The Business of Quantum Technologies: Innovation Dynamics in the Energy Sector

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1. The Energy Sector

The energy transition is the shift from fossil-based to renewable energy sources, a movement from large-scale centralised systems toward a decentralised electricity system based on distributed and demand-side energy resources, and the decarbonisation of demand through increased electrification and reduced fossil-fuel consumption (Ozkan et al., 2025; Hargroves et al., 2023; Sakamoto et al., 2021; Nykamp et al., 2023). Hence, the energy transition is at the vanguard of global action for continued economic prosperity and to address changes in the Earth's climate and the associated societal detriments. The need to decarbonise the energy system is a primary lever in climate action (Clarke, 2022). Moreover, energy security and affordability are national priorities and are linked to economic security and societal stability. Hence, it is no surprise that energy infrastructure is considered critical national infrastructure (WEF, 2026). The empirical evidence reinforces this characterisation. For example, in the UK, the domestic energy system links generation, transmission, distribution and retail markets under government policy and Ofgem regulation, supplying approximately 30.4 million electricity and 24.6 million gas consumers (Stewart, 2025). Security exposure is also evident: for example, only half of UK gas consumption was met from domestic production and the rest depended on imports (Stewart, 2025).

Pursuing an energy transition strategy based on a shift to renewable generation is leading to a more distributed approach to the supply side, with opportunities for new models based around local and community energy provision. However, renewable generation is more intermittent (dependent on wind, time of day, time of year, cloud cover, etc) and nuclear generation is less flexible in its output compared with conventional, dispatchable fossil fuel generation. The system need for flexibility has been met from dispatchable fossil fuel generation. As these dispatchable power stations come to end-of-life and are retired, the system need for flexibility must be met from alternative sources, with the ability to turn supply up and down to match available demand.

As a concrete example, consider the electricity system. Changes in the nature of the assets comprising the electricity system are fundamentally changing the dynamics of the system. The electricity system has three subsystems, namely, generation, grid infrastructure and consumption. As the electricity system becomes increasingly distributed and the number of connected assets grows, the challenge of forecasting local supply, demand, and pricing becomes significantly more complex. Moreover, cross-market evidence from the IEA shows the associated market stress: since 2019, many jurisdictions have seen wholesale electricity price volatility rise to five to nine times 2019 levels, while European wholesale electricity prices in 2021 were more than four times 2019 levels, largely because of gas price volatility (IEA, 2025). In addition, undertaking power flow analysis to identify potential network congestion, and making informed operational decisions to optimise system performance in near real time, also becomes more difficult. Given this complexity, there have been calls to build a digital energy grid that assigns universal identities to energy resources with cryptographic verifiability to enable secure, optimised energy flow (FIDE, 2025).

For most developed economies, the energy transition is centred on a move away from fossil fuels as primary energy sources and towards electricity through the electrification of heat and transport, and towards hydrogen for high temperature thermal processes. Decarbonisation of the electricity system requires decarbonisation of the supply side generation. Some countries or states / territories within countries already have low carbon electricity systems based on the nature of their sovereign energy resources, such as Quebec in Canada and Nordics states that have a high proportion of hydro power, or France, where a large proportion of electricity comes from nuclear generation. Other countries, such as the UK, have been transitioning their generation mix towards renewable sources, notably wind and solar. Moreover, global net zero requires a transformation in how energy is produced, transported and consumed, against the backdrop of worldwide CO_2 emissions of around 33 billion tonnes in 2021 and long-lived energy assets such as pipelines, refineries and fossil-fuel power plants with lifespans over fifty years (Velu, 2024).

The electricity system transition brings with it opportunities in how the system is physically structured and governed. Policy and associated regulation play a key role in defining how the system transitions, both in terms of structure and pace. Decisions on the target physical system are informed by a state's sovereign energy resources and attitude to establishing global supply chain partnerships to underpin energy security and limit exposure to volatility in global markets. This is also moderated by the structure of the existing system and its age; the residual operational life of existing generation assets determines the potential for capital stranding and need to attract investment, the approach to which can be influenced by the political environment in a nation state or region and its associated prevailing approach to capitalism (Tayur, 2025; Hall and Soskice, 2001). The associated system structure also plays a part. For example, the degree of vertical integration vs horizontal consolidation (or unbundling across the value chain) of utilities operating in a market and the scale of those utilities play a role.

Markets such as France have a high degree of vertical integration at a national level. Germany and some states in the USA have a high degree of vertical integration at a municipality level. Conversely, the British market is highly liberalized with a high degree of unbundling across the value chain, which has led to horizonal consolidation in elements of the value chain, but where those utilities still have significant scale.

The decentralization of energy generation and the need to balance supply and demand that is less predictable presents an opportunity for the use of quantum compute to simulate and optimise the system, and other quantum technologies to support sensing, imaging, timing and communications. This chapter addresses three questions:

1. Which quantum technologies are likely to matter for energy systems?
2. How does adoption depend on market archetype and institutional structure?
3. How might quantum technologies reshape business models and industry structure?

We provide an overview of quantum technologies, followed by the framework for the analysis of the business model and transition challenges for the energy markets. We posit that energy security and the associated quantum technology adoption dynamics should also be considered as a global supply chain issue influenced by the political nature of energy sources. This lends itself to study quantum technology adoption in energy markets through the lens of an integrative agenda combining political economy and operations management (POEM) by taking account of institutions, ideologies and the exercise of power (Tayur, 2025).

2. Quantum Technologies And Innovation Dynamics

Quantum computing (QC) is a developing technology for processing information that has the potential to perform calculations that are infeasible for classical computers. As the hardware matures over the coming years, quantum computers are likely be able explore a vastly larger computational space than classical systems operating with the same number of information units. Although the field is still in its early technological stages, quantum computing is predicted to transform numerous sectors of society and industry (BCG, 2024).

For example, optimization and forecasting problems in distributed energy systems are currently solved using “classical” (i.e., non-quantum) computing techniques. However, there is a risk that as energy grids become more granular, certain classes of these problems will become computationally prohibitive. While there is currently no demonstrated quantum advantage for operational grid optimisation at an industrial scale, several research groups are investigating the potential of quantum computing in this arena (Jing, 2023; Morstyn, 2024).

