list-style-type: none"> → Secure smart meters and IoT nodes
 Storage <ul style="list-style-type: none"> → Battery → Mechanical storage 	<ul style="list-style-type: none"> → Simulate new battery chemistries beyond lithium-ion → Catalyst design for hydrogen electrolysis and storage 	<ul style="list-style-type: none"> → Monitor degradation of large-scale battery farms 	<ul style="list-style-type: none"> → Secure storage facilities that connect to national grids

*SCADA (supervisory control and data acquisition) is a software and hardware system designed to monitor, manage and control industrial processes, machines and infrastructure from a centralized location.

TABLE 1 | Quantum opportunities by subsector (continued)

Utilities (public services and critical infrastructure)	Quantum computing	Quantum sensing	Quantum security and communication
 Electricity → Generation, transmission and retail electricity providers	→ Long-term planning of generation and retail mix	→ Asset health monitoring (transformers, substations)	→ Harden customer data and billing platforms
 Natural gas → Natural gas delivery for heating, cooking and industrial use	→ Optimize gas network flows under dynamic demand	→ Detect leaks in urban gas distribution	→ Secure gas SCADA and distribution networks
 Water and wastewater → Potable water supply, treatment plants and sewerage systems	→ Optimize desalination and water treatment processes → Smart water distribution under drought conditions	→ Detect contaminants and micro-leaks in pipelines	→ Protect critical water infrastructure from cyberattacks

Notes: This table is representative and non-exhaustive.

Source: World Economic Forum's Quantum for Energy and Utilities Working Group.



2

Energy (generation and supply)

From seismic imaging and methane sensing to wind optimization and smart charging, quantum is advancing energy generation and supply.



Energy generation and supply includes the extraction, production and processing of primary energy sources. This sector is characterized by intensive capital expenditure, global logistics networks and molecular-level engineering challenges that push classical simulation to its limits.

2.1 Fossil fuels

“ Quantum technologies are a potential source of competitive advantage across the entire hydrocarbon value chain.

The oil and gas industry has long relied on HPC to address computationally intensive challenges, from upstream seismic data inversion to downstream molecular design. However, as the complexity of these problems grows, the industry is exploring new computational paradigms. Quantum technologies are a potential source of competitive advantage across the entire hydrocarbon value chain.

Upstream (exploration and production)

The upstream segment remains the most capital-intensive phase of the hydrocarbon value chain. It has to balance two competing priorities: extracting as much value as possible from existing oil fields while keeping the environmental impact of exploration as low as possible. The biggest computational constraints are in subsurface imaging and reservoir simulation.

Subsurface imaging and seismic inversion

Seismic imaging requires processing petabytes of data to rebuild detailed pictures of underground geology. The central maths problem is an inverse one: using recorded seismic waves to infer the subsurface properties that produced them, which means effectively working backwards from the wave equation. Seismic data-processing techniques such as traditional full waveform inversion (FWI) often struggle because the optimization landscape is highly non-convex, so it can get stuck in local minima and produce misleading subsurface models. Quantum computing approaches such as quantum annealing are expected to yield improved solutions over classical computing approaches.

Quantum sensing for gravimetry

Beyond advances in computing, quantum sensing is starting to reshape exploration workflows, allowing for precise, non-invasive imaging of oil and gas reservoirs. Quantum gravimeters that use cold-atom interferometry can measure absolute gravity with exceptionally high stability and essentially no drift. That is a major advantage over traditional spring-based gravimeters, which tend to drift mechanically and need frequent recalibration. By leveraging the wave-like behaviour of atoms, these quantum sensors can estimate gravitational acceleration with extremely high precision.

Reservoir simulation

Modelling fluid flow in porous rock means solving non-linear partial differential equations (PDEs) on grids with millions of cells. Most of the runtime comes from the large linear systems that have to be solved at every time step, and the cost grows mainly with the size of those systems. Quantum solutions for solving difficult PDEs are being developed in anticipation of hardware availability.

Midstream (transportation and pipelines)

Midstream operations are essentially about logistics and network optimization. Moving hydrocarbons requires coordinating pipelines, ships and terminals through intricate schedules, and these challenges are often framed as NP-hard combinatorial optimization problems. Hybrid quantum-classical solvers (for example variational approaches such as QAOA or quantum

“ Even small percentage improvements can translate into meaningful fuel savings and higher asset utilization at scale.

annealing) target these NP-hard search spaces by exploring many candidate configurations efficiently, with the practical goal of finding better solutions under tight time limits, not perfect global optima. If validated, even small percentage improvements can translate into meaningful fuel savings and higher asset utilization at scale.

Pipeline flow optimization

Moving gas or oil through transcontinental pipelines means continuously tuning compressor stations and valve settings to cut fuel use while still satisfying pressure limits and meeting contract delivery requirements. Hybrid classical-quantum computing solutions are expected to provide improved real-time decision making to better optimize pipeline flow.

LNG shipping and maritime logistics

Optimizing liquefied natural gas (LNG) tanker routes is among the most computationally difficult challenges in the industry. It requires coordinating a global fleet while accounting for changing boil-off rates, port and berth constraints, contract delivery windows and opportunities to capture value through spot-market arbitrage. In addition, sudden geopolitical and maritime disruptions can rapidly alter trade flows and heighten transit risk. Even when the routing problem is simplified to just a few dozen ships, the number of possible decisions becomes exponentially large. That is far beyond what anyone could search exhaustively. Because of that, traditional heuristic methods often land on “good enough” solutions that are not truly optimal, which means real opportunities for efficiency gains are still possible.

Downstream (refining and retail)

Downstream operations combine complex chemical processing with high-volume, low-margin retail logistics. The priority is improving

process efficiency, designing and optimizing molecules and formulations, and using customer analytics to sharpen pricing, demand forecasting and sales performance.

Refinery optimization (blending and scheduling)

Refineries have to coordinate crude unloading, tank storage and blending so they can hit tight product specs, such as octane and sulphur limits, while protecting margins. It is essentially a resource-constrained scheduling problem.

Retail and trading

On the retail side, the business focuses on keeping customers from leaving and refining trading strategies to perform well in volatile markets. Downstream benefits most from quantum simulation of chemistry and materials. Accurate quantum models of catalysts, adsorption and reaction pathways could reduce costly trial and error in catalyst selection and process tuning, while supporting the design of cleaner fuels and additives that meet increasingly tight specifications. In parallel, quantum optimization can be applied to refinery blending and scheduling, and emerging quantum machine-learning techniques may complement classical models for demand forecasting and trading analytics where uncertainty and non-linear interactions dominate.

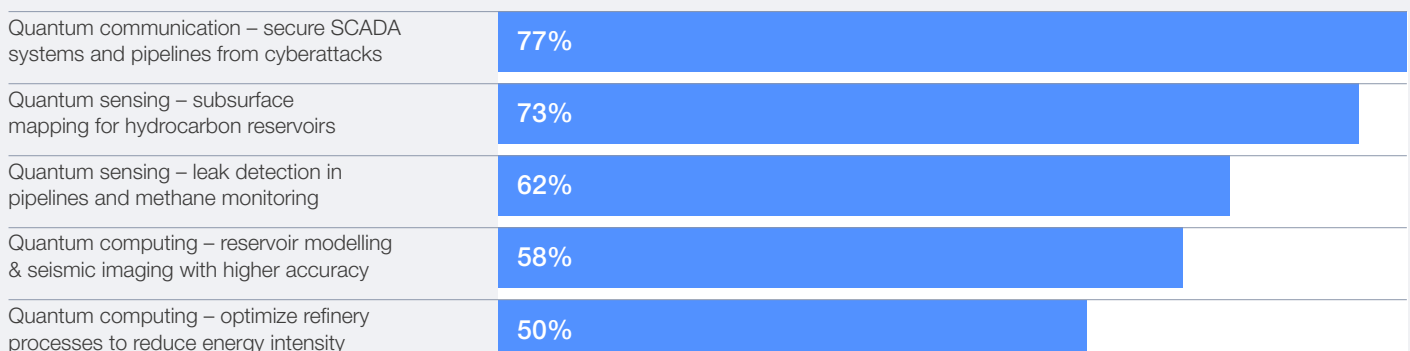


Community insights for quantum solutions in fossil fuels

In fossil fuels, securing SCADA systems and pipelines was seen as the most promising near-term quantum application, highlighting a strong emphasis on cyber resilience. Other promising areas include surface mapping, pipeline leak detection and methane monitoring, demonstrating quantum’s potential to boost efficiency and performance.

FIGURE 5 Top near-term quantum solutions in fossil fuels

Fossil fuels (oil, gas and coal)



Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.



