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Executive Summary

Quantum computing is an emerging paradigm that leverages the principles of quantum mechanics – **superposition** (qubits existing in multiple states simultaneously) and **entanglement** (deep correlations between qubits) – to tackle computational problems that are intractable for classical computers. Unlike classical bits which are strictly 0 or 1, quantum bits or **qubits** can encode a range of values at once, enabling quantum computers to explore a vast solution space in parallel. This report provides a comprehensive overview of quantum computing from fundamentals to cutting-edge applications in the energy sector, with a focus on a landmark 2025 demonstration by IonQ and Oak Ridge National Laboratory (ORNL). In that collaboration, a **hybrid quantum-classical algorithm** running on IonQ's trapped-ion quantum hardware was used to solve a **power grid optimization** challenge known as the *Unit Commitment* problem – determining an optimal generation schedule to meet electricity demand at minimal cost. The IonQ–ORNL team successfully found solutions for 26 power generators over 24 time periods using IonQ's 36-qubit *Forte Enterprise* quantum computer in conjunction with classical computing resources. This achievement, part of the U.S. Department of Energy's GRID-Q program, highlights both the **potential** of quantum computing to revolutionize grid management and the **remaining challenges** before this technology can be deployed in real-world operations [1] [2].

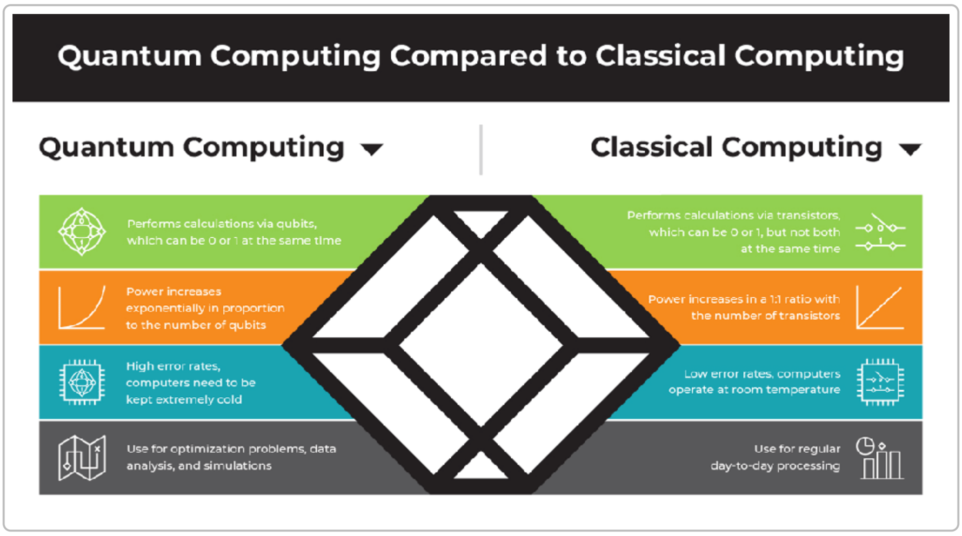
In the **global context**, multiple organizations are racing to apply quantum computing to energy problems. Companies like **IBM**, **D-Wave**, and **Pasqal** have initiatives exploring grid optimization, energy market simulations, and renewable integration. For example, IBM is working with European utility E.ON on quantum algorithms for energy pricing and grid complexity, aiming for quantum advantage by the late 2020s. D-Wave's quantum annealers – with thousands of qubits – have been tested on similar scheduling problems, though their hybrid solvers have yet to outperform classical methods for full-scale grid models [3] [4]. Pasqal in France is using **neutral-atom** quantum processors to model renewable energy variability and optimize electric vehicle charging with partners like EDF. In the U.S., the DOE's ARPA-E recently funded Infleqtion (ColdQuanta) to develop quantum-enhanced grid optimization algorithms with national labs and industry. These parallel efforts underscore a broad recognition that quantum computing could become a **transformative tool** for power system operators.

For **transmission system operators (TSOs)** such as Denmark's **Energinet**, quantum computing promises new capabilities to address pressing challenges in grid planning and operation. With Denmark targeting high renewable penetration and electrification, Energinet faces complex tasks: balancing intermittent wind and solar, expanding cross-border interconnections, and ensuring reliability under extreme conditions. Quantum algorithms could enhance **grid planning** (optimizing network expansion or storage placement under many scenarios), **real-time operations** (fast contingency analysis and stability assessments), **dispatch and market optimization** (more efficient unit commitment, economic dispatch, and electricity market clearing), as well as **forecasting** (improving demand and renewable generation predictions using quantum-assisted machine learning). Early use cases would likely be decision-support tools that run quantum computations in tandem with classical systems. In the near term, quantum computers are small and error-prone, so any practical deployment will be **hybrid** – combining quantum subroutines with classical optimization. Over a 5–10 year horizon, as quantum hardware scales to hundreds or thousands of qubits, TSOs could begin to see **concrete benefits**: lower operating costs through better optimization, reduced curtailment and energy waste, and improved grid resilience by evaluating more contingencies and control options than classical computing allows.

However, significant **barriers** remain before TSOs integrate quantum solutions. Today's quantum processors (typically tens of high-quality qubits, or a few thousand lower-quality qubits in annealers) are in the **Noisy Intermediate-Scale Quantum (NISQ)** era, lacking error correction and limited by short coherence times. Technical milestones like achieving error-corrected logical qubits, scaling hardware, and developing robust algorithms must be met in the coming years. On the policy and organizational side, energy regulators and grid operators will need to develop **standards** for validating quantum-derived solutions, ensure cybersecurity of quantum cloud services, and cultivate quantum expertise on their teams. Forward-looking TSOs like Energinet can prepare by supporting pilot projects, partnering with quantum tech firms, and upskilling engineers – as E.ON advocates, capturing "low-hanging fruit" early to build institutional knowledge. Based on industry roadmaps, **quantum advantage** for certain optimization tasks may be reached in the **late 2020s**, with broader deployment through the 2030s [5]. This report dives deeper into these topics, beginning with a primer on quantum computing basics and culminating in an outlook for quantum applications in the energy sector.

Introduction to Quantum Computing

Quantum computing is a new computing paradigm that **harnesses quantum mechanics** to process information in fundamentally different ways than classical computers. Where classical computing relies on transistors and bits that are strictly 0 or 1, quantum computing uses **quantum bits, or qubits**, which can exist in multiple states at once. This property, known as **superposition**, allows qubits to represent an exponential amount of information compared to classical bits. For example, whereas two classical bits can encode only one of four possible states at a time, two qubits in superposition can effectively represent all four states simultaneously until measured. Furthermore, qubits can become **entangled**, meaning the state of one qubit is correlated with the state of another in ways that have no classical equivalent. **Entanglement** enables coordination between qubits such that operations on an entangled pair affect them as a unified system, allowing complex multi-variable correlations to be computed directly. These phenomena give quantum computers access to a **computational space** that grows exponentially with the number of qubits, enabling certain problems to be solved with exponentially fewer steps than a classical computer would require.