Quantum compute could also be applied to simulation to accelerate the development of energy sector-relevant materials, such as battery storage and photo-voltaic materials. Even the most powerful supercomputers struggle to model the structure of moderately complex molecules. Quantum computers, by contrast, operate according to the same physical principles as the systems being simulated, making them naturally suited for modelling these processes. This could accelerate progress in materials science, including the discovery of novel superconductors, and improved catalysts for chemical reactions such as ammonia production or carbon capture. All of these could have very practical positive environmental impacts. Furthermore, the production of battery storage assets and photo-voltaic panels is reliant on access to critical minerals from global supply chains, the derisking of which ‘is a multidimensional process shaped by geopolitics, not just logistics’ (Dai and Tang, 2024) and providing an example of ‘the entanglement of political instability, institutional weakness and economic necessity in global supply chains.’ (Tayur, 2025). As such, the application of quantum computing to simulation of these energy-relevant materials has the potential to derisk the global supply chain for the critical minerals required for their production.

Many real-world problems involve identifying the best solution among a vast number of possibilities. Examples include scheduling and managing electrical grids, optimising demand and supply of energy sources, designing the configuration of energy assets, and improving forecasting of energy demands. These problems are often combinatorial in nature and become increasingly difficult as system complexity grows. Quantum approaches aim to search solution spaces more efficiently than classical methods. Current quantum processors are still limited in scale, but future fault-tolerant quantum computers could provide substantial advantages for industries where optimisation is central to operational efficiency, for example in spatial optimization for new wind turbine arrays and the positioning of individual turbines within the array in order to minimise the impact of wake effects and maximise output (Hancock, 2025).

Quantum computing may also enhance machine learning and data analysis. In particular, quantum algorithms could accelerate the training of some machine learning models. Although the precise scale of potential speedups remains an active area of research, the integration of quantum processors into hybrid classical-quantum architectures may offer performance improvements for specific classes of problems.

Despite these advantages, there are currently several technological challenges that limit practical quantum computing. Today's devices are limited by noise, quantum errors and restricted qubit counts. Ongoing research and industrial development are developing quantum error correction techniques and scalable hardware architectures that, in the coming years, are expected to enable large, fault-tolerant quantum processors capable of executing complex algorithms reliably (Cai, 2023; Velu *et al,* 2025). Achieving these benefits will still require advances in hardware scalability, error correction, and algorithms, but these three core areas suggest that quantum computing could reshape sectors ranging from pharmaceuticals and energy to transportation and artificial intelligence.

2.1 Quantum Technologies for Critical National Infrastructure and Energy Systems

Beyond quantum computing, other quantum technologies have significant implications for the security and resilience of critical national infrastructure (CNI), including energy systems. As energy grids become increasingly interconnected, ensuring secure communication and data integrity becomes a strategic priority, and quantum technologies offer potential approaches for enhancing security and protecting critical infrastructure.

For example, Quantum Key Distribution (QKD) enables two parties to generate a shared cryptographic key using quantum states transmitted through optical fibre or free-space links. Quantum Physics ensures that any attempt by an eavesdropper to intercept the measure inevitably disturbs the quantum states, revealing the presence of the intrusion, and allowing communicating parties to discard compromised keys. QKD has already been demonstrated in metropolitan fibre networks and satellite-based communication systems, and could potentially be integrated with secure infrastructure networks (Gisin, 2002).

A second relevant example is Post-Quantum Cryptography (PQC). While QKD offers hardware-based security, PQC focuses on developing classical cryptographic algorithms that remain secure even in the presence of large-scale quantum computers. Many current widely used public-key cryptographic systems rely on mathematical problems that could be efficiently solved using quantum algorithms like Shor’s algorithm (Shor, 1994). PQC algorithms instead rely on alternative mathematical structures that are believed to resist both classical and quantum attacks. Governments and standards bodies, including the U.S. National Institute of Standards and Technology (NIST), are actively developing and standardising PQC protocols to ensure future-proof cybersecurity (NIST, 2024).

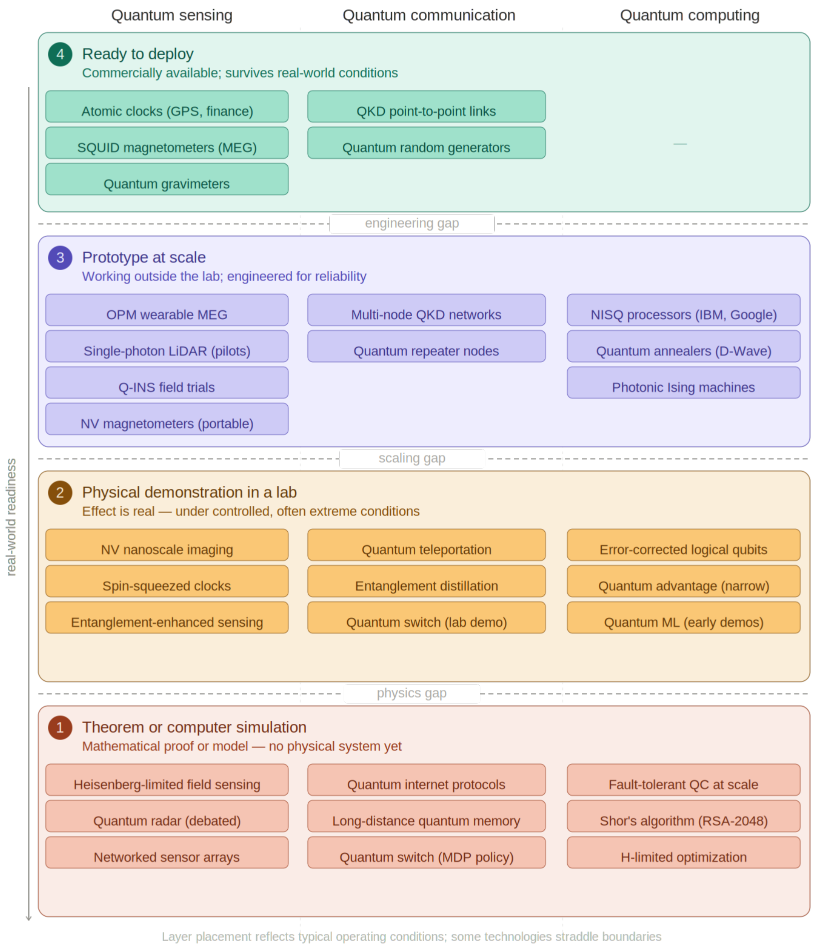
A final example relevant to infrastructure security is blind quantum computing (Barz, 2012). Using this technique, computations are performed in a quantum encrypted state. This means that a user can delegate a computation to a powerful quantum server without revealing to the owner of the server what the input data was, or what algorithm was applied. This could enable secure cloud-based quantum computing services in which data remains completely confidential even when processed on external quantum hardware.