CASE STUDY 1

Quantum computing

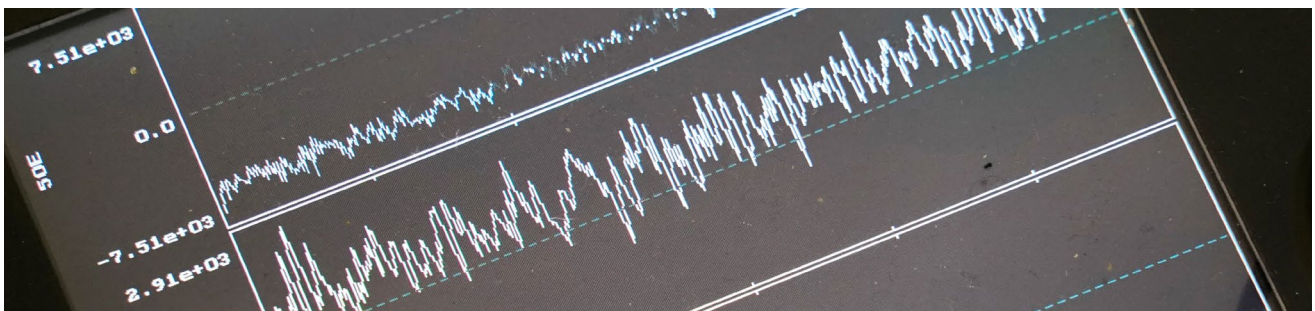
Optimizing seismic imaging using hybrid quantum to build subsurface maps from large 3D seismic volumes

Aramco researchers have made progress in creating clearer images of the Earth's subsurface using a new combination of quantum and classical computing technologies. This early-stage work focused on improving a key process in seismic imaging, the technique used to create detailed pictures of geological subsurface layers that help guide energy exploration and development.

The team used D-Wave's hybrid quantum-classical systems to enhance a step that sharpens seismic images by identifying key geological features from noisy data. Unlike traditional

computers, which struggle to efficiently enforce the right level of simplicity and clarity in these images, the quantum-assisted method was able to achieve better results by focusing on the most relevant data points.

Because of current hardware limits, the test was run on 2D seismic data, simpler than the full 3D datasets typically used in industry, yet it still showed promising improvements in speed and image quality. This early success suggests that quantum-based methods could one day help solve more complex imaging challenges, such as building highly accurate models of subsurface geological properties, which are critical for finding and developing energy resources.⁵



CASE STUDY 2

Quantum sensing

Monitoring methane at oil terminals with quantum lidar

Oil terminals are hard to monitor because leaks can be small, intermittent and spread across dense equipment, so periodic manual inspections can miss short-lived events. Quantum gas light detection and ranging (lidar) is suited to this because it can scan large areas from fixed positions and quantify emissions remotely.

In a 2023 case study, Repsol Sinopec Resources UK tested the methane lidar from QLM Technology at the Flotta Oil

Terminal in Scotland. Over a week-long trial, two systems were mounted on platforms up to 20 metres high to detect and quantify methane across the site, including minor and intermittent emissions that are difficult to capture with walkover surveys.

Reported benefits for this field-validated pilot were better detection of small leaks, site-wide source localization and quantification, and evidence that fixed-placement monitoring could support longer-duration terminal surveillance.⁶





CASE STUDY 3 Quantum sensing

Mapping subsurface structures and tracking mass changes in reservoirs/storage sites using quantum gravimeters

Tracking subsurface mass movement is central to underground mapping and to time-lapse monitoring of reservoirs and storage sites, because gravity responds directly to changes in mass distribution, for example when fluids migrate through rock or when storage inventories change. The practical barrier has traditionally been instrumentation: field gravimetry is often expensive, difficult to deploy at scale, and prone to drift and operational constraints that make long-duration monitoring and repeatable surveys challenging.

To make gravity-based monitoring more operational, Exail commercialized the absolute quantum gravimeter (AQG), a cold-atom interferometry instrument designed to deliver continuous absolute gravity measurements over long periods while remaining transportable for survey and time-lapse use. Exail positions AQG explicitly for applications including reservoir monitoring and subsurface imaging, emphasizing stability, repeatability and multi-year continuous acquisition as differentiators versus conventional approaches.

Key reported benefits included drift-free absolute gravity measurements suitable for long-duration monitoring and repeatable time-lapse surveys, an architecture for scaling-up from single-station sensing to gravity imaging using an anchored sensor array, and clear evidence of increasing operational maturity.⁷





CASE STUDY 4 Quantum computing

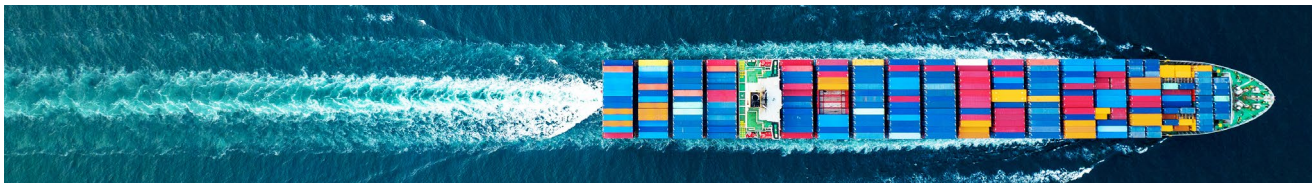
Optimizing maritime inventory routing (VRP or vehicle routing problem, with time windows) for LNG shipping using hybrid quantum-classical optimization to reduce routing cost and improve delivery reliability

LNG shipping and other bulk maritime supply chains face tightly constrained routing and scheduling: vessels must satisfy port time windows, capacity and safety constraints, and inventory balance across multiple terminals over a planning horizon. Because routing decisions and inventory feasibility are coupled (the classic maritime inventory routing structure), the problem scales up quickly beyond what “plain exact solving” can handle without decomposition and heuristics, making it a natural target for experimentation with new optimization paradigms.

ExxonMobil and IBM Research have publicly documented a collaboration focused on casting maritime inventory

routing as vehicle routing with time windows and then analysing which mathematical formulations are most suitable for execution in quantum or hybrid workflows. Their published work discusses quadratic unconstrained binary optimization or QUBO-style encodings and references quantum optimization methods commonly explored for near-term devices. IBM’s case-study framing describes this as laying a foundation for “practical solutions” rather than reporting a deployed production optimizer.

Key benefits would include lower fuel and demurrage costs, improved fleet utilization and more reliable “right-time” deliveries; however, the public record supports R&D/prototype formulation and benchmarking. While not yet at operational scale, these efforts provide the mathematical foundation for future quantum-advantaged logistics.⁸



CASE STUDY 5 Quantum computing

Advancing quantum computational materials design of metalorganic frameworks for carbon capture applications

Adsorbents largely determine carbon-capture performance. Metal-organic frameworks (MOFs) – recognized by the 2025 Nobel Prize in Chemistry – are promising because their porous, tuneable lattices enable strong, selective CO₂ uptake. Electrochemical CO₂ capture can cut regeneration energy, yet predicting MOF adsorption at scale remains difficult: subtle, many-body interactions force a speed-accuracy trade-off in classical simulations.

TotalEnergies and Quantinuum publicly described a workflow that studies CO₂ binding in an Al fumarate MOF

by breaking the problem into smaller building block models and inserting a quantum step where the hardest chemistry appears. Rather than attempting to simulate an entire porous crystal, the approach focuses on the active site that captures CO₂ and treats the surrounding framework with established classical methods, then compares results against high level classical benchmarks to understand where the quantum component helps and where it still falls short.

Key benefits reported so far are a repeatable research, clearer visibility into what must improve before it can scale up, and a practical path toward more predictive sorbent modelling as devices and software become more dependable.⁹





2.2 Renewable and nuclear energy

“ In renewables, optimization for variable renewable integration emerges as the top near-term use case.

As the global energy mix shifts toward renewables, the operational challenge moves from resource extraction to forecasting variable generation, integrating distributed assets and improving material efficiency.

Solar

Solar generation is driven by advances in photovoltaic materials, manufacturing and real-time forecasting to manage intermittency. The highest-impact computational bottlenecks are in materials discovery and in modelling micro-weather dynamics that determine near-term output.

Material discovery (perovskites and organic photovoltaics)

The efficiency of solar PV is fundamentally constrained by the bandgap properties of the absorber material. Discovering new candidates, such as perovskites, is slowed by the difficulty of accurately simulating electronic structure and charge-transport behaviour at scale. Quantum simulation can accelerate this discovery cycle by modelling exciton dynamics and charge-transfer pathways with higher fidelity, enabling faster screening of high-efficiency materials and reducing years of trial-and-error synthesis.

Irradiance forecasting

Accurate short-term forecasts of solar output are critical for grid stability, but performance is often limited by micro-weather variability that is difficult to capture with classical models. Quantum machine learning approaches (for example, quantum support vector machines and quantum neural networks) are being evaluated to process high-dimensional meteorological features more efficiently and improve short-horizon predictions of cloud cover and irradiance, supporting better reserve management and dispatch decisions.

Wind

Wind power performance depends on complex aerodynamics at the wind-farm scale and on high-availability operations in harsh environments. Key challenges include wake-aware layout optimization and condition monitoring to reduce downtime and improve yield.