Differences between quantum and classical computing. Classical computers operate on **bits** (electrical on/off states) and process information through deterministic logic gates. In contrast, **quantum computers** operate on **qubits** (quantum states) manipulated by quantum logic gates, which can create superposition and entanglement. Adding classical bits increases computing power linearly, but adding qubits increases power exponentially because a system of n qubits can explore 2^n basis states in parallel. For example, IonQ notes that ~60 high-quality qubits could run certain algorithms in minutes that would take the world's fastest supercomputer **billions of years**. This exponential advantage is what makes quantum computing so promising for complex tasks like chemistry simulations, cryptography, and large-scale optimization. On the flip side, quantum hardware is **fragile** – qubits are prone to decoherence (loss of their quantum state) from the slightest environmental interference. They often require extreme conditions (e.g. superconducting circuits at millikelvin temperatures, or ions in ultra-high vacuum) to operate reliably [6] . Quantum computations also must contend with higher error rates and the fact that measuring a qubit collapses its superposition to a single outcome, so algorithms must be carefully designed to get useful results probabilistically without destroying the quantum state too early.

To perform computations, quantum computers use **quantum gates** analogous to classical logic gates, but these gates are reversible unitary operations that act on the complex amplitudes of qubit states. Common single-qubit gates include rotations (to change a qubit's state on the Bloch sphere), and two-qubit gates (like the CNOT or controlled-Z) create entanglement between qubits. By arranging sequences of quantum gates – i.e. a **quantum circuit** – one can perform algorithms that leverage superposition and entanglement to solve problems. A crucial difference is that quantum algorithms often produce a *probability distribution* over possible answers, so they may need to be run multiple times and combined with classical processing to extract the final result. Despite these challenges, a number of landmark algorithms have been developed to demonstrate quantum speed-ups: **Shor's algorithm** for factoring integers can break RSA encryption by factoring large numbers exponentially faster than known classical methods, and **Grover's algorithm** provides a quadratic speedup for unstructured search problems. These algorithms highlight that *in principle*, quantum computers can outperform classical ones by enormous margins on certain tasks. The big question is **when** practical devices will have sufficient qubits and low enough error rates to realize those theoretical advantages outside the lab.

Quantum Computing in Practice

Current State of Quantum Hardware: Today's quantum computers are early-stage devices, but they have rapidly progressed in scale and performance over the last few years. Several technological approaches exist, each with pros and cons. The most mature platform is **superconducting qubits**, used by IBM, Google, and others, where tiny superconducting circuits act as qubits that are manipulated with microwave pulses at near absolute-zero temperatures. IBM, for instance, has built superconducting processors with **127 qubits** (the "Eagle" processor) and even announced a 433-qubit chip ("Osprey") in 2022, with plans for >1000 qubits by 2025. These qubits operate at nanosecond speeds, but they suffer from relatively short coherence times (microseconds to milliseconds) and require extensive error correction in the long run. Another approach is **trapped-ion qubits**, employed by IonQ and others, which use individual atoms as qubits. IonQ's systems use ytterbium ions confined in an electromagnetic trap and controlled with lasers. All ions of a given species are identical and have very stable energy levels, giving this platform excellent consistency and long coherence times (seconds or more). IonQ's traps can hold a chain of dozens of ions – in fact, IonQ has demonstrated operations on chains of **35+ ions**, and has loaded up to 79 ions in a single device in the lab. One major advantage of trapped ions is **full connectivity**: because ions interact via collective phonon modes, any qubit can be entangled with any other without needing physical wiring in between. This simplifies implementing complex quantum circuits. The trade-off is that gate operations with lasers are slower (microsecond-scale) than superconducting gates, but their higher fidelity can offset some speed loss. IonQ's current flagship system, *IonQ Forte*, has **36 qubits** with 99.9% one-qubit gate fidelity and all-to-all connectivity [7] [8] . IonQ and other ion-trap developers are also exploring modular architectures – linking multiple ion traps with photonic interconnects – as a route to scale beyond 100+ qubits.

Another prominent approach is **quantum annealing**, used by D-Wave Systems. D-Wave's devices are not gate-model quantum computers but specialized machines designed to solve optimization problems by evolving a system of thousands of qubits towards a low-energy state that encodes the optimal solution. D-Wave's latest Advantage annealer uses over **5000 superconducting qubits** connected in a sparse graph (each qubit connected to 15 others in the "Pegasus" topology) [9]. While these qubits are noisy and not general-purpose in the way gate-model qubits are, D-Wave's system can tackle certain optimization formulations (like Ising models or quadratic unconstrained binary optimization) at scale. In fact, quantum annealers have been tested on grid problems like network reconfiguration and unit commitment. However, studies show that current D-Wave hybrid solvers (which combine the quantum annealer with classical algorithms) have not yet outperformed best-in-class classical solvers on realistic power grid optimization tasks [3] [4] – a sign that further hardware improvements and algorithmic tuning are needed.

Beyond these, other hardware modalities include **neutral atoms** (e.g. Pasqal and QuEra use arrays of cold atoms manipulated with lasers), **photonic quantum computers** (e.g. Xanadu's optical qubits that operate at room temperature), and **semiconductor spin qubits** (quantum dots or defects in diamond). Each approach is being pursued by various startups and research labs. For instance, Pasqal's neutral-atom processors have reached 100+ atoms and are naturally suited to analog quantum simulations; Infleqtion (formerly ColdQuanta) is developing cold-atom qubits with an emphasis on integrating quantum computing with sensing and networks. It's expected that different technologies may co-exist, and hybrid approaches could integrate the strengths of each. At present, **qubit counts alone are not the best measure** of a quantum computer's capability – qubit *quality*, gate fidelity, and connectivity play a huge role. Thus, a 50-qubit trapped-ion machine with high fidelity and full connectivity might execute certain algorithms more effectively than a 1000-qubit superconducting chip with more errors or connectivity limits. Researchers use benchmarks like **quantum volume**, **circuit layer operations per second (CLOPS)**, and application-specific metrics to compare devices. The field is evolving quickly, with both academic and commercial roadmaps anticipating **hundreds of qubits with error rates ~10^{-3} or better in the next 2-3 years**, and fault-tolerant quantum computers (millions of physical qubits forming thousands of logical qubits) by the end of the decade [10] [7].

Types of Quantum Algorithms: The power of quantum computing lies not just in hardware, but in algorithms that exploit quantum phenomena. Quantum algorithms can be grouped into several categories:

- **Unstructured Search and Grover's Algorithm:** Grover's algorithm provides a quadratic speed-up for searching an unsorted database or solution space. While quadratic ($O(\sqrt{N})$ vs $O(N)$) is modest compared to exponential, it could be impactful for very large N. Grover's approach has applications in solving NP-complete problems by brute force (though it doesn't evade the exponential nature, just reduces it) and in cryptography (e.g. speeding up brute-force key searches).

- **Quantum Fourier Transform and Shor's Algorithm:** The Quantum Fourier Transform (QFT) underpins algorithms for period-finding. Shor's algorithm for integer factorization uses QFT to achieve an exponential speedup over classical factoring methods. Shor's algorithm famously would break RSA encryption if run on a large enough quantum computer, as it can factor large semiprimes in polynomial time. This algorithm, along with related ones for discrete logarithms, drove a lot of early interest in quantum computing. However, Shor's requires thousands of logical (error-corrected) qubits to factor numbers of cryptographic size, beyond current capabilities.

- **Quantum Simulation of Physical Systems:** Because quantum computers naturally emulate quantum mechanics, they excel at simulating molecular and materials systems. Algorithms based on **Hamiltonian simulation** and **phase estimation** can, in theory, simulate chemical reactions or quantum dynamics exponentially faster than classical simulation. This is valuable in **quantum chemistry**, materials science, and drug discovery. For example, simulating a molecule's ground state energy can be framed as an eigenvalue problem that quantum phase estimation can solve efficiently given a suitable Hamiltonian encoding.