The integration of these technologies could play an important role in the future resilience of critical infrastructure. McKinsey (McKinsey, 2022) estimates that quantum-enabled climate technologies could contribute to the abatement of around 7 gigatons of additional CO_2 emissions annually by 2035 and potentially place the world on a pathway closer to the 1.5°C climate target. The study identifies energy-related applications such as higher-density battery storage, optimisation of grid-scale storage systems, improved solar-cell efficiency, lower-cost hydrogen production and advanced carbon-capture materials as areas where quantum computing could create transformational impacts. Distributed renewable energy systems and smart grids also rely on secure communication channels and advanced data-processing capabilities. Quantum-enhanced security mechanisms could therefore help protect these systems against both conventional cyber threats and future quantum-enabled attacks.

In addition to quantum computing and communications, quantum technologies could be used for improved sensing and imaging and more accurate timing systems. Such technologies include next-generation quantum clocks, ultra-sensitive magnetometers and gravimeters, and single photon detection. Quantum sensing technologies of this nature could be applied to pipeline monitoring and gas-leak detection, infrastructure inspection, and subsurface imaging.

There have been significant press announcements about the readiness of quantum technologies for industry applications. It is often helpful to delineate these announcements across four principal levels such as theorem development, physical demonstration in the lab, developing prototype with scale and finally to get them ready for commercial deployment. We outline the details of these four levels in Figure 1 below.

Figure 1: Quantum readiness matrix across the three pillars of quantum technology, organized by maturity layer.



	Quantum sensing	Quantum communication	Quantum computing
4 Ready to deploy Commercially available; survives real-world conditions	Atomic clocks (GPS, finance) SQUID magnetometers (MEG) Quantum gravimeters	QKD point-to-point links Quantum random generators	—
3 Prototype at scale Working outside the lab; engineered for reliability	OPM wearable MEG Single-photon LiDAR (pilots) Q-INS field trials NV magnetometers (portable)	Multi-node QKD networks Quantum repeater nodes	NISQ processors (IBM, Google) Quantum annealers (D-Wave) Photonic Ising machines
2 Physical demonstration in a lab Effect is real — under controlled, often extreme conditions	NV nanoscale imaging Spin-squeezed clocks Entanglement-enhanced sensing	Quantum teleportation Entanglement distillation Quantum switch (lab demo)	Error-corrected logical qubits Quantum advantage (narrow) Quantum ML (early demos)
1 Theorem or computer simulation Mathematical proof or model — no physical system yet	Heisenberg-limited field sensing Quantum radar (debated) Networked sensor arrays	Quantum internet protocols Long-distance quantum memory Quantum switch (MDP policy)	Fault-tolerant QC at scale Shor's algorithm (RSA-2048) H-limited optimization

Layer placement reflects typical operating conditions; some technologies straddle boundaries

Caption: Layer 1 (bottom): Theorem or computer simulation. At the foundational level sit capabilities that exist today only as mathematical proofs or computational models, with no physical system yet built to realize them. Layer 2: Physical demonstration in a lab. Here the underlying physics has been experimentally confirmed, but only under controlled and often extreme conditions that preclude practical deployment. Layer 3: Prototype at scale. Technologies here operate outside the lab and are engineered for reliability, though not yet broadly commercial. Layer 4 (top): Ready to deploy.

The figure organizes the quantum technology landscape into a readiness matrix, with three pillars—quantum sensing, quantum communication, and quantum computing—arrayed as columns, and four maturity layers stacked vertically from least to most deployment-ready.

The figure conveys a clear strategic message: quantum sensing is the most mature pillar, with multiple technologies already deployed at scale; quantum communication is close behind with commercially available point-to-point security products; and quantum computing, despite commanding the most attention and investment, remains at the prototype stage—making the threat it poses to current cryptography real but not yet imminent, and making post-quantum cryptographic migration the most time-sensitive organizational priority.

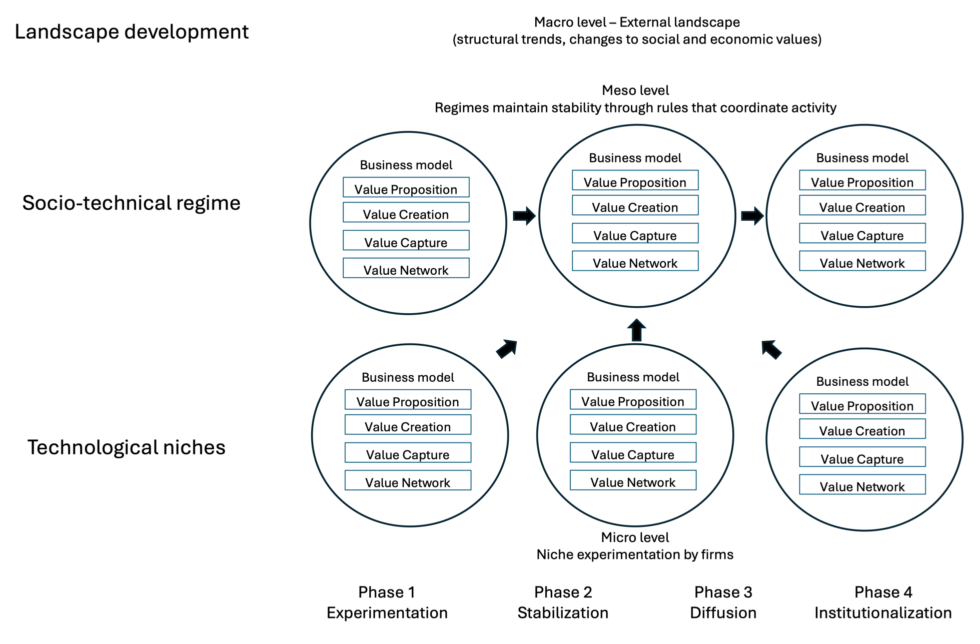
2.2 A Theoretical Framework for analyzing Technology-driven Innovation Dynamics