Wind farm layout optimization

Within a wind farm, turbines create wake. Optimizing turbine placement to minimize wake losses is a high-dimensional, non-convex optimization problem. A near term approach is through quantum-inspired optimization to model wake interactions as a complex graph and search for layouts that increase energy yield without additional hardware.

Predictive maintenance

Wind turbines generate continuous streams of sensor data. Detecting subtle anomalies in vibration signatures before they progress into gearbox or blade failures is a core reliability challenge. Hybrid quantum classical machine learning approaches are being explored to improve early anomaly detection in vibration data, helping operators schedule maintenance during low-wind periods and reduce costly unplanned downtime.

Hydro

Hydropower sits at the intersection of physics-based constraints and market operations, requiring coordinated scheduling across cascaded assets. Operators must optimize water-value trade-offs while meeting environmental flow limits and safety requirements.

Generation scheduling and unit commitment

Optimizing water releases through cascades of dams involves hydraulic coupling, non-linear turbine efficiency curves, environmental flow constraints and market-price uncertainty. The resulting unit commitment and scheduling problems are computationally intensive. Quantum and quantum-inspired optimization algorithms are being benchmarked to navigate these complex solution spaces and improve water-value trade-offs.

Structural simulation

Current developments aim to explore photonic quantum computing for faster and more accurate finite-element analysis of hydroelectric dam structures, supporting safety assessments and life-extension planning for aging assets.

Nuclear fission and future technologies

In nuclear fission, quantum technologies mainly add value through better modelling, better monitoring

and stronger cybersecurity. Quantum computing and quantum simulation can help accelerate parts of reactor-physics and thermo-hydraulic modelling workflows and speed materials discovery for longer-life, radiation-tolerant components. Quantum sensing can improve the precision and stability of radiation and environmental monitoring, while quantum-safe communication protects operational data against future cryptographic threats.

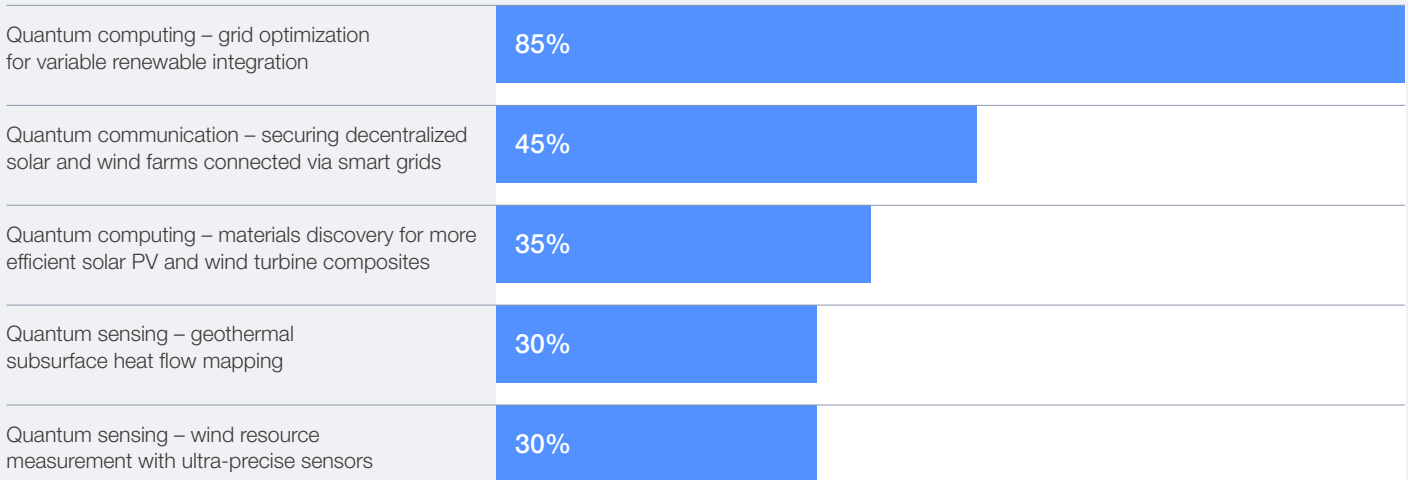


Community insights for quantum solutions in renewable energy

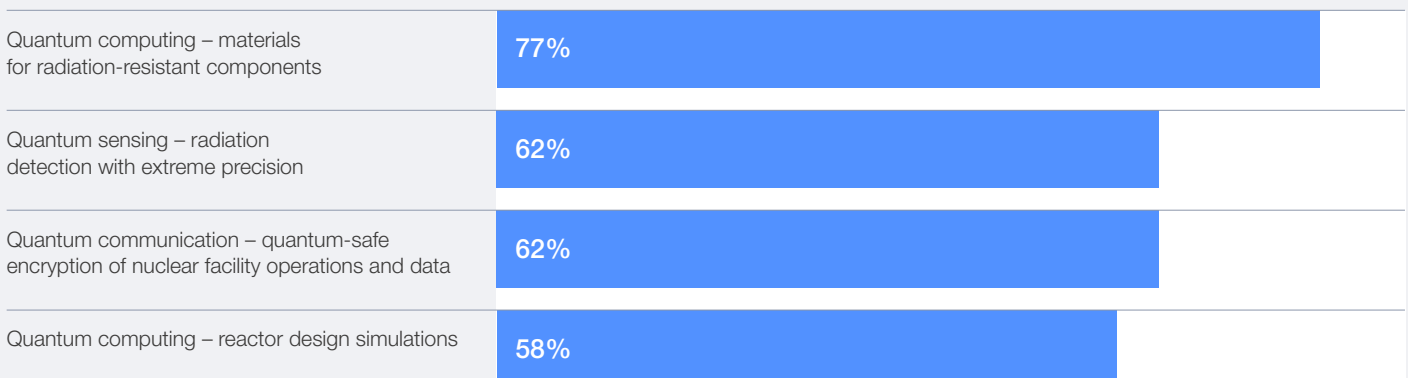
In renewables, optimization for variable renewable integration emerges as the top near-term use case, far exceeding other options such as securing decentralized grids and materials discovery. In nuclear energy, quantum computing for advanced materials and high-precision radiation detection is viewed as a priority.

FIGURE 6 Top near-term quantum solutions in renewable energy and nuclear

Renewable (solar, wind and hydro)



Nuclear (fission future tech)



Source: Community survey, World Economic Forum's Quantum for Energy and Utilities Working Group, February 2026.



Optimizing EV smart charging by forecasting demand and scheduling charging to align with renewable energy

The rapid growth of electric vehicle charging is adding a large, flexible load to power systems that are already coping with intermittent renewables. That makes two tasks harder at the same time: forecasting demand with enough fidelity to plan operations and optimizing charging schedules so consumption shifts towards lower carbon generation windows without violating grid constraints.

EDF and Pasqal experimentally implemented an EV smart-charging use case on Pasqal's neutral-atom platform, reporting an experimental realization that executed a quantum annealing-based schedule optimizer component on

up to 100 qubits, therefore positioning the work as a hybrid quantum classical coupled forecasting-and-optimization challenge for future energy-system orchestration.

Key reported benefits included successfully running the EV smart-charging scheduling use case on a physical neutral-atom system at the 100+ qubit level, and providing a documented, reproducible reference implementation through the joint EDF-Pasqal publication, with the additional practical advantage that the supporting hardware is now part of an inaugurated HPC-quantum hybrid infrastructure intended to enable scaling-up and broader experimentation within the French Atomic Agency. The public reporting frames this as an R&D proof of concept milestone.¹⁰





CASE STUDY 7

Quantum sensing

Improving wind resource management with more sensitive quantum-interference lidar for long-range, low-signal wind measurements

For wind energy, being able to measure wind accurately from farther away, even when the signal is faint, helps at every stage. It supports choosing sites, producing lender-ready energy estimates, understanding turbine wakes and running the plant day to day through better forecasting and control. This is especially useful when you need dependable wind data across the full rotor sweep and several kilometres upwind or across a large onshore or offshore site.

Higher sensitivity means the lidar stays useful in more real-world conditions. It can reach farther and cope better with haze, low aerosol levels and bright background light. When the measurements stay reliable more often, you cut down the

uncertainty in energy forecasts and make smarter decisions about turbine layout and operating settings.

A research team at the University of Science and Technology of China, part of the Chinese Academy of Sciences, built an early prototype of a new kind of atmospheric lidar system that uses quantum interference ideas to pick out very weak signals. It combines up-conversion detection with a Hong Ou Mandel-style interference approach to make wind measurements easier to detect when the return signal is faint.

In field tests, they reported measuring wind fields out to 16 kilometres using 70 microjoules per pulse. They also reported about seven times higher detection sensitivity than conventional methods, with wind-field results that closely matched their reference comparison.¹¹





CASE STUDY 8

Quantum computing

Optimizing wind farm layout with VQE hybrid quantum-computing algorithms

Turbine performance is affected by changing environmental conditions, such as humidity, temperature, salinity, airflow, turbulence and geographic location, which influence energy density and can cause wear or corrosion over time. Carefully adjusting turbine configurations and layout can reduce wake effects between turbines, maximize power output and extend equipment lifespan by up to 25%, as analysed in a study published in the European Academy of Wind Energy.¹²

However, evaluating the vast number of possible positioning combinations makes wind farm layout optimization a

computationally challenging combinatorial problem. Quantum computing offers a way to accelerate this optimization process, helping balance aerodynamics, structural weight, efficiency and durability more effectively.