- **Quantum Machine Learning:** There is a growing family of algorithms (e.g. quantum support vector machines, quantum neural network variants, Grover-based data search) that attempt to accelerate machine learning tasks. Some promise polynomial speedups (like using amplitude amplification for sampling tasks), while others explore the use of high-dimensional Hilbert space for better model expressivity. It's an area of active research, though practical advantage for ML tasks hasn't been clearly demonstrated yet on hardware.

- **Optimization and** Hybrid Quantum-Classical Algorithms***: Many of the most exciting near-term applications are in optimization and combinatorial problems – from routing and scheduling to portfolio optimization.*** ***Hybrid algorithms** like the **Variational Quantum Eigensolver (VQE)** and **Quantum Approximate Optimization Algorithm (QAOA)** are designed for NISQ hardware and combine quantum circuits with classical feedback [11] [12]. In these algorithms, a parameterized quantum circuit (ansatz) is executed, and measurements from the quantum hardware are used by a classical optimizer to adjust the parameters iteratively, seeking to minimize a cost function (often the energy of a system or the objective of an optimization problem). VQE was originally conceived for finding molecular ground states by minimizing the quantum expectation value of a molecule's Hamiltonian [12]. It has since been applied to general optimization: for instance, mapping an optimization problem to finding the ground state of a corresponding "Ising" Hamiltonian. QAOA, on the other hand, is a specific type of variational algorithm for combinatorial problems. It alternates between applying a problem-specific Hamiltonian (to encode the cost function) and a mixing Hamiltonian, with tunable angles at each step. In essence, QAOA produces a quantum state that is a superposition of candidate solutions, then interference biases the probabilities toward good solutions; the classical routine then adjusts angles to amplify the probability of finding an optimal or near-optimal solution [13]. These hybrid algorithms are promising because they can often work with shallow circuits (important for NISQ devices), and the classical optimizer helps find good results despite hardware noise. Recent research by IonQ and ORNL even developed a *noise-tolerant* hybrid algorithm based on **Quantum Imaginary Time Evolution (QITE)** that achieved better results with shorter circuits than standard QAOA [14] [15]. In December 2024 they reported that this QITE-based approach could reach optimal solutions for certain optimization problems using 85% fewer two-qubit gates than QAOA, an important improvement for near-term machines [14]. (We will discuss this further in the IonQ–ORNL case study.) Aside from VQE/QAOA, another kind of hybrid approach is to use quantum solvers inside classical algorithms – for example, using a quantum step to evaluate or improve a candidate solution inside an otherwise classical optimization workflow (sometimes called quantum-assisted heuristics or "BQC" – Best of Both Worlds Quantum-Classical algorithms).

In summary, a **hybrid quantum-classical paradigm** is expected to be the way quantum computing delivers value in the next few years [16]. The quantum processor acts as an accelerator for specific subproblems (like evaluating a cost function or propagating a quantum state), while a classical processor orchestrates the overall algorithm, handles data loading, and post-processes results. This synergy plays out clearly in the IonQ–ORNL demonstration, where a quantum computer tackled the core combinatorial part of a grid optimization, guided by classical optimization routines – achieving results beyond what a naive quantum-only or classical-only approach could do on that problem size.

Overview of the IonQ–Oak Ridge Collaboration

Objectives and Partners: In mid-2025, IonQ (a leading quantum computing company specializing in trapped-ion technology) partnered with Oak Ridge National Laboratory (ORNL) to demonstrate how a quantum computer could help solve a **power grid optimization** problem in practice. This effort was part of a U.S. Department of Energy initiative called **GRID-Q (Grid Research, Integration and Deployment for Quantum)**. GRID-Q is a multi-year program (launched in 2024) bringing together national labs, universities, and companies to identify use cases for quantum computing, sensing, and communication in grid operations. ORNL leads the project, and IonQ is one of only two quantum industry partners selected to develop *scalable quantum algorithms for grid optimization* [1]. (The other partner is a Colorado-based quantum startup, indicating DOE's interest in multiple platforms.) The specific challenge addressed by IonQ and ORNL was the **Unit Commitment problem** – a canonical optimization task for electric power systems.

The Unit Commitment Problem: Unit commitment (UC) involves deciding, over a future time horizon (e.g. 24 hours split into hourly intervals), which power generating units to turn on or off and at what output levels, in order to meet projected electricity demand at minimum cost while respecting operational constraints. These constraints include generator capacities, minimum up/down times (once a unit is started or stopped), ramp rate limits, fuel or emission limits, and reserve requirements for reliability. As described by IonQ, *"The Unit Commitment problem involves determining the optimal schedule for power generators to meet electricity demand at minimal cost"*. It's a complex **mixed-integer optimization** problem that grows combinatorially hard as the number of generators and time periods increases. Grid operators typically solve UC (and the related Economic Dispatch problem) daily using classical optimization (mixed-integer linear programming or dynamic programming heuristics), but as power systems expand and incorporate more intermittent renewables, UC becomes more challenging. The volatility of wind and solar production means more scenarios to consider, and the sheer size of the search space can strain classical solvers – which might resort to simplifications or run out of time for very large systems. Quantum computing is seen as a potential way to explore many generation scheduling combinations more efficiently than brute-force classical computation.

Hybrid Quantum-Classical Algorithm (Simple Explanation): The IonQ–ORNL team devised a **hybrid algorithm** to solve a simplified UC instance using IonQ's *Forte* quantum computer coupled with classical processing. In simple terms, the approach works like this: the quantum computer generates candidate solutions to the unit commitment (generator on/off schedules) in the form of quantum states, and evaluates the "cost" (objective value) of those solutions by encoding the UC cost function into the quantum circuit. A classical computer then takes the measurement results (which reflect the quality of the quantum-generated solution) and uses an optimization routine to tweak the quantum circuit's parameters to try for a better solution. This iterative loop – quantum evaluation of a solution, classical adjustment of parameters – continues until it finds a good (near-optimal) schedule. By leveraging quantum superposition, the algorithm can sample and **explore many possible generation schedules in parallel**, rather than one-by-one as a classical algorithm might. Essentially, the quantum processor acts as a specialized solver for the combinatorial core of the problem, while the classical processor guides the search towards lower-cost solutions. This kind of algorithm is a form of **Variational Quantum Optimization** (related to QAOA), tailored to the structure of the UC problem.

Hybrid Algorithm (Technical Detail): More technically, IonQ and ORNL implemented a **QITE-based variational algorithm**. QITE stands for Quantum Imaginary Time Evolution – a method that simulates imaginary time propagation to drive a quantum state toward the ground state of a given Hamiltonian (in this case, the Hamiltonian would encode the UC cost function) [14]. The beauty of QITE-based algorithms is that they can converge to optimal solutions with shorter circuits by effectively incorporating certain problem structure and mitigating noise. According to IonQ, their novel algorithm *"enables near-optimal and optimal solutions for complex combinatorial optimization problems on IonQ's hardware"* and *"showed QITE can significantly outperform other quantum optimization algorithms such as QAOA in both time-to-solution and circuit depth"* [14] [17]. In practice, they constructed a parameterized quantum circuit (ansatz) that represented on/off states of the 26 generators and their commitments over 24 periods. The cost (fuel cost of generators, penalties for violating demand balance, etc.) was encoded as an effective energy in the quantum system. The QITE algorithm then effectively adjusted the circuit parameters to minimize this energy, akin to finding the lowest-cost schedule. This was all done while keeping the circuit shallow enough to run on IonQ Forte's 36 physical qubits without significant error. The algorithm took advantage of IonQ's high-fidelity **entangling gates** (implemented via laser pulses on pairs of trapped ions) and complete qubit connectivity, which simplifies mapping of the problem onto hardware. ORNL's expertise in quantum algorithms and power systems helped in formulating the problem and guiding the hybrid approach to ensure that the quantum computer's efforts were steered towards physically feasible, low-cost schedules.