A business model is a complex organisational system that transforms inputs into outputs in terms of valuable propositions for customers and often connects technology with the ability to deliver the benefits to users (Velu, 2024). Business models consists of the activity system that connects the internal properties of the firm, such as resources and processes, with the external aspects, such as partners, markets, and customers and hence, defines how the firm goes to market to implement the strategy (Baden-Fuller and Haefliger 2013; Zott and Amit 2010; Zott, Amit, and Massa 2011). The components of the business model consist of "4Vs" (incorporated in Figure 2), namely *value proposition* - how the firm defines and communicates the benefits for its stakeholders, *value creation* - refers to the process through which the firm generates and distributes the value, *value capture* – refers to the revenue and cost architectures and the associated financing structures, and *value network* - describes the ecosystem of partners that the firm needs to develop its business value (Velu, 2024). Business model innovation redefines an existing product or service or creates new ones to serve existing or new markets through unique configurations of business model components.

Business model innovation often happens within a wider industrial architecture and is driven by the dynamics of changes in customer preferences, the emergence of new technologies, policy interventions and the existing industrial architecture. A useful way to comprehend these is through the framework of the multi-level perspective (MLP) which explains how technology-enabled transition takes place in a multi-connected system over time. The MLP highlights three levels – landscape, regime, and niche – to understand changes in consumption–production systems (Geels, 2002) – see Figure 2. The landscape level covers relatively slowly changing macro factors of transitions consisting of deep structural trends, social values and generally held views by society. The regime level refers to a meso-level socio-technical system, composed of multiple interconnected elements that enable a co-evolutionary development, where change in one element could lead to change in others. This level is dominated by existing incumbent firms and industrial structures that could be prompted to change by the landscape or niche levels respectively. The response of incumbent firms could be lethargic due to inertia from lock-ins which could manifest in three ways. First is techno-economic lock-in due to sunk investments and economies of scale economies from learnings on previous generation technologies. Second is social and cognitive lock-ins due to deeply engrained mindsets/dominant design and networks/relationships and third is, institutional and political lock-ins due to regulatory and also privileged access from political connections. Niches describe the micro-level change from the result of novel technological practices by new and emerging firms that experiment and learn during the technological development. New firms could dethrone incumbent firms in three ways. First, by growing non-rival resources in original niche segment and then the main segment. For example, Amazon initially sold primarily technical and hard-to-get books, categories that were not significant to Barnes and Noble's sales. Second, by not depending on one or more of the hard-to-imitate resources that are used by the existing business model. For example, Netflix did not use physical stores in competing with Blockbuster. Third, avoiding the entry barriers that have protected the incumbent in the past. For example, Nike outsourced production compared to Puma and Adidas. MLP identifies four phases in technology transition. The combination of the incumbents and new entrants' incentives to innovate could lead to either incumbent led or new entrant inspired industry structures respectively.

The MLP framework includes experimentation (phase 1) - firms experiment and learning from trials, stabilisation (phase 2) - innovations gaining traction and clarity, diffusion (phase 3) - adoption in mainstream markets, and institutionalisation (phase 4) - replacing the components of the previous consumption–production system. The market characteristics will drive the rate of change across these phases. In particular, the scale of utilities and degree of unbundling will act as drivers to classify the broad archetypes of market structure. Moreover, the lifecycle maturity of the existing infrastructure acts as a driver for the adoption of technological innovations.

Figure 2: Technology transitions multi-level perspective



Source: Geels, F. W. and Schot, J. (2007). Typology of sociotechnical transition pathways. Research Policy 36(3): 399–417.Laudan R (1984) The Nature of Technological Knowledge, D. Redel Publishing Company. 83-104; Janeway, W. (2018) Doing Capitalism in the Innovation Economy, CUP.

3. The Energy Sector and Quantum Technologies

For the purposes of the analysis, we use two industrial market archetypes based on the degree of electricity market liberalization and the associated segregation of functions across the value chain. This is illustrated in Figure 3.

Figure 3: Factors influencing industrial archetypes

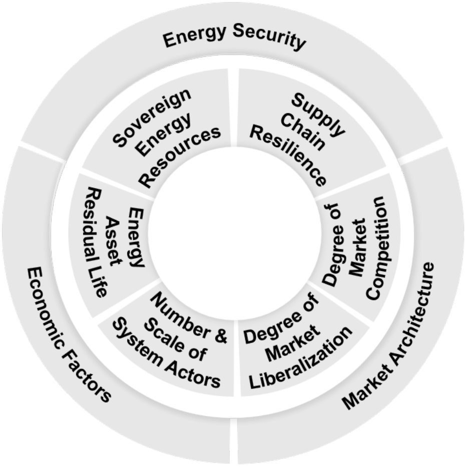


Figure 3 illustrates three factors shaping the pace of the energy transition and, therefore, the associated timescales for the opportunities for quantum technologies. Each of the three factors are divided into two considerations, used to analyse the archetypes.