A test is conducted by formulating the wind farm layout optimization into a QUBO model and applying a hybrid quantum-classical variational quantum eigensolver (VQE) algorithm. Implemented using IBM's Qiskit gate-based quantum circuit simulator, the approach serves as a proof of concept, demonstrating the viability of the quantum algorithm to find optimal or near-optimal wind layout for small instances.¹³





Securing energy grid environment using quantum key distribution (QKD)

In 2024, Verbund, Austria's leading electricity provider, carried out a field trial of quantum-safe communication technologies, using hardware from Hitachi Energy together with ID Quantique's QKD systems. The objective was to demonstrate that quantum-secure communication can operate reliably within a live energy grid environment, beyond laboratory conditions.

The project secured communications between a power plant and a substation via a fibre-optic link deployed on an aerial (overhead) fibre line. Conducted under real operating conditions, the trial confirmed that QKD can be integrated into existing utility infrastructure without disrupting normal grid operations. By leveraging overhead line fibre assets, the implementation further demonstrated that quantum-safe key exchange can be embedded into conventional transmission and distribution network architectures.¹⁴



3

Power and grid infrastructure

As power systems become more decentralized and volatile, quantum technologies could improve grid control, security and energy storage.



The power grid is evolving from a centralized, unidirectional system into a “system of systems”, requiring real-time orchestration of millions of active endpoints. The integration of renewable energy and distributed energy resources (DERs) introduces stochasticity that challenges traditional grid management paradigms.

3.1 Transmission

Transmission system operators (TSOs) manage the high-voltage backbone of the grid. Their core challenge is maintaining stability and flow control in a network increasingly dominated by inverter-based resources.

Optimal power flow (OPF)

OPF is the mathematical problem of determining the most efficient generator dispatch settings to meet demand while respecting physical grid constraints (such as thermal limits and voltage stability).

Optimizing power flows across a large grid is computationally hard, so real operations often use simplified models. Quantum methods, typically paired with classical computers, aim to explore more options faster and surface better operating points; pilots such as E.ON working with D-Wave have tested this method on renewable-heavy grid scenarios.

Grid partitioning and contingency analysis

To manage resilience, grids can be partitioned into self-sustaining islands (microgrids) during faults to prevent cascading blackouts. Quantum-classical hybrid solvers can optimize how a decentralized grid is split into local clusters that can “island” as microgrids. This can help absorb local surplus power and reduce the risk of cascading outages, and it fits well because the task is essentially a network-splitting problem.

Real-time fault detection

Transmission operators increasingly depend on high-frequency measurement streams to identify abnormal conditions before they propagate into outages. As inverter-based resources and weather-driven generation increase volatility, the value of low-latency detection and control grows. Quantum-enhanced signal processing and anomaly detection sensors are being explored to accelerate pattern recognition in high-frequency phasor measurement streams, with the goal of flagging line stress or incipient faults early enough for preventive re-dispatch, protection adjustments or operator intervention.

3.2 Distribution

“ Distribution networks are moving towards local energy markets that balance supply and demand within a constrained feeder or microgrid.

Distribution system operators (DSOs) face the “last mile” complexity of bidirectional power flows from prosumers, EVs and residential solar.

Distributed energy resources (DERs) optimization and EV charging

Coordinating the charging of thousands of EVs to avoid transformer overloads while accommodating user preferences is a massive scheduling problem. Neutral-atom quantum processors have been tested for EV smart-charging: forecast demand and renewable output, then schedule charging to use cleaner power while avoiding local bottlenecks and transformer overloads. The approach fits distribution grids because the hardware can represent network constraints efficiently.

Local energy markets and peer-to-peer trading

As prosumers and behind-the-meter storage grow, distribution networks are moving towards local energy markets that balance supply and demand within a constrained feeder or microgrid. These markets require fast clearing and constraint-aware

matching between buyers and sellers. Quantum optimization methods are being investigated to accelerate market clearing and matching under network constraints, enabling near-real-time peer-to-peer trading while maintaining voltage and thermal limits. In principle, better clearing can increase the economic viability of DERs and provide more transparent price signals to consumers.

Fault detection and network reconfiguration

Fault isolation in distribution is a last-mile problem: there are many switching options, limited observability and strong pressure to restore service quickly. Improvements in measurement fidelity and automated reconfiguration can reduce outage duration and limit equipment damage. Quantum sensors could provide more precise current and voltage measurements, improving the detection of subtle anomalies. In parallel, quantum-inspired and quantum optimization routines can be applied to feeder reconfiguration (switching) to isolate faults and restore power to the maximum number of customers within operational constraints.

3.3 Storage

Energy storage is the critical buffer required to smooth out renewable intermittency. Quantum technologies are being applied to both the design of better batteries and the optimal deployment of storage assets.

Battery materials discovery

Improving the energy density, safety and charging speed of batteries depends on discovering new electrolyte and electrode materials. Quantum simulation is being pursued for battery chemistry, including lithium-air and solid-state systems, aiming to narrow the search space for higher-capacity, safer and faster-charging materials.

Hydrogen storage catalysts

Long-duration storage options extend beyond batteries; hydrogen is a leading candidate where energy must be stored for long periods or transported. Improving electrolyzers and storage media depends heavily on catalyst and materials performance. Quantum computing is being explored to model hydrogen interactions with different durable and sustainable catalysts and storage materials (including porous frameworks),

with the goal of identifying combinations that reduce energy losses and improve safety.



Community insights for quantum solutions in power and grid infrastructure

In the near-term, quantum application concentrates on strengthening grid reliability and optimizing system performance.

In transmission, large-scale grid-flow optimization and ultra-secure communication lead, underscoring resilience and complexity management.

In distribution, focus shifts to local DERs optimization and EV charging orchestration, indicating decentralized grid control requirements.

In storage, emphasis centres on next-generation battery chemistries and hydrogen catalysts, alongside asset degradation monitoring, signalling expectations that quantum computing will accelerate materials innovation while enhancing lifecycle management of energy assets.

FIGURE 7 | Top near-term quantum solutions in power and grid infrastructure

Transmission

Quantum computing – large-scale optimization of high-voltage grid flows	76%
Quantum communication – quantum key distribution for ultra-secure grid communication	72%
Quantum computing – cross-border power trading optimization	64%
Quantum sensing – detect faults and line stress in real time	56%

Distribution

Quantum computing – local optimization of distributed energy resources	75%
Quantum computing – EV charging scheduling at grid scale	67%
Quantum communication – smart meters and IoT nodes secure	58%
Quantum sensing – detect anomalies in local distribution networks	54%

Storage

Quantum computing – simulate new battery chemistries beyond lithium-ion	77%
Quantum communication – monitor degradation of large-scale battery farms	54%
Quantum computing – catalysts for hydrogen electrolysis and storage	54%
Quantum sensing – monitor degradation of large-scale battery farms	50%

Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.



CASE STUDY 10
Quantum computing

Modelling battery cathode materials with quantum computing to design better lithium-ion batteries

Cathode materials largely determine how well a lithium-ion battery performs and how it degrades over time. Many cathodes are metal-oxide materials where the chemistry shifts as the battery charges and discharges, which makes them hard to predict accurately with today’s computer models. Conventional simulations often have to choose between being fast but less reliable or more accurate but too slow and costly to use broadly, so these cathode materials are a promising place to try quantum computing as the technology becomes more capable.

Ford and Quantinuum publicly described a workflow to study a representative cathode material (LiCoO₂) by breaking the problem into smaller “building-block” models that capture key parts of the chemistry during charging and discharging.

The goal was not to fully simulate an entire battery particle, but to show a practical way quantum computing could be used inside a materials research process, running the quantum step where the hardest chemistry shows up, and comparing the results against established classical methods to see where it helps and where it falls short.

Key benefits reported so far are that the work shows a repeatable research approach (not just a one-time demo), makes it clear what still needs to improve before it can scale up (today’s quantum computers are still limited), and outlines a practical path toward more accurate battery-material predictions as the technology gets more reliable. Quantinuum’s newer results on more dependable quantum calculations are relevant because they aim to solve the biggest hurdle, getting answers stable and accurate enough to be useful, but the overall state is still early-stage R&D.¹⁵



Securing distribution-grid communications using photonic QKD over utility fibre to harden smart-grid control traffic

Electric grid control systems manage generation, transmission and distribution of energy. They must provide secure communications of multiple energy devices over a single encrypted channel. DSO networks depend on machine-to-machine communications (e.g. SCADA/control messaging) and long-lived grid assets that must remain secure over multi-decade lifecycles, exactly the time horizon in which cryptographic assumptions can be disrupted by advances in computing. QKD addresses key exchange by using quantum-physics effects to detect interception and to generate/distribute secret keys, and utility “dark fibre” between substations is often a practical substrate for metro-scale QKD deployments.