Problem Instance and Demonstration Results: The demonstration case was a scaled-down but representative UC problem: **26 generators** supplying demand over **24 time periods** (e.g. one day with hourly intervals). These generators would include a mix of dispatchable units (like nuclear, gas, hydro) and possibly some representation of intermittent sources. The goal was to meet each hour's forecasted demand at minimum total cost. Using their hybrid quantum-classical algorithm on IonQ's 36-qubit system, the team *"found varied solutions for power generation scheduling across 24 time periods and 26 generators"*. This phrasing suggests the algorithm was able to identify multiple feasible generation schedules near the optimal cost, illustrating the quantum approach's ability to explore different solutions. It's noteworthy that the quantum solution was not a single run giving a single answer, but rather the process likely sampled many bitstring outcomes (each representing a commitment schedule) and gradually honed in on high-quality ones through the variational loop. The outcome demonstrated **proof-of-concept**: even with today's noisy hardware, a quantum-classical method could handle a unit commitment instance of moderate size, producing correct or near-optimal solutions.

While the exact performance metrics (like how close to optimal cost, or how runtime compared to classical solvers) were not fully detailed in public releases, the emphasis was that this was a *feasibility study*. ORNL's Suman Debnath, who led the project, stated the experiment *"demonstrated the feasibility of using an ion-trapped quantum computing device to solve the Unit Commitment problem in the power grid"* [18]. The collaboration showed that even **noisy quantum devices** can contribute to real energy applications when paired cleverly with classical computation. It also validates the structure of the GRID-Q program: by having domain experts (grid scientists at ORNL) work hand-in-hand with quantum engineers (IonQ), they could tailor algorithms to meaningful problems rather than abstract math.

Comparison to Classical Approaches: For this specific 26-generator test case, classical optimization methods (like mixed-integer linear programming solvers) can certainly solve the problem to optimality in reasonable time – after all, power companies solve larger UC instances daily. The significance of the IonQ–ORNL result is not that it beat classical computing *at this scale*, but that it lays groundwork for quantum scaling to regimes that classical methods struggle with. The press release notes *"the quantum optimization methods demonstrated in this work are applicable to a broad range of industries"* and that as quantum systems scale, they expect to tackle grid optimization *"at a scale that classical computing methods cannot match"* [2]. IonQ's CEO Niccolo de Masi highlighted that when their machines reach **thousands or millions of qubits**, they foresee solving *"grid optimization challenges at a scale that classical methods cannot match"*. This is aspirational, but backed by the logic that an exponentially growing state space of qubits will eventually leave classical brute-force or heuristic methods in the dust for huge combinatorial problems.

It's worth mentioning that other attempts to apply quantum algorithms to unit commitment have found it challenging to beat classical state-of-the-art. For instance, a 2025 study benchmarked D-Wave's hybrid annealer on a similar UC problem and found it did *not* outperform a classical MILP solver in solution quality or speed [3] [4]. The IonQ–ORNL work did not claim a quantum **speedup** over classical in absolute terms; instead it demonstrated a new *approach* that could become competitive as hardware improves. They did observe that their QITE-based algorithm outperformed more "novel quantum algorithms" (like plain QAOA) on the same problem [14] [17] – meaning the hybrid method was an advance in the *quantum algorithm domain*. In essence, they showed that *quantum-aware algorithm design* (reducing circuit depth, mitigating noise) can significantly improve results, which is a key lesson for achieving quantum advantage.

Outcomes and Future Implications: This case study is a milestone for quantum computing in the energy sector. It proved out the end-to-end integration: formulating a real grid problem into a quantum-friendly form, solving it on actual quantum hardware (IonQ Forte) in concert with classical computing, and interpreting the results in an energy context. The announcement garnered attention as one of the first times a quantum computer tackled a power systems optimization with real data. The collaboration is ongoing – ORNL plans to continue testing the approach on larger problem sizes and more complex grid scenarios as IonQ's machines improve. Both IonQ and ORNL expressed optimism that *quantum advantage* in grid problems is on the horizon. IonQ stated that systems with **100–200 high-fidelity qubits**, which they **expect by 2026**, should be capable of solving "grid-scale" unit commitment instances (meaning something closer to the full size and complexity that a regional grid operator deals with) [2]. If that timeline holds, within a few years we might see a quantum computer co-optimize the commitment of hundreds of generators or handle stochastic variants of the problem that are extremely hard for classical solvers. Additionally, IonQ pointed out that improvements here could translate to **huge efficiency gains**: over 60% of generated energy is currently lost before use (through inefficiencies and curtailment), so better optimization via advanced computation could yield major economic and environmental benefits in the electricity sector.

It's also notable that IonQ is involved in a **$22 million project with EPB of Chattanooga** (an electric utility) to apply quantum computing to grid operations [19]. This separate project (announced in 2023) is establishing a quantum networking and computing hub in Tennessee and includes use cases like dynamic grid reconfiguration and real-time voltage optimization. The success of the ORNL collaboration likely feeds into such utility partnerships, demonstrating tangible progress. ORNL and IonQ have worked together on other quantum R&D as well, including error mitigation techniques for optimization [19] and exploring modular quantum architectures [19]. All these efforts contribute to building a **quantum-ready ecosystem** in the energy domain.

In summary, the IonQ–ORNL demonstration in June/July 2025 showed that **hybrid quantum-classical algorithms** can solve non-trivial power grid problems today, foreshadowing a future where larger quantum computers could give TSOs and utilities a powerful new tool for optimization. It's a **significant step** on the path from academic algorithms to practical quantum computing applications in critical infrastructure.

Global Context and Comparisons

The quest to apply quantum computing to energy and grid optimization is truly global. Multiple companies and research institutions are tackling similar problems with different technologies. This section highlights a few key efforts and how they compare or complement the IonQ–ORNL milestone.

- **IBM and E.ON (Europe):** IBM has been investing heavily in quantum computing and has identified the energy sector as a prime application area. One notable collaboration is with **E.ON**, a major European utility operating across 17 countries. In 2024, IBM and E.ON began exploring quantum algorithms for **energy grid complexity and pricing** challenges. E.ON's grid faces variability from renewables and new consumption patterns (like EVs), making forecasting and hedging difficult. Together with IBM, they developed quantum algorithms to better calculate energy procurement costs under uncertain weather and demand conditions. Using IBM's Qiskit software and a 27-qubit quantum processor, they implemented a dynamic circuits approach to repeatedly compute pricing outcomes for different weather scenarios, helping inform hedging decisions. While this is a different focus than unit commitment, it's another piece of the puzzle – managing financial risk and market operations in the energy sector via quantum computing. IBM has publicly stated a **goal of achieving quantum advantage by 2029** for real-world use cases. Their work with E.ON underlines the importance of **early adoption and talent-building**; E.ON's leadership emphasizes gaining quantum expertise now to not fall behind as the technology matures. IBM is also involved in various research projects (like with national labs) on grid optimization and has built quantum centers in Germany, highlighting Europe's active role. The **Quantum Computing at E.ON** initiative and similar projects (e.g. by EDF in France) indicate that TSOs/utilities worldwide are scouting quantum's potential.