The first factor is the policy imperative of energy security in the context of economic security and societal stability. For the purposes of this analysis, energy security is considered in the context of the available sovereign energy resources vs exposure to global markets for primary energy resources and the associated exposure to geo-political risks and to price shocks. Supply chain resilience is also considered, specifically in respect of energy assets (such as wind turbines, photo-voltaic solar panels, batteries, as well as transmission and distribution assets) and the supply chains for critical minerals.

The second factor relates to economic factors. The economic factors are considered in the context of the remaining economic life of existing energy assets and the associated techno-economic lock-in that creates resistance to rapid, orderly energy transition. The number and scale of system actors (organisations operating within the electricity system) are also considered in the context of the ability to attract investment.

The third factor relates to the market architecture. The degree of market liberalization and the associated barriers to competition and innovation in different parts of the electricity value chain tend to be determined by policy imperatives and the regulatory and related market architectures imposed on the physical electricity system.

The archetypes used in this analysis are based on the degree of market liberalization and the scale of the market actors. They are intended to provide a framework to understand each electricity system and that factors that influence its behavior.

We segregate the electricity system into three subsystems, namely, generation, grid infrastructure and consumption. We recognise that the each of these subsystems are parts of separate supply chains. Traditional fossil fuel based thermal generation has dependencies on the global supply chains for coal, oil or gas as primary fuels. Renewable generators and storage are dependent on the global supply chains for wind turbines, photo-voltaic panels and lithium-ion batteries, which are in turn reliant on the supply chain for critical minerals. Energy security can therefore be framed as a global supply chain issue and energy policy influenced by the availability of sovereign energy resources and geo-political alliances, aligned to 'how political economy considerations manifest in supply chain adjustments. For example…. sourcing from politically allied countries, balancing economic efficiency with geopolitical alignment.' (Tayur, 2025).

3.1 Market Archetype 1: Vertically Integrated Utilities

Electricity systems can have a high degree of vertical integration across the three subsystems of generation, grid infrastructure and consumption of the electricity value chain at either a national level (e.g., France; China; hydro-rich public utility systems such as some Canadian provinces) or local level (e.g., Germany's Stadtwerkes and regional utilities; some Nordic structures; many US regulated, cooperative or municipal utilities) face different challenges and opportunities to more liberalized energy markets.

National vertically integrated markets typically have a large, dominant player that is either state owned (eg, EDF in France) or publicly listed (such as EDP in Portugal) that is highly regulated by the state. These utilities have significant scale. As such, this market archetype can be regarded as being predominantly state-guided capitalism, in which government steers the energy sector through policy and regulation (Hall and Soskice, 2001). Such integrated structures make it much easier to take a holistic view of the value of technology-enabled transitions, with the costs and benefits accruing within the same organisation.

Market's characterised by regional or municipality-scale vertically integrated utilities present a specific challenge for policy makers and regulators in securing the necessary investments. The vertically integrated business models based on municipality-based utilities can lack the scale over which to spread fixed cost elements of investment, whereas other municipality utilities can be part of multinational energy corporations.

Policy and Regulation play a key role in securing investment and accelerating the integration of niche technologies in the micro level to bring about change in the socio-technical regime at the meso level and ultimately reconfigure of the system landscape at the macro-level on a country-wide basis.

The challenge for energy system actors (including policy makers, regulators and the energy companies) becomes one of ensuring the incentives are right to encourage engagement with consumers given that the consumption / retail subsystem within the electricity value chain may not yet be as sophisticated, given the lower levels of competition in the provision of energy and associated services, than it is in more liberalized territories. Hence, the business model design to ensure value creation and value capture within and across firms to create the right business ecosystem is key.

Municipality-scale vertically integrated utilities present an additional challenge. Each system actor is an integrated business that is dominant in its own region and faces regionally-specific challenges, yet they are all bound by a common regulatory regime. Often these utilities do not have the scale to access some of the economies necessary to establish a viable investment case for integration of emerging, niche technologies, and so risk being late adopters.

The challenge for the policy makers and regulators is to ensure that all of a country's consumers have equitable access to broadly the same levels of service and benefits, regardless of where they live. Differences in process, capitalisation, population and demand across the regional incumbents presents regulators with challenges in creating the appropriate incentives that will secure the required levels of investment from the system actors and their parent organisations.

In such environments, finding consistent ways to integrate niche technologies into the electricity system while evolving existing infrastructure at the same rate across the country can be more challenging than markets where there is a national-scale vertically integrated utility. The overriding challenge is to find ways to promote collaboration between system actors on standardisation to the benefit of consumers.

3.1.1. Applying MLP to policy interventions

Policy makers and regulators should use the dominant system actor as an implementation lever for transition policy. Early-stage technology niches, such as quantum-enabled grid optimisation, should be tested through innovation programmes and public demonstration projects to provide an evidential base to support policy and regulatory development. Governments or regional administrative authorities can use their procurement policies to develop early niches for emerging innovations, create early demand and standardise learning faster than a purely market-led system. This aligns with strategic niche management, where protected spaces enable performance, social acceptance and institutional learning (Meadowcroft and Rosenbloom, 2023, pp. 3-5; Geels, 2024, pp. 29-38).

In the case of regional or municipality-scale vertically integrated utilities, policy makers and regulators should treat system actors as transition intermediaries. Intermediaries connect system actors, exchange knowledge, build narratives, run experiments, develop standards and lobby for supportive policy (Meadowcroft and Rosenbloom, 2023, pp. 6-7). In municipal systems, the intermediary function often already exists in local utilities and regional energy agencies. Policy should fund them to test emerging niche technologies driven business models, such as quantum computing, to develop an evidential base on which decisions can be taken on policy interventions and fiscal incentives. For example, regional energy agencies in this archetype may have better local access to technology expertise than national government, and may thus be able to better connect to regional quantum computing, communications and sensing/imaging skills. This would enable them to be in a position to test new quantum applications such as detecting buried legacy infrastructure, or quantum optimisation of regional grids.