The EPB (electric power board) in Chattanooga, together with Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL) and industry partner Qubitekk, now part of IonQ, ran a field pilot of entangled photons discrete-variable QKD on an isolated segment of EPB’s utility fibre network, including a dedicated 21-kilometre fibre test bed separate from operational infrastructure. The demonstration work is commonly framed as “QKD-secured” smart-grid fibre communications using trusted-node concepts and substation-to-substation fibre links.

Key reported benefits included establishing a real-world utility-fibre test environment (the 21-kilometre EPB test bed) and demonstrating trusted-node QKD techniques intended to extend effective reach using realistic grid fibre infrastructure, with multiple QKD implementations used in the field context.¹⁶





Enhancing power grid anomaly detection through sensor placement

Sensor placement in power grids refers to strategically deciding where to install sensors (such as PMUs – phasor measurement units or other monitoring devices) across the grid network to monitor electrical parameters such as voltage, current, frequency and phase angles. These sensors help detect anomalies such as equipment malfunctions, cyber-attacks, line overloads, faults or unexpected power flows that can threaten the reliability and stability of the grid.

Proper sensor placement using optimization techniques ensures that power grids are monitored efficiently, economically and securely, preventing faults or attacks from causing widespread damage or blackouts. Without optimization, placement may be suboptimal, leading to unnecessary costs, vulnerability gaps and reduced reliability.

Pasqal, alongside European energy and utility actors, has been experimenting on a quantum-enhanced solution to this problem by leveraging the inherent connections between a power grid and its graph-based representation, and the underlying minimum vertex cover combinatorial optimization problem. Pasqal's neutral-atom quantum processors are physically engineered for independent set-related problems: the physical system itself embodies the independency constraints without artificial encoding.

With appropriate hybridization and decomposition methods, the 80-qubit instances can be coupled to be able to experiment on grid sizes reaching 1,000 nodes as well. The physical experiments on the currently available device reach beyond a proof of concept-type investigation and pave the way to a progressive industrial adoption of such hybrid solution workflows.¹⁷





Enhancing unit commitment in grid operations with quantum optimization

Modern power systems face rising complexity in unit commitment (UC): scheduling generators at minimum cost while meeting demand and operational constraints. The growth of intermittent renewable generation expands the combinatorial search space, challenging classical optimization approaches used by grid operators.

IonQ and Oak Ridge National Laboratory (ORNL), under the US Department of Energy GRID-Q effort,

reported a hybrid quantum-classical UC formulation executed on IonQ's 36-qubit Forte Enterprise system. In a demonstration instance (26 generators, 24-hour horizon), they used a layered variational method (MAL-VQA) to explore feasible schedules and introduced a cost-function design aimed at handling inequality constraints without qubit-intensive slack variables.

At scale, such methods could enable faster exploration of feasible schedules, supporting lower operating costs and improved grid flexibility under renewable variability.¹⁸





Scheduling vehicle-to-grid fleets using hybrid learning and quantum kernels

Modern power systems are increasingly treating electric vehicles as distributed storage that can provide grid services, but turning a large, heterogeneous EV fleet into a reliable vehicle-to-grid “virtual battery” requires real-time scheduling under tight operational constraints (availability windows, state-of-charge targets, site limits, user requirements and volatile prices). As fleet size and variability grow, the scheduling and control problem becomes high-dimensional and time-sensitive, which pushes classical optimization and forecasting stacks toward higher complexity and shorter decision cycles.

E.ON and IBM tackled the practicality gap in vehicle-to-grid (V2G) scheduling by training a learning-based model to quickly predict near-optimal EV charging and discharging actions from simulated scenarios. Their approach derives policies using approximate dynamic programming and then learns them with kernel methods, so decisions can be generated fast while still respecting real constraints. They report that the learned model achieves objective values

comparable to those obtained by approximate dynamic programming with CPLEX on a classical computer, but with lower runtimes, enabling more frequent re-optimization.

In parallel, they investigated quantum machine learning for high-dimensional prediction tasks linked to scheduling uncertainty. Because fidelity-based quantum kernels can suffer from “exponential concentration”, they introduced an error-mitigation method called bit flip tolerance (BFT) in the scientific journal *npj Quantum Information*. They reported that BFT significantly improved results on 40+ qubits (about 80% accuracy with mitigation versus ~33% without) and demonstrated experiments up to 156 qubits with performance close to classical baselines.

Key reported benefits included faster operational decision-making through learning-guided scheduling that reduces solver runtimes while retaining competitive solution quality, a practical path to frequent re-optimization for large fleets as grid conditions vary, and a demonstrated mitigation strategy for quantum kernels that improves robustness on real EV scheduling-related data and scales up experiments into the 100+ qubit regime.^{19,20}



4

Utilities (public services and critical infrastructure)

Quantum tools could make utilities safer, smarter and more efficient, from grid security and pricing to leak detection and heat-network design.



Utilities are the interface between the energy system and the end consumer. Their focus is on service reliability, efficiency, customer engagement and the management of water and thermal networks.

4.1 Electricity and gas

As smart grids become more digital and interconnected, they become vulnerable to cyberattacks. The advent of large-scale quantum computers poses a specific threat to standard RSA encryption used in SCADA systems and smart meters (“harvest now, decrypt later”). Multiple entities are piloting QKD over existing fibre optic lines to secure critical data transmission between substations.

Smart meter security

QKD is also being explored to secure the communication between smart meters and the utility, ensuring customer privacy and preventing data manipulation.

Customer churn and dynamic pricing

Retail energy providers operate in increasingly competitive markets. Pricing and retention decisions depend on granular consumption data, customer segmentation and fast-changing wholesale conditions. Quantum machine learning is being applied to customer data to predict churn with higher accuracy.

Dynamic pricing

Quantum algorithms can optimize dynamic pricing models in real-time. By analysing market conditions, grid load and customer elasticity simultaneously, utilities can set prices that incentivize load shifting (demand response) while maximizing revenue.

4.2 Water and wastewater

The water sector is increasingly adopting quantum technologies for network management, leak detection and treatment efficiency.

Water distribution network (WDN) optimization

WDNs are complex graphs where operators must optimize pressure and flow to minimize leakage and energy use (pumping costs). A hybrid quantum-classical approach was tested for water-network optimization: classical simulation estimated network states, while quantum solvers searched valve settings that improved performance under constraints. Although still proof-of-concept, it suggests these hybrid workflows could better tackle the non-linear hydraulic maths that makes large networks hard to optimize.

Leak detection via quantum sensing

Leaks in underground pipes are a major source of water loss and are notoriously hard to locate. Quantum gravimeters and sensors can detect the micro-changes in density caused by water voids or saturated soil around a leak. This non-invasive technique allows for precise localization of leaks without excavation.

Wastewater treatment optimization

Aeration is the most energy-intensive part of wastewater treatment, accounting for a significant portion of a plant's energy bill. Optimizing the airflow to biological reactors is a complex control problem involving biological dynamics and variable influent rates. Startups like Quantum Mads are

developing hybrid quantum-classical algorithms to optimize aeration processes. This approach aims to reduce energy consumption and operational costs

by dynamically adjusting control parameters based on real-time data.

4.3 Heating and cooling

“Quantum annealing technology has been utilized to optimize the design of HVAC networks for buildings.

District heating network optimization

District heating involves distributing heat from a central source to multiple buildings through a pipe network. Optimizing the flow temperature and pressure to minimize heat loss while satisfying customer demand is a complex hydraulic and thermodynamic challenge.

Quantum annealing technology has been utilized to optimize the design of heating, ventilation and air-conditioning (HVAC) networks for buildings. The problem of “network generation” – connecting HVAC elements efficiently while complying with safety and sustainability constraints – is computationally expensive. The quantum-hybrid application successfully generated lower-cost and more efficient network designs compared to traditional methods, demonstrating the value of quantum annealing in infrastructure design.



Community insights for quantum solutions in utilities

In electric and gas, quantum communication for hardening customer data and billing platforms is rated as the most promising near-term application in electricity.

In natural gas, quantum sensing for leak detection dominates as the most immediate value area, improving safety and environmental compliance.

In water and wastewater, quantum computing for smart distribution and treatment optimization leads as the near-term use case and demonstrates growing potential for resource efficiency and drought resilience.

FIGURE 8 Top near-term quantum solutions in utilities

Electricity

Quantum communication – harden customer data and billing platforms	79%
Quantum computing – long-term planning of generation and retail mix	58%
Quantum sensing – asset health monitoring (transformers, substations)	54%

Natural gas

Quantum sensing – detect leaks in urban gas distribution	73%
Quantum computing – optimize gas network flows under dynamic demand	62%
Quantum communication – secure gas SCADA and distribution networks	58%

Water & wastewater

Quantum computing – optimize desalination and water treatment processes	65%
Quantum communication – protect critical water infrastructure from cyberattacks	61%
Quantum computing – smart water distribution under drought conditions	61%
Quantum sensing – detect contaminants and micro-leaks in pipelines	61%

Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.