- **D-Wave and Quantum Annealing for Grid:** D-Wave, based in Canada, offers a different paradigm with its quantum annealers. Over the past few years, D-Wave has engaged utilities and researchers to apply its machines to grid problems like **unit commitment, optimal power flow, and capacity expansion**. For example, D-Wave worked with Japan's NEC on a pilot for optimizing EV charging schedules, and with a California utility on transmission line switching. In 2023, a Nature Scientific Reports article analyzed **D-Wave's hybrid constrained quadratic model (CQM) solver on a unit commitment problem** [20]. The study benchmarked D-Wave's performance vs. classical solver Gurobi on different scales of the UC problem. The findings were that D-Wave's approach could find feasible solutions for small instances, but *"was unable to surpass Gurobi in terms of solution quality or computational time"* on larger instances [4]. Specifically, even after problem reductions, the D-Wave hybrid solver did not match classical optimal results within reasonable time for full-scale UC cases [3] [4]. This highlights both the current limitations and the progress needed – annealing requires careful formulation and embedding of the problem, and current hardware (despite thousands of qubits) has noise and connectivity limitations that impede optimal solutions. D-Wave is continually improving its quantum processors (its upcoming Pegasus and Zephyr topologies with increased connectivity) [21] [22] and integrating **error mitigation techniques** like drift correction and zero-noise extrapolation [23]. They project that by around 2028, quantum annealing might deliver practical applications in areas like energy unit commitment (as hinted in D-Wave investor materials) [24]. So while D-Wave's approach hasn't shown a clear advantage yet, it remains a parallel path – particularly for **discrete optimization** problems relevant to TSOs. D-Wave's advantage is the raw qubit count (allowing larger problems to be embedded, if only at low precision), and a relatively accessible cloud platform that some grid researchers are already experimenting with.

- **Pasqal and European Efforts:** Europe has a vibrant quantum technology scene with several startups focusing on energy use cases. **Pasqal**, a French company, builds quantum processors using *neutral atoms controlled by laser pulses*. Their machines operate more analogously, naturally implementing certain Ising-model physics. Pasqal has partnered with the French utility **EDF** on a project to **optimize renewable energy integration and manage new electricity demand from EV charging**. By using quantum computing to better forecast renewable generation (by simulating weather-influenced variables) and to optimize charging schedules for electric vehicles, they aim to reduce grid congestion and improve efficiency. This is conceptually similar to unit commitment but focused on the distribution side and demand response. They reportedly have algorithms that help *"forecast renewable availability and reduce reliance on backup systems"*, and to optimally schedule EV charging to flatten demand peaks. Pasqal's work is part of broader EU initiatives (it was a **Hello Tomorrow Deep Tech Pioneer** in 2019). Additionally, startups like **IQM (Finland/Germany)** and **Atom Computing** are exploring grid applications. IQM, for instance, works with Volkswagen on battery research and is involved in a Finnish project on power grid stability. **NREL** (National Renewable Energy Lab in the US) has created a **quantum "sandbox" for grid algorithms** – linking quantum computers with real-time simulators to test things like coordinating EV chargers using quantum optimization. This involved Atom Computing's hardware and showed early proof that a quantum-in-the-loop approach can work for realistic grid control systems. All these efforts indicate a *convergence of interest*: from North America, Europe to Asia, many believe that complex energy systems are a prime candidate for quantum acceleration.

- **Other Key Players:** Besides IBM, IonQ, D-Wave, and Pasqal, we have **Google**, which achieved quantum supremacy in 2019 for a contrived task and now is pursuing error-corrected superconducting qubits (they have a roadmap with milestones toward a million physical qubits). Google's team has discussed power grid applications conceptually (e.g. using quantum algorithms for power flow or grid simulation), but no public demonstration yet like IonQ's. **Microsoft** is providing quantum services via Azure and researching algorithms like quantum optimal power flow through collaborations (they have a unique topological qubit approach in the works, but also support algorithms on others' hardware). **Rigetti Computing** worked on a project with Los Alamos Lab on wildfire risk in grids (optimizing grid configurations to reduce wildfire ignition risk). **Quantum Computing Inc (QCI)** and others have also shown interest in energy. On the research side, numerous academic papers are coming out on applying quantum algorithms to power system problems – from **state estimation** to **contingency analysis**. For instance, a 2025 study by researchers (Feng et al.) demonstrated a quantum algorithm for **contingency analysis** that identifies critical grid outages with exponential scaling benefits. By encoding power grid state equations into qubit states and using quantum amplitude amplification, they showed the potential to check many outage scenarios much faster than classical brute force. Such research, while early, foreshadows that *quantum advantage might first appear in niche but vital computations* that grid operators perform, like scanning through N-1 contingencies or optimizing restoration plans after outages.

In comparing these approaches: IonQ's trapped-ion gate model and IBM's superconducting gate model are both targeting **general-purpose quantum computing** for broad applications, including grid optimization, using **hybrid variational algorithms**. D-Wave's annealing is more *special-purpose* but currently can handle more variables (at lower precision). Neutral atoms by Pasqal offer a middle ground: highly connected systems good for optimization and analog simulations. It's quite possible that **different quantum technologies will find different sweet spots** in the power sector. For example, annealers might handle certain scheduling sub-problems quickly, while gate-model machines tackle others that require more complex logic or arithmetic. Collaborative projects like DOE's **ENCODE program** (Energy Optimization with NISQ Computing for Decarbonization & Efficiency) are bringing together multiple players. The ARPA-E award to **Infleqtion (ColdQuanta)** in 2025 is one such example – they are working with Argonne National Lab, EPRI, and NREL to integrate neutral-atom quantum optimizers into grid planning tools. The rationale is that AI and renewables are making grid operation a *data-rich, computationally intense* activity, and quantum could provide the next leap in solution quality or speed. Early projections from that project suggest quantum-assisted models *"could deliver faster, more detailed [results] than current mixed-integer solvers"* and potentially yield cost savings and better strategies for distribution utilities.

In summary, the IonQ–ORNL success is part of a **larger wave** of quantum innovation targeting energy. It stands out as one of the more concrete demonstrations, but it's by no means isolated. **IBM** brings massive technological resources and a full-stack approach (software to hardware) and is actively engaging with grid companies. **D-Wave** brings a unique, currently scalable approach to optimization that might complement gate-model methods. **Pasqal, Infleqtion, IQM, and others** add diversity with different hardware and focus areas like forecasting and materials for energy. This healthy competition and variety increase the odds that breakthroughs will occur. It also means TSOs like Energinet should keep abreast of multiple platforms – the best solution for a given problem might come from a surprising place.