In markets made up of multiple municipality-scale vertically integrated utilities, local pilot projects and initiatives risk being unable to scale unless rules are established for data interoperability, consumer protection, cybersecurity, settlement and market access. Central government has the ability to provide the standards and incentives that allow local experimentation to develop into national capabilities. For example, the general provision of standardised quantum timing to both incumbents and niche actors, or of quantum secure (i.e., not susceptible to quantum attacks) network infrastructure across the board are areas where central government policy could unlock novel business models and innovation.

Municipal energy system actors also need incentives to establish equity across consumer segments. Local energy assets can create asymmetric distribution of benefits where affluent households install PV, batteries and EVs while lower-income households carry an increasing proportion of network costs. Policy should therefore, where justified, support socialisation of the costs of the energy transition (including the contribution of quantum computing to the energy transition), and target tariffs or grants for low-income households. This converts the niche from a benefit for affluent consumers into a system resource.

At stabilisation (where new business models establish a foothold in one or more market niches and become institutionalised in design guidelines, product specifications, best practice formulations, and standards) and diffusion (where new business models become established in mainstream markets) (Geels & Turnheim, 2022), the state should avoid a single-technology monoculture. Technology niches, such as quantum technologies, can have long learning curves, but national policies should maintain option value across the technologies. Incentives should reward system value. For example, the value of quantum compute could be measured as the benefit (avoided costs) against the next best counterfactual approach, where those values can be measured.

Managed decline in the meso- (socio technical regime) and macro- (socio technical landscape) levels should be handled explicitly. Whether the incumbent regime is state-owned or publicly listed, the state has both power and responsibility to manage stranded assets, labour redeployment or reskilling, and regional impacts. In this context, technologies such as quantum sensing of gas leaks, or quantum imaging of buried pipes could have a role to play in scrutiny of existing and ageing infrastructure. The MLP framework highlights that destabilisation is not simply a technological event; it is a political and organisational process in which incumbents move from denial to incremental response, diversification, decline and possible dissolution or reinvention (Geels, 2024, pp. 59-70). State systems can plan this sequence more coherently (for example, in the longer term by using quantum techniques to model these complex systems), but only if fiscal transparency and independent scrutiny are strong.

3.1.2. Incumbent Lock-Ins and Opportunities for New Entrant

Markets dominated by a large-scale, vertically integrated utility, where the utility is state owned (e.g., China, France), align with the centralized, publicly owned political economic structure. The state's wider political and economic considerations around energy security, risks around stranding investment in the energy infrastructure and the associated supply chain, and wider social considerations can be a source of institutional and political lock-in at the macro landscape level, cause inertia at the meso socio-technical regime and discourage experimentation by innovators at the micro technological niche level.

Markets where the dominant, vertically integrated utility is a publicly traded company with no single controlling entity, but dominated by institutional investors and sovereign wealth funds (eg Spain, Italy), align with the centralized, private sector ownership political economic structure. The dominance of a single large corporation lends itself to being classified as corporate capitalism (Hall and Soskice, 2001; Tayur, 2025). However, this has some overlap with state-guided capitalism due to the significant power of the state to direct the utility through the use of policy and economic regulation. There is a natural tension between the two varieties of capitalism due to the utility's ability to leverage its significant economic power to influence policy and regulation. This can create inertia where state's imperative to accelerate change does not align with the utility's strategic imperatives, implying this could also be regarded as an incumbent-led industry structure (Velu, 2024).

Markets comprising of multiple municipality or sub-national, vertically integrated utilities, where the utility is owned by the municipality or regional authority, align with the decentralized, publicly owned political economic structure. Markets where the municipality and sub-national, vertically integrated utilities are publicly traded companies (eg Germany, Nordics countries, some US states) align with the decentralized, private sector ownership political economic structure.

The municipality's or regional authority's wider political and economic considerations about energy security, risks of stranding investment in the energy infrastructure and the associated supply chain, and local social considerations exist within the national energy policy context. The tension between national and regional policy imperatives can be a source of institutional and political lock-in at the macro-landscape level, cause inertia at the meso socio-technical regime and discourage experimentation of business models by innovators at the micro-technological niche level. The smaller scale of these municipality and regional utilities can also create techno-economic lock-in, as can tensions between national and local policy and legislative powers, presenting a particular barrier to the adoption of quantum technologies at their early stage of development.

Where municipality or regional-scale utilities are publicly traded (albeit individual municipality or regional utilities can belong to large, multinational corporations), it aligns with state-guided capitalism due to the significant power of the state to direct the utilities through the use of policy and economic regulation. Where a utility is part of a corporate group, or where municipality and regional utilities collaborate, then the dynamics associated with corporate capitalism may be seen to overlap with state-guided capitalism. There is a natural tension between the two varieties of capitalism. Where municipality and regional utilities collaborate, they have the ability to leverage their combined economic power to influence policy and regulation. Where a utility is part of a larger corporate entity, they can leverage the group's wider economic influence with respect to the opportunity for, say, foreign direct investment to influence policy and regulation. This can create inertia where a state's imperative to accelerate change does not align with the utilities', or their corporate parents', strategic imperatives, implying this could also be regarded as an incumbent-led industry structure (Velu, 2024).

In all cases where there is a high degree of vertical integration, the state has the opportunity to use its policy and legislative powers to influence the pace of change, albeit moderated by inertia created by techno-economic and institutional and political lock-ins.

3.2 Market Archetype 2: Liberalised or Horizontally Consolidated Utilities

Highly liberalized energy markets with a diversity of system actors (e.g., Great Britain; the Australian NEM; ERCOT; PJM; much of the EU/Nord Pool architecture) present a different challenge for policy makers and regulators seeking to accelerate the learning curves for niche technologies to deliver energy security in a transitioning energy system.

On the one hand, low barriers to competition and low cost of market entry encourage innovation right across the value chain, from established network and communication technologies to the adoption of emerging niche technologies. At the same time, however, this diversity of system actors and their respective responsibilities can create structural challenges in aligning commercial arrangements of their respective business models and securing the necessary investment.