CASE STUDY 15 Quantum sensing

Detecting leaks and integrity risks in buried utility networks using cold-atom quantum gravity sensing to reduce excavation and improve service resilience

Gas pipelines are commonly buried, underground electric cables create serious hazards when damaged and district heating networks are largely underground, while leaks in buried heating pipelines can accumulate in surrounding soil and change local conditions. These are precisely the types of anomaly that gravity-based sensing targets.

Sydney Water, in collaboration with the New South Wales Smart Sensing Network (NSSN), the Australian National University (ANU) and the University of Canberra (UC), undertook a “quantum sensing” initiative aimed at detecting

leaks from buried pipes by measuring density changes in surrounding soil as it transitions from dry to wet. Public disclosures describe a pathway from successful tests with simulated leaks toward operational validation, and outline plans for ANU (with Nomad Atomics) to develop a quantum-sensing prototype for utility leak detection, including expansion from water mains toward sewer mains.

Key reported benefits included a non-invasive detection approach (reducing the need to drill, dig or connect into pipes), successful validation activities with simulated leaks as a stepping-stone to operational trials, and a documented roadmap toward a deployable quantum-sensing prototype for live utility networks.²¹





Optimizing energy communities and peer-to-peer energy exchange

Energy communities let prosumers, municipalities and businesses jointly generate, consume and share renewable energy locally, but the hard part is coordination: deciding who should participate, aligning objectives such as local balancing and cost reduction, and managing flows under real operational constraints. Peer-to-peer (P2P) trading adds a transactional layer that matches local supply and demand, yet turning aggregated supply and demand into a minimal, feasible set of simultaneous trades quickly becomes a large combinatorial optimization problem.

To push beyond the scaling-up limits of classical solvers, E.ON worked with IBM and D-Wave on hybrid quantum-classical optimization approaches within the Q-GRID research line, targeting two bottlenecks: energy community formation (coalition structure generation) and

P2P trade decomposition (a sparse graph decomposition problem related to Birkhoff-style decompositions). In the community-formation benchmark, researchers compared classical heuristics and exact methods against quantum approaches, reporting evidence that quantum annealing on D-Wave can reach comparable solution quality with more favourable runtime scaling-up for approximate optimization in instances exceeding 100 agents, while also benchmarking against QAOA-style approaches on IBM hardware.

For P2P trading, a 2025 preprint introduced a hybrid method that plugs a QAOA-based sampling subroutine into a classical Fully-Corrective Frank-Wolfe framework, with experiments spanning simulators and IBM hardware up to 111 qubits. The authors report that the quantum-assisted sampling yields consistently sparser trade decompositions and can improve approximation error on larger graph families, which directly translates to cleaner, more implementable sets of simultaneous P2P transactions.^{22,23,24}



Strategic roadmap for leaders

From pilots to impact, leaders need to prove value fast, strengthen security, build capability and scale up quantum responsibly across energy and utilities.

Energy and utilities leaders must keep services reliable, affordable and secure as operations become more digital and complex. This roadmap sets out what leaders should do in a staged manner, so that quantum moves from interest to practical impact:

Stage 1 (within 2 years): Focus on a small number of high-value problems, run low-risk pilots with clear success measures, build internal capability and trusted partners, and start planning for post-quantum cryptography.

Stage 2 (3-5 years): Move from pilots to scale up by embedding quantum work into business strategy and wider digital and security roadmaps, standardizing delivery and integration, and beginning broader security upgrades.

Stage 3 (5+ years): Treat quantum as a normal part of the technology stack, supported by a steady innovation pipeline and sector alignment on standards, procurement and regulation.

5.1 What holds quantum technology adoption back?

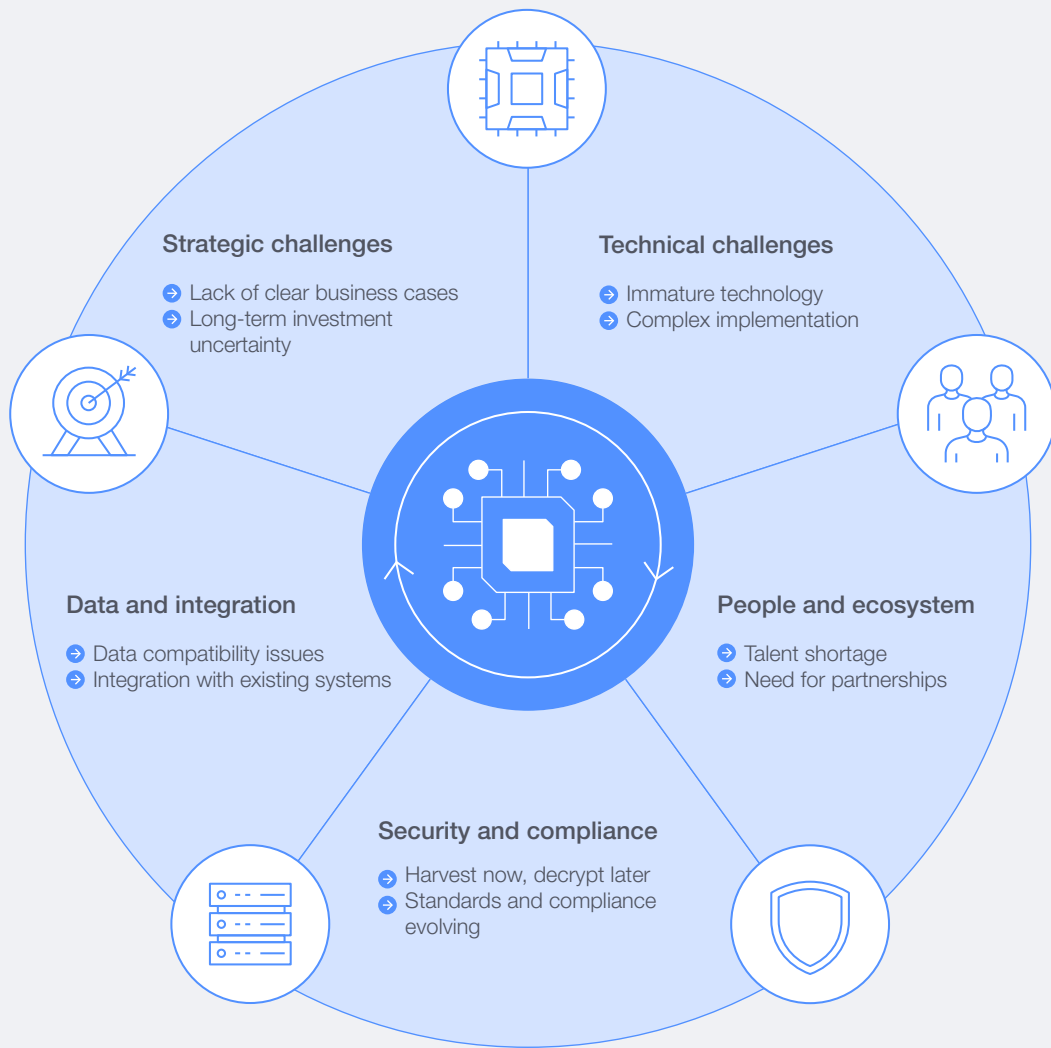
Energy and utilities companies see quantum as promising for grid optimization and planning, but adoption is difficult in practice. Strategically, it is hard to fund work when benefits depend on very specific problems; and much of today's progress is still in pilots and benchmarking rather than having proven operational impact.

Technically, current systems are limited by noise and scale, so results can be fragile and often require hybrid quantum and classical workflows plus rigorous validation. Data and integration can be a bigger barrier than algorithms, because useful

experiments depend on clean network models and operational data; they must then connect back into long-lived OT and IT platforms used for control and planning.

Security and compliance add urgency, because critical infrastructure must plan for post-quantum cryptography and manage the risk of data being captured now and decrypted later, while meeting strict regulatory controls. Finally, progress is constrained by scarce talent and a still maturing ecosystem, pushing utilities toward partnerships with labs, vendors and industry initiatives.

FIGURE 9 | Challenges to adopting quantum technologies in energy and utilities



Source: World Economic Forum's Quantum for Energy and Utilities Working Group.