Implications for TSOs and Energinet

Energinet's Mission and Challenges: Energinet is Denmark's national TSO (Transmission System Operator) for electricity and natural gas. Its mandate is to ensure a safe, reliable energy supply, operate and develop the high-voltage electricity grid and gas pipeline network, and facilitate Denmark's transition to a **green energy system**. Denmark is a world leader in renewable energy integration – at times over 50% of its power comes from wind turbines, with ambitions to reach 100% renewable electricity by 2030. This brings significant challenges: balancing supply and demand with high wind/solar variability, maintaining grid stability with lower inertia, expanding interconnectors and energy storage, and planning infrastructure for electrification (like powering electric heating and transport). Energinet also runs electricity and gas markets, coordinates cross-border flows with neighboring countries, and must plan long-term investments in grid reinforcement and offshore wind connections. All these tasks involve **complex optimization under uncertainty**, precisely the kind of problems quantum computing promises to help with. While classical tools (like EMS/SCADA systems, state estimators, and market algorithms) are currently used, the scale and complexity of computations are growing. For example, Denmark's grid often relies on **cross-border trading and inter-area optimization** (via Nord Pool market) – optimizing this multi-area, multi-period dispatch with increased renewable uncertainty is computationally demanding.

Potential Quantum Applications for Energinet:

1. **Advanced Grid Planning:** Quantum algorithms could assist in long-term transmission planning. One example is **network expansion optimization** – deciding where to build new lines or cables, or where to locate big batteries or flexible resources, to meet future demand and renewable build-out. This is a combinatorial problem (choose a set of projects out of many candidates) often approached with linearized power flow models and heuristics. A quantum computer might handle the combinatorial explosion better, evaluating many expansion combinations in parallel to find a truly optimal or near-optimal grid design under various scenarios. Similarly, **cross-border capacity allocation** – planning how much capacity to dedicate to cross-border trades or new interconnectors – could be optimized with quantum methods that consider hundreds of scenarios of future supply/demand. The benefit to Energinet would be more **robust investment decisions**, potentially saving costs and avoiding bottlenecks by exploring a broader solution space.

2. **Operational Optimization (Unit Commitment & Dispatch):** As demonstrated by IonQ and ORNL, **unit commitment** is a prime candidate for quantum acceleration. Energinet, as a TSO, doesn't directly commit power plants (that's typically the job of a market operator or generation companies in a liberalized system), but Energinet does manage ancillary services and reserves. Quantum algorithms could optimize **reserve activation and scheduling**: for instance, deciding the optimal provision of spinning reserve, frequency control, and standby generation each hour, given uncertainties in wind forecasts. This is akin to a stochastic unit commitment problem. In the future, if Energinet were to operate a **strategic reserve or battery storage portfolio** to balance renewables (as some TSOs are considering), quantum optimization could help decide charging/discharging schedules of dozens of large batteries or flexible loads to maintain grid balance at least cost. Additionally, **economic dispatch** (calculating the optimal generation dispatch after unit commitment) could be enhanced. While dispatch is a continuous optimization (solved by linear programming typically), incorporating *non-linear AC power flow constraints* makes it very hard (ACOPF is non-convex). There's academic work on formulating AC optimal power flow as a polynomial optimization that might be tackled with quantum algorithms in the future. A quantum solver could potentially handle the non-linear nature directly, yielding better loss minimization and voltage profiles than today's iterative classical solvers.

3. **State Estimation and Real-Time Control:** TSOs perform state estimation every few minutes to know voltages and flows throughout the network using SCADA measurements. Quantum computing could aid **dynamic state estimation** for faster and more robust convergence, especially as grids become more complex and distributed. One imaginative possibility is using a quantum computer to solve the power flow equations via simulation – encoding bus voltages as qubit states and letting a quantum algorithm find the steady-state that satisfies Kirchhoff's laws. This could, in theory, identify grid states or even suggest control actions extremely quickly. Moreover, **contingency analysis** (evaluating N-1 or N-k outages) is a routine yet computationally heavy task. As referenced earlier, a quantum algorithm showed exponential scaling in identifying critical contingencies. Energinet could leverage such algorithms to **pre-compute many outage scenarios** and pinpoint vulnerabilities faster than today's tools. During a crisis (like multiple simultaneous outages), a quantum computer might explore reconfiguration or load-shedding combinations to find the best way to keep the system stable – effectively solving a **combinatorial restoration optimization** in real time, which is almost impossible classically for large grids.

4. **Renewable Forecasting and Energy Trading:** Quantum machine learning might improve **demand and renewable generation forecasting** by finding patterns in weather and consumption data that classical ML could miss. For example, a quantum algorithm could analyze decades of weather satellite data to better predict wind ramp events or solar irradiance fluctuations. Improved forecasts directly benefit TSOs by reducing reserve needs and improving dispatch efficiency. In terms of markets, Energinet operates day-ahead, intraday, and balancing markets in coordination with Nord Pool and neighboring TSOs. **Quantum algorithms could optimize market clearing** – which is essentially a very large optimization problem (minimize total cost subject to bids and network constraints). With hundreds of thousands of bids across Europe, coupling markets with transmission constraints leads to a very large mixed-integer program. A quantum solver might handle such a scale if hardware matures, potentially finding more optimal market outcomes or doing it faster (allowing more frequent intra-day clears). Additionally, **risk management** for TSOs (for instance, managing the financial risk of countertrade or reserve procurement costs which depend on uncertain events) could utilize quantum-enhanced Monte Carlo simulations or optimizations. For example, if Energinet needs to procure strategic reserves for winter, a quantum algorithm could better sample the tail risks of extreme cold/dunkelflaute scenarios to decide how much reserve to buy.

5. **Sector Coupling and Flexibility Optimization:** Denmark is exploring Power-to-X (converting surplus wind power to hydrogen or e-fuels) and electrification of transport and heating. This creates a coupled system where electricity, gas, and heat networks interact. Optimizing energy flow across sectors (like when to use surplus wind to produce hydrogen vs. curtail, or when to import/export via gas-based generation) becomes a **multi-network optimization** problem of enormous complexity. Quantum computing, with its ability to handle high-dimensional state spaces, could coordinate such sector-coupling decisions. For instance, an Energinet-controlled quantum algorithm could determine optimal operation of large electrolyzers, batteries, and gas peaking plants to minimize carbon emissions while keeping energy supply secure. This might involve solving a **unit commitment extended with sector constraints**, something beyond current market algorithms. The benefit would be maximizing the use of renewables and minimizing waste (aligning with Denmark's climate goals) – an area where IonQ's demo of reducing wasted energy in generation scheduling is directly relevant.

Benefits for Energinet and Denmark: If and when these quantum applications become viable, Energinet could see multiple benefits. **Economically**, better optimization means lower generation costs and possibly lower electricity prices for consumers (e.g. by cutting the expensive last-resort generation or imports). A study in the U.S. cited that 60% of energy is lost from generation to end-use; even saving a fraction of that through smarter scheduling and routing could be worth tens of millions of euros. **Reliability-wise**, faster contingency analysis and state estimation means improved grid security – operators could prevent outages by seeing problems coming earlier, or recover faster by evaluating many remedial actions quickly. This could reduce the risk of blackouts, which have huge societal costs. **Environmentally**, quantum-enhanced integration of renewables could help Denmark hit its aggressive CO_2 reduction targets by enabling more wind/solar to be used (less curtailment) and optimizing storage and sector coupling to displace fossil fuel backup. Essentially, quantum computing could act as an "accelerator" for the green transition, squeezing more efficiency and stability out of a renewable-heavy grid than classical methods can.