Such effects are regularly seen in regions such as Great Britain, where high levels of competition between energy retailers and the unbundling of services, such as metering, has generally been seen as beneficial both to the industry and to consumers. From electricity privatisation in 1990 to 2010, for example, real electricity operating costs per unit fell by 5.5% per year in distribution, while there was a 30% reduction in the number and duration of power outages. Unbundling of metering from electricity network operators opened the door for more innovative and competitive services, with corresponding long-term benefits to consumers – in terms of choice, affordability and reliability of supply.

Perhaps the greatest challenge for governments and regulators is to align policy, legislation and regulation coherently in order to attract the required investment. Whilst this type of highly liberalised electricity market might be initially considered a liberalised market economy (Hall and Soskice, 2001), the fact that many of the system actors are parts of multi-national energy corporations that can use their economic power to influence policy might indicate closer alignment with corporate capitalism.

Attracting that required level of investment by system actors across the value chain in highly liberalized markets presents challenges for policy makers and regulators. This is because the economic leverage from regulation of the return on the regulated asset base does not apply equally to all the system actors' business models across the value chain.

3.2.1. Applying MLP to policy interventions

In liberalized markets, policy makers and regulators should work with markets but not wholly rely on them to deliver policy objectives without intervention. Long-lived low-carbon assets, grid infrastructure assets and flexible assets require credible revenue certainty to secure the required investments. Policy makers and regulators can use fiscal incentives and other economic levers available to them, such as the allowable returns on regulated assets bases, to translate policy objectives into investable cash flows.

The MLP framework can be used to help identify and remove regime rules that act as barriers to adoption of niche technologies or create advantage for incumbent technologies. This can include addressing barriers to market access for system actors (such as providers of flexibility services), and modifying market rules and regulatory obligations to deliver appropriate investment signals and enable fair returns on investments. The IEA's evidence that a 0.03 per cent demand reduction in Spain in January 2023 could have cut wholesale prices by about 9 per cent illustrates the economic value of demand-side flexibility at the margin (IEA, 2025). However, realizing this benefit would have required investment in deep digitalisation of the energy system. Similarly, the potential use of quantum compute for optimisation of the electricity distribution system would require a democratization of access to quantum resources, such that cost does not act as a barrier to market participation by small or new entrant players who cannot afford expensive quantum processors. In these cases, government acting as a buyer and provider of quantum compute resource could have an important role.

Liberalized energy markets also require politically credible managed decline. Carbon pricing, emissions performance standards, coal phase-outs, gas capacity standards and fossil subsidy reform should be sequenced with replacement capacity and social protection. Meadowcroft and Rosenbloom argue that policy mixes should combine build-out of new arrangements with destabilisation of old arrangements and should manage feedback effects to avoid backlash (Meadowcroft and Rosenbloom, 2023). For Great Britain and similar systems, the policy challenge is to make the transition to a clean power system investible while insulating consumers from gas-linked volatility.

3.2.2. Incumbent Lock-Ins and Opportunities for New Entrant

Highly liberalized markets typically comprise of multiple utilities operating in specific elements of the electricity value chain. Utilities are typically privately owned or publicly traded companies (eg Great Britain). This aligns with decentralized, public ownership in the political economic structure.

The lack of a dominant, single large corporation (albeit individual utilities operating in parts of the electricity system value chain can belong to large, multinational corporations) lends itself to being classified as state-guided capitalism due to the significant power of the state to direct the utilities through the use of policy and economic regulation. This is especially relevant for those elements of the electricity supply chain that form natural monopolies, such as national transmission networks or regional distribution networks, where there is a greater degree of regulation. The more liberalized parts of the electricity supply chain are also likely to appear to follow state guided capitalism through the state's use of policy and associated fiscal interventions. Examples include the use of contracts for difference (CfDs are long-term agreements between power generators and governments that aims to stabilize energy revenues through the use of guarantee of a fixed "strike price") to attract investment into large, capital-intensive generation projects, and innovation funding mechanisms to attract investment into technological niches and new ways of operating in the retail and services parts of the electricity value chain. There is overlap with the definition of coordinated market economies (CMEs) through interventions where the market has failed to deliver coordination mechanisms and without which there are barriers to the market functioning well, and the role of bank-based finance. (Hall and Soskice, 2001; Tayur, 2025).

Liberalized markets create a tension between the techno-economic and the institutional & political lock-ins seen in vertically integrated market structures. This arises due to the tension between the need to attract long-term investment in infrastructure and policy objectives of accelerating change in the meso-level socio-technical regime. Policies designed to accelerate change work against maintaining investor confidence. Incumbent system actors can exploit their economic power to influence policy and create inertia to change. The objective of policies designed to accelerate change in the meso-level is to bring about macro-level landscape reconfiguration by addressing barriers to technological niche adoption.

Utilities operating in liberalized markets tend to achieve scale through consolidation of local and regional infrastructures within, typically, multi-national utility corporations; or achieve scale through growth of market share, either organically or through acquisition, in competitive energy retail and services markets. Barriers to market entry tend to be lower in liberalized markets at the retail and services end of the electricity value chain. New entrants with innovative business models based on taking advantage of technological niches tend to be able to enter the market and scale through a combination of organic and acquisitary growth, or are themselves acquired by incumbents. Access to quantum computing resources has the potential to provide new market entrants with significant operational and competitive advantages in an electricity system that has transitioned towards renewable generation on the supply side and integration of low carbon technologies on the demand side. Policy makers have an important role to play in ensuring that cost does not act as a barrier to equitable access to quantum resources by all system actors. Not addressing access to quantum capabilities risks inertia in the energy transition, and also risks incumbent system actors who have the scale and economic resources to access quantum computing capability at the earlier stages of the technology's maturity (see Figure 1) consolidating their position in the system.

The state has the opportunity to use its policy and legislative powers to influence the pace of change, albeit moderated by inertia created by techno-economic and institutional & political lock-ins and tensions between actors in different parts of the value chain.

Table 1 provides a summary analysis of the archetypes.