Community insights for technology adoption challenges

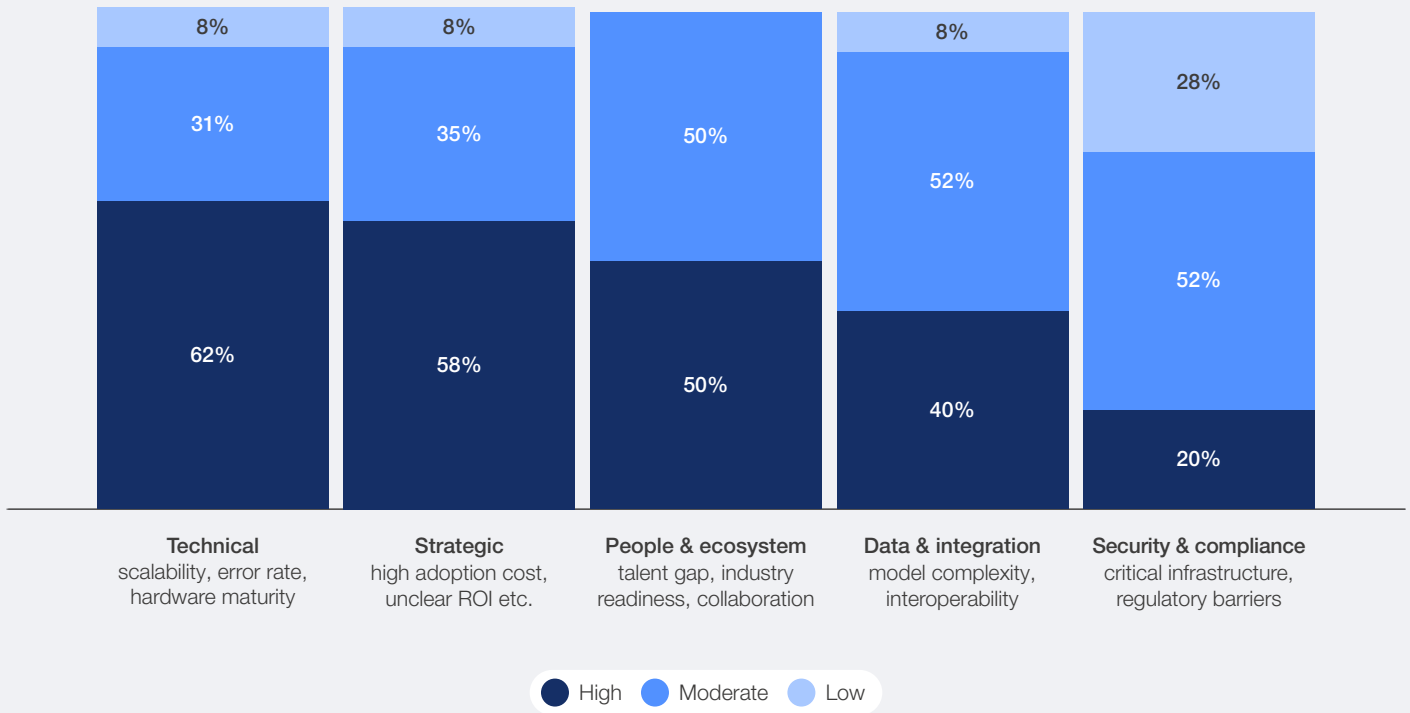
Quantum adoption in the energy and utilities sector is most constrained by scalability, error rates and hardware maturity as major technical obstacles. Without addressing these challenges, commercial readiness remains limited.

Economic and technical barriers are viewed as the secondary adoption challenge, with the majority of respondents identifying high implementation costs and unclear ROI as the main inhibitors to investment.

Finally, talent shortages and weak industry collaboration underline that the broader quantum ecosystem is still taking shape.

Together, these findings suggest that realizing quantum's promise will depend on reducing costs, increasing ROI, advancing hardware performance and strengthening cross-sector coordination to translate early innovation into sustainable adoption.

FIGURE 10 | Top technology adoption challenges



Source: Community survey, World Economic Forum’s Quantum for Energy and Utilities Working Group, February 2026.

5.2 Actions to overcome quantum technology adoption challenges

“The priorities are clear: targeted low-risk pilots, incremental technical integration, strong security foundations and workforce readiness.”

Organizations’ near-term quantum technology adoption should follow a pragmatic, risk-managed approach across the following five key areas:

- Strategy
- Technology
- Data and integration
- Security and compliance
- People and culture

The priorities are clear: targeted low-risk pilots, incremental technical integration, strong security

foundations and workforce readiness. This approach ensures early quantum adoption is incremental and responsible rather than a disruptive overhaul.



Community insights for actions toward technology adoption challenges

Early actions focus on budget allocation, feasibility studies, prioritization and piloting.

Mid-term actions emphasize scaling-up, institutional embedding and standard training.

Long-term actions envision quantum as a permanent infrastructure capability.

FIGURE 11 | Technology adoption actions across five key areas

Adoption action (strategy)

Pilot on clear pain points	92%
Co-fund with partners or public programmes	69%
Integrate quantum into existing strategy	58%
Pursue quick wins with long-term upside	50%
Set quantitative pilot KPIs	46%
Appoint senior value sponsor	42%
Create reusable ROI and business-case tools	38%
Replace costly or painful analyses first	27%

Adoption action (technology)

Set technical acceptance criteria	81%
Focus early pilots on hybrid approaches	81%
Document and share lessons from failures as well as successes	69%
Participate in joint benchmark exercises	69%
Use realistic test cases based on actual system models	58%
Work with specialized partners with energy-specific expertise	54%
Re-use existing HPC/AI infrastructure and workflows	50%
Limit operational pilots to non-critical or shadow modes	46%

Adoption action (data and integration)

Start with use cases needing limited high-quality data	72%
Standardize data formats and interfaces	64%
Allocate a dedicated integration champion for each pilot	52%
Create clean reference models for key systems	52%
Create a shared internal library of models and datasets	48%
Use synthetic or anonymized datasets for early tests	44%
Build APIs and adapters for operational integration	36%
Involve OT/SCADA and IT teams from day one	36%

Adoption action (security and compliance)

Develop a quantum-safe security roadmap	88%
Work with regulators on acceptable quantum use	71%
Involve cybersecurity and compliance teams from day one	71%
Conduct a crypto and security audit	71%
Establish clear data-handling policies	67%
Start pilot deployments of quantum-safe cryptography	67%
Require security and compliance clauses in vendor contracts	54%
Create incident and fallback procedures	42%

Adoption action (people and culture)

Provide basic quantum awareness sessions	80%
Encourage safe experimentation with no guaranteed ROI	68%
Create mixed teams of domain and technical specialists	68%
Include quantum topics in existing training programmes	64%
Identify a small group of internal champions	60%
Use storytelling and concrete examples	48%
Recognize pilot and learning time in performance objectives	48%
Rotate staff through pilot projects for hands-on exposure	32%

Source: Community survey, World Economic Forum's Quantum for Energy and Utilities Working Group, February 2026.

5.3 Organization roadmap to adopt quantum technologies in energy and utilities

The roadmap results show a clear progression. Early actions focus on budget allocation, feasibility studies, prioritization and piloting. Mid-term actions emphasize scaling-up and institutional embedding and standard training. Long-term actions envision quantum as a permanent infrastructure capability.

Stage 1 (within 2 years)

- Organizations should define dedicated pilot budgets, launch a limited number of high-impact use cases tied to organizational pain points and secure executive sponsorship.
- Cross-functional governance structures, initial crypto-risk mapping, early regulatory engagement and joint pilots with ecosystem partners create a controlled environment for experimentation.
- The objective is to validate technical feasibility and operational relevance without exposing to critical systems risks.

Stage 2 (in 3-5 years)

- Quantum should be embedded into corporate strategy and digital/OT roadmaps.

- Dedicated scaling-up budgets, permanent teams and formal collaboration frameworks support expansion of quantum-safe cryptography and sensing beyond pilots.
- The focus shifts to integrating quantum into standard workflows, aligning procurement and vendor models, and ensuring measurable performance against defined KPIs.

Stage 3 (beyond 5 years)

- Quantum capabilities become part of mainstream infrastructure planning.
- Achieving full quantum-safe status, deploying sensing at scale and adopting quantum-accelerated simulations as standard tools position quantum alongside AI and HPC as a permanent innovation pillar.
- Long-term capex alignment, regulatory coordination, workforce evolution and cross-sector collaboration ensure resilient, technology-agnostic energy systems capable of continuous modernization.