Technical and Policy Readiness: For Energinet to leverage quantum computing, several prerequisites must be met. On the **technical side**, the quantum hardware needs to reach a level where it can handle the scale of Denmark's grid problems. IonQ's projection of ~100 qubits by 2026 tackling full grid UC [2] is optimistic but not guaranteed. It's likely that for a national-scale problem (say hundreds of generators, or thousands of buses in a network), **error-corrected qubits** or clever problem decomposition will be required. This might push the timeline further out (late 2020s or beyond for fault-tolerant quantum computers). In the meantime, TSOs could start with **smaller subproblems** or use quantum solvers as advisory tools. For example, Energinet could begin by using a quantum solver to optimize a regional subset of the grid or a single day's reserve schedule as a pilot, then compare with classical results. This kind of shadow testing builds confidence and expertise.

On the **human and policy side**, Energinet would need to develop or hire quantum computing expertise. This means power engineers who understand quantum algorithms, or partnering with quantum computing firms or universities. Given that Energinet is government-owned and mission-driven, there may need to be **policy frameworks** for adopting a new technology that could impact critical operations. Regulators might need assurance that quantum-derived decisions are safe and robust. One likely scenario is that quantum tools will initially be used in a **decision support** capacity – providing recommendations while humans remain in the loop. For instance, a quantum algorithm might suggest an optimal generator schedule, but the final dispatch might still be validated by a classical run or operator judgment until trust is built. Over time, if quantum solutions consistently prove better and reliable, policies would adapt to allow more autonomous quantum-driven control.

Another consideration is **cybersecurity and cloud access**. Many quantum computers are accessed via cloud platforms (e.g., AWS Braket for IonQ, Azure Quantum for others). Energinet would need to ensure that sending potentially sensitive grid data to a cloud-based quantum computer is secure and compliant with data regulations. This could involve on-premises quantum hardware in the future (some countries are establishing national quantum computing hubs – Denmark itself is investing in quantum tech, like the Novo Nordisk Foundation's initiative to acquire a quantum computer for Danish research). Energinet could collaborate with national research centers so that some quantum computing capacity is available domestically under appropriate security.

Cost is also a factor – quantum computing as a service is currently expensive for large numbers of runs, and TSOs operate under regulated cost structures. A cost-benefit analysis would be needed to justify quantum investments. However, if quantum optimization can shave even a small percentage off the billions spent on generation or infrastructure, it would likely justify itself.

Finally, Energinet would likely coordinate with other **Nordic and European TSOs** on quantum readiness. Through organizations like ENTSO-E (European Network of TSOs) and research programs, they might share knowledge or jointly develop quantum applications. This can spread the risk and ensure interoperability; for example, if quantum computing helps coordinate cross-border flows, all involved TSOs need to agree on its use and trust its outcomes.

In conclusion, Energinet stands to gain significantly from quantum computing in addressing its future grid challenges. The IonQ–ORNL project is a strong signal that quantum solutions are moving from theory to practice. Energinet's next steps could be to start **pilot projects** (perhaps in partnership with universities like DTU or companies like IBM which has a presence in the Nordic region) to explore quantum algorithms on simplified models of the Danish grid. By engaging early, Energinet can position itself as a **quantum-ready TSO**, potentially leading in Europe's adoption of these advanced tools for a sustainable energy future.

Timeline and Outlook

When might we realistically see quantum computing deployed for grid operations? Below is a timeline of recent milestones and anticipated developments on the path toward practical quantum advantage in the energy sector, with a focus on grid optimization:

Year	Milestone in Quantum Computing & Grid Optimization
2024	**Launch of DOE GRID-Q Program:** U.S. Department of Energy kicks off a 3-year initiative (GRID-Q) to explore quantum applications for the power grid. ORNL leads, partnering with IonQ and others, signaling official support for quantum R&D in grid management. European TSOs begin quantum feasibility studies; E.ON and IBM publish a case study on using a 27-qubit quantum computer for energy pricing optimization under variable weather.

Year	Milestone in Quantum Computing & Grid Optimization
2025	**IonQ–ORNL Demonstration:** In June–July, IonQ and Oak Ridge National Lab successfully use a 36-qubit trapped-ion quantum computer (*Forte*) in a hybrid algorithm to solve a unit commitment scheduling problem (26 generators, 24 hours). Marks one of the first real-world optimization problems run on quantum hardware. *Outcome:* Feasible generation schedules found, validating the approach. Around the same time, **ARPA-E awards $6.2M to Infleqtion** (ColdQuanta) to integrate neutral-atom quantum optimization into power grid models with Argonne, EPRI, and NREL. This is ARPA-E's first quantum energy grant, underscoring growing confidence. **D-Wave & Others:** Scientific Reports study finds D-Wave's hybrid quantum annealing solver not yet outperforming classical Gurobi for full-scale unit commitment, but work is ongoing to improve performance [3] [4].
2026 (Expected)	**Next-Gen Quantum Hardware (100+ Qubits):** IonQ anticipates delivering systems with 100–200 high-fidelity qubits as early as 2026 [2]. If achieved, these devices could tackle larger grid optimization problems (e.g. a national-scale unit commitment or optimal power flow) with higher fidelity. IBM likewise is on track with its roadmap (433-qubit and 1121-qubit processors by 2024–2025). We may see **pilot projects** where TSOs (possibly Energinet or other innovative TSOs) run side-by-side comparisons: quantum vs classical solutions for day-ahead dispatch or congestion management on smaller networks. Energinet could at this stage be running quantum algorithms on parts of its system in a testing environment.
2027–2028	**Early Quantum Advantage?** If hardware scaling and error reduction continue, by 2027 we might have **quantum processors with >1000 physical qubits or ~50+ logical qubits** (with error correction). This could enable running more complex algorithms or deeper circuits beyond NISQ variational ones. Potentially, a **demonstration of quantum advantage** in a constrained setting could occur – for instance, solving a simplified grid optimization faster or better than any classical supercomputer (similar in spirit to Google's 2019 quantum supremacy but for a practical problem). D-Wave's roadmap suggests real-world applications by 2028; they project use cases like energy **unit commitment** and network optimization for customers by then [24]. TSOs might begin incorporating quantum-driven recommendations into operational planning (e.g., using a quantum optimizer for weekly outage scheduling or complex auction clearing). Regulatory bodies start drafting guidelines for quantum computing use in critical infrastructure.

Year	Milestone in Quantum Computing & Grid Optimization
2029–2030	**Broad Deployment and Fault-Tolerant Era:** IBM has publicly aimed for quantum advantage in useful applications by 2029. By 2030, IonQ's ambitious goal is to have a fault-tolerant quantum computer with *2 million physical qubits yielding ~80,000 logical qubits* [10] [7]. While this is an aggressive target, even reaching a fraction of that could be revolutionary. In this time frame, we expect **quantum computing to transition from experimental to operational for TSOs**. Energinet and peers could be using quantum-optimized solutions in daily grid operations – for instance, a quantum co-processor in the control center advising on dispatch, or quantum-enhanced algorithms embedded in market clearing software. We might also see **quantum-secured communication networks** (quantum key distribution) protecting grid control signals – another aspect of quantum tech beneficial to TSOs. Policymakers would have established frameworks for certifying quantum algorithms for grid reliability standards. By the early 2030s, a TSO that has not at least experimented with quantum tools might be at a disadvantage, especially as energy systems become more complex with climate change stresses and decentralized resources.

Beyond 2030, experts predict quantum computers (with thousands of logical qubits) will form part of **"quantum-centric" supercomputers**, solving previously infeasible problems in real-time grid optimization, molecular simulation for batteries, and more [25]. However, reaching that stage requires overcoming many technical hurdles: achieving **error correction** (which demands orders of magnitude more qubits), improving qubit coherence, and developing software toolchains for domain experts. There is also a possibility of **disillusionment or delays** – if quantum hardware hits unforeseen roadblocks, timelines could slip into the 2030s for clear advantage.

From a **risk management** perspective, Energinet and other TSOs should follow a strategy of **explore and watch**: invest modestly in exploring quantum methods now (as many are doing via innovation projects), stay informed on breakthroughs, and be ready to scale up investment as the technology matures. Given the competitive landscape (with nations and companies pouring resources into quantum), the tipping point could come faster than expected – or specific to a certain application (e.g. a breakthrough algorithm that suddenly makes a certain grid calculation trivial for a quantum computer). The prudent outlook is that **by the late 2020s, pilot implementations of quantum computing in grid operations will emerge**, and by the early 2030s, quantum computing could be a routine part of the toolkit for advanced TSOs, much like advanced AI/ML is becoming today.

References and Further Reading

- **IonQ & ORNL Quantum Grid Optimization Press Release (2025):** *IonQ Partners with Oak Ridge National Laboratory, Demonstrating Quantum Power Grid Optimization Advancements* – Business Wire release, July 31, 2025. Describes the 26-generator unit commitment demo using IonQ's 36-qubit system and the DOE GRID-Q collaboration.

- **The Quantum Insider News Article (2025):** Greg Bock, *IonQ and ORNL Demonstrating Quantum Power Grid Optimization*, July 31, 2025. Provides an accessible summary of the IonQ–ORNL result and its significance, noting the use of a hybrid system and the broader GRID-Q project.

- **Hello Tomorrow Report – *Quantum Computing in the Energy Sector* (2025):** Massera Winigah et al., *"From Experiment to Competitive Edge"*. Discusses five promise areas for quantum in energy,

including grid optimization. Highlights projects like NREL's quantum-in-the-loop and Pasqal's work with EDF on renewables and EV charging.

- **IBM–E.ON Case Study (2024):** *Powering the Future: IBM & E.ON Engineer Quantum Solutions*, IBM/ Quantum Insider, Dec 2024. Details how E.ON uses IBM quantum tech (27-qubit, Qiskit) for energy pricing optimization and advises early adoption to build quantum talent.

- **Quantum Computing Report – IonQ/ORNL (2025):** Mohamed Abdel-Kareem, *IonQ and ORNL Demonstrate Quantum-Classical Power Grid Optimization*, July 31, 2025. A brief recap that emphasizes IonQ's 36-qubit Forte and finding solutions for 24 periods, 26 generators, and mentions IonQ's roadmap for 100–200 qubits by 2026 [26].

- **Nature Scientific Reports – Quantum Contingency Analysis (2025):** Fei Feng et al., *"Quantum contingency analysis for power system steady-state security"*, Sci. Rep. 15, 15148 (30 Apr 2025). Introduces a quantum method for power grid outage identification, claiming exponential scalability via superposition/entanglement, and demonstrates identifying critical line/generator outages on sample systems.

- **Nature Scientific Reports – Quantum vs Classical Optimization (2025):** (Hansen et al., 2025) *"Quantum annealing applications, challenges and limitations for optimization problems compared to classical solvers"*. Benchmarks D-Wave's hybrid solver on unit commitment. Concludes that while D-Wave can solve small UC instances, it did not outperform classical Gurobi in solution quality or time for larger cases; highlights need for further improvements [3] [4].

- **IonQ Technical Primer & Roadmap:** *Quantum Computing 101: Introduction, Evaluation, and Applications* – IonQ Resource Center (Jan 8, 2025) and IonQ's public *Roadmap* (accessed 2026) outlining plans for 2 million qubits by 2030 and fault-tolerance through modular trapped-ion systems [10].

- **ARPA-E ENCODE Program Press Release (2025):** Berenice Baker, *"DOE Awards $6.2M for Quantum Energy Grid Optimization"*, IoT World Today – March 17, 2025. Details Infleqtion's project to integrate quantum algorithms (on cold-atom hardware) with Argonne and others, targeting improvements in mixed-integer grid optimization solvers.

- **Black & Veatch/BlackBox Infographic (2024):** *Quantum Computing vs Classical Computing* – an infographic illustrating differences (qubits vs bits, superposition, etc.) and future outlook (quantum computers expected to surpass supercomputers by 2030s) [6] [5]. Helps in visualizing key concept differences.

- **Energinet Strategy Documents:** *Energinet: Across Borders* (2022) and other whitepapers from Energinet and State of Green – to understand Denmark's grid plans (though not directly cited above, these provide context on Energinet's focus on integration, digitalization, and cross-border coordination, aligning with potential quantum use cases).

For further reading, interested readers might look into **ENTSO-E reports on digitalization**, which increasingly mention quantum tech as a horizon technology for grid management, and technical papers on **quantum algorithms for Optimal Power Flow** and **quantum machine learning for renewables forecasting** (an emerging niche). As the field is moving fast, following sources like *The Quantum Insider*, *Quantum Computing Report*, and DOE workshop proceedings on quantum for energy can provide the latest updates beyond the 2025 snapshot captured in this report.

1 2 18 19 IonQ - IonQ Partners with Oak Ridge National Laboratory, Demonstrating Quantum Power Grid Optimization Advancements
https://investors.ionq.com/news/news-details/2025/IonQ-Partners-with-Oak-Ridge-National-Laboratory-Demonstrating-Quantum-Power-Grid-Optimization-Advancements/default.aspx

3 4 9 20 21 22 23 Quantum annealing applications, challenges and limitations for optimisation problems compared to classical solvers | Scientific Reports
https://www.nature.com/articles/s41598-025-96220-2?error=cookies_not_supported&code=49d17109-2ec9-4e0a-a9bb-5809667f23bd

5 6 Quantum Computing vs. Classical Computing
http://www.blackbox.com/insights/blogs/detail/tps/2024/03/12/more-than-a-bit-about-quantum-qubit-computing

7 14 15 17 IonQ | IonQ and Oak Ridge National Laboratory Unveil Novel Approach to Scalable Quantum Computing
https://www.ionq.com/news/ionq-and-oak-ridge-national-laboratory-unveil-novel-approach-to-scalable

8 10 IonQ | Roadmap
https://www.ionq.com/roadmap

11 Variational quantum eigensolver - Wikipedia
https://en.wikipedia.org/wiki/Variational_quantum_eigensolver

12 Quantum Algorithms: Variational Quantum Eigensolver (VQE)
https://www.classiq.io/insights/quantum-algorithms-vqe

13 Comparing VQE and QAOA: Two Quantum Algorithms for ...
https://www.quantumgrad.com/article/700

16 Variational quantum algorithm - Quandela
https://www.quandela.com/resources/quantum-computing-glossary/variational-quantum-algorithm/

24 [PDF] d-wave-q3-investor-presentation.pdf
https://s201.q4cdn.com/339170267/files/doc_presentation/2023/12/d-wave-q3-investor-presentation.pdf

25 IBM Quantum Roadmap
https://www.ibm.com/roadmaps/quantum/2030/

26 IonQ and Oak Ridge National Laboratory Demonstrate Quantum-Classical Power Grid Optimization - Quantum Computing Report
https://quantumcomputingreport.com/ionq-and-oak-ridge-national-laboratory-demonstrate-quantum-classical-power-grid-optimization/