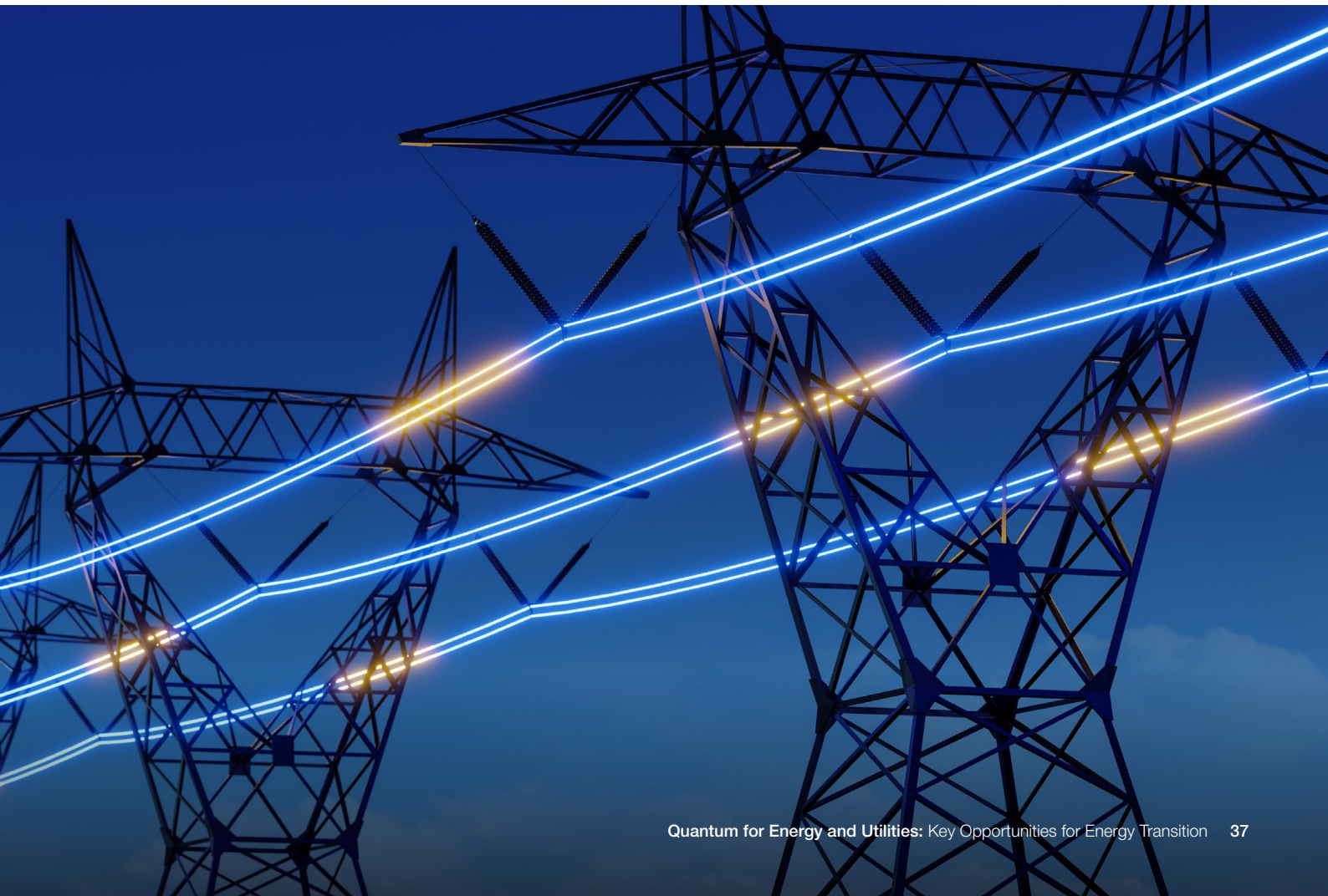
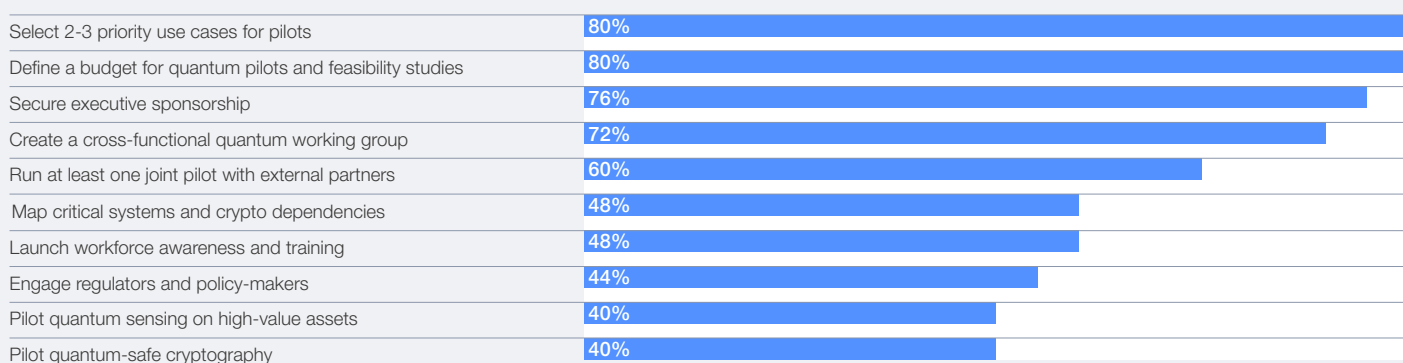
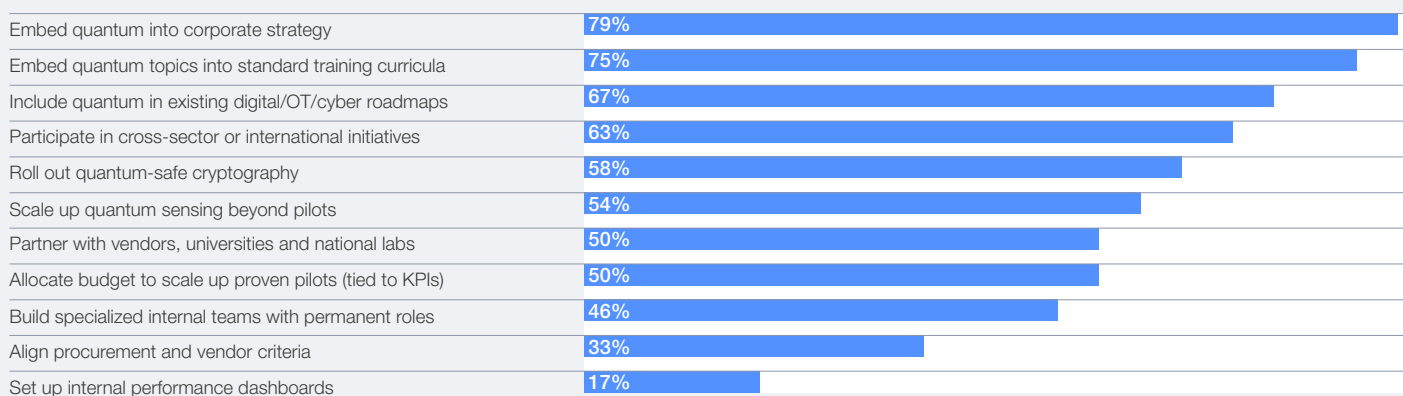


FIGURE 12 | Quantum technologies adoption roadmap, by stages

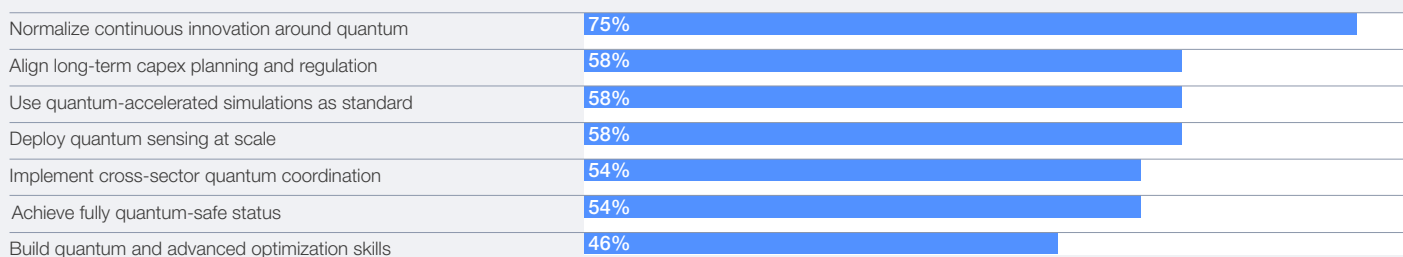
Stage 1 (within 2 years) adoption action



Stage 2 (in 3-5 years) adoption action



Stage 3 (beyond 5 years) adoption action



Source: Community survey, World Economic Forum's Quantum for Energy and Utilities Working Group, February 2026.

Conclusion

Rising operational complexity and cyber risk are driving energy leaders to pilot quantum for optimization, security and simulation, avoiding a widening competitive gap. This turns today's pressure into tomorrow's competitive advantage.

Energy and utilities are under growing strain on multiple fronts: operations are getting more complex and cost pressure is mounting, while reliability and cybersecurity risks keep climbing. That combination is pushing companies to look past incremental fixes and consider quantum as a real tool for improving performance today and building an edge over the long term. Major players like Aramco, ExxonMobil and E.ON are piloting quantum solutions to solve specific, high-value problems *today*.

The immediate value proposition lies in optimization, squeezing efficiency out of complex logistics chains and power grids using quantum annealers and hybrid algorithms. The strategic imperative lies in security, hardening critical infrastructure against the inevitable quantum decryption threat. The long-term transformative potential lies in simulation, unlocking the molecular secrets that will power the next generation of clean energy technologies.

For energy leaders, the risk of inaction is substantial. As quantum capabilities mature, the gap between early adopters and laggards will widen into a significant competitive disadvantage. The recommendation is clear: begin with targeted optimization pilots, secure the network with quantum-safe protocols and invest in the workforce of the future.

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