Table 1: Market Archetype Summary

Archetype	Indicative examples	How policy power is transmitted	Main strengths	Main risks
1 Vertically integrated or state-directed markets	**National:** France; China; hydro-rich public utility systems such as Quebec **Municipality / Regional:** Germany's Stadtwerke and regional utilities; some Nordic structures; many US regulated,	Regulation, national plans, public balance sheet, regulated rates of return, procurement, industrial strategy	Rapid alignment of generation, networks and industrial policy; state capacity to underwrite strategic projects	Central planning errors; political interference; slower technological innovation and niche adoption; fiscal and balance-sheet exposure At a municipality level: Misalignment of national and

Archetype	Indicative examples	How policy power is transmitted	Main strengths	Main risks
	cooperative or municipal utilities			regional /devolved policies; Fragmentation; uneven capability; slow standardization; coordination problems across grids and markets
2 Liberalized or horizontally consolidated markets	Great Britain; the Australian NEM; ERCOT; PJM; much of the EU/Nord Pool architecture	network regulation; wholesale market competition; independent system operators; retail competition; targeted support mechanisms, such as innovation funding	Transparent dispatch, innovation by entrants, private capital mobilisation, price discovery	Gas-price pass-through, underinvestment without long-term mechanisms, policy volatility, complex coordination

4. Concluding Remarks

We have argued in this chapter that the emergence of quantum technologies coincides with a period of profound structural transition in global energy systems, where pressures for decarbonisation, energy security and affordability are reshaping both market design and industrial strategy. The adoption of these quantum technologies in the energy sector is mediated by the market structure, the political economy, and the dynamics of the energy transition. We have highlighted that the implications of quantum computing extend beyond technical optimisation problems, and instead interact directly with questions of governance, regulation, industrial architecture and business model innovation. Across the market archetypes that we have described, the capacity to adopt and scale quantum-enabled capabilities is shaped not only by technological readiness, but also by the institutional structures, incentives and political-economic conditions within which energy systems operate. In this sense, quantum technologies should not be understood as isolated technical tools, but as enabling components within wider socio-technical transitions.

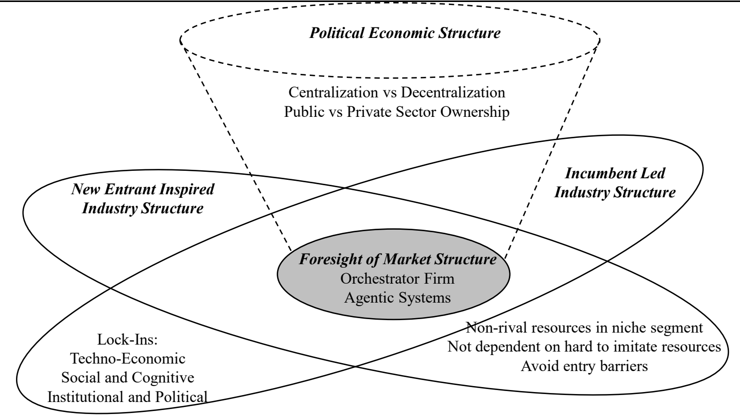
By using the analytical framework and applying it to the two market archetypes, we have discussed a trade-off in the adoption of quantum technologies and the associated opportunities for business model innovation. Vertically integrated markets are better positioned to coordinate investments and capture system-wide benefits, making them more likely to adopt quantum technologies that require changes across multiple parts of the energy value chain. However, their concentrated structures may reduce incentives for experimentation and limit innovation. In contrast, liberalized markets are more conducive to experimentation because lower barriers to entry and greater competitive pressures encourage firms to explore novel applications and business models. That said, these same characteristics can make system-wide deployment more difficult, as benefits and costs are distributed across multiple actors with different incentives. The central policy challenge is therefore to design institutional and regulatory arrangements that combine the coordination advantages of vertically integrated systems with the innovation advantages of liberalized markets. While vertical integration provides a relatively direct implementation lever through regulation and strategic planning, liberalized markets require more complex mechanisms to align incentives, allocate costs and benefits fairly, and encourage collective investment in emerging technologies and facilitate business model innovation.

Applying the analytical framework described in this chapter also helps clarify the principal barriers and enablers associated with the adoption of quantum technologies in the energy sector. Barriers include technological immaturity, high infrastructure and compute costs, limited access to specialist skills, fragmented data architectures, cybersecurity concerns and institutional lock-ins associated with incumbent market structures and legacy infrastructure.

Enablers include supportive policy frameworks, coordinated standards development, access to trusted digital and quantum infrastructure, public-private collaboration and the creation of protected niches in which experimentation and learning can take place. The adoption of quantum computing is unlikely to simply improve existing operational processes; rather, it may reshape business models through new forms of value creation based on optimisation services, secure data exchange, distributed energy coordination and quantum-enabled infrastructure management. This has implications for future industry structure, including the balance between incumbents and new entrants, the role of platform-based ecosystems and the strategic importance of access to compute and data resources.

Our analysis of the energy markets to evaluate the attractiveness of quantum technologies have enabled us to inductively develop a summary conceptual framework for senior managers and policy makers to consider in order to facilitate productivity improvements and economic growth. These can be organised into four broad categories summarized in Figure 4. First, is a foresight of the market structure that might emerge. Phase 1 of the quantum computing revolution could see the emergence of ecosystem orchestrator firm(s) that manages the network using quantum computing capabilities. Phase 2 might involve further fragmentation and generation of electricity and hence the need for more accurate forecasting and optimisation of the network which could in principle move to a more artificial intelligence based agentic optimisation model. Second, relates to the political economy structure which asks what degree of control do governments want given that energy is a critical national infrastructure. This could be a combination of public and private ownership of the assets and capabilities with varying degree of centralization of the governance model. Third, is the level of incumbent led industry structure. In particular, the degree of techno-economic, social and cognitive and institutional and political lock-ins that could shape their business models and hence, the structure of the energy markets as a result of the adoption of quantum technologies. Fourth, is the new entrant inspired industry structure. This involves an understanding how new entrants could adopt quantum technologies to design business models that grow non-rival resources in niche segments and then the main segment, which are not dependent on one or more of the hard-to-imitate resources that are used by the incumbents and to avoid the entry barriers that have protected the incumbent in the past. These strategies by the new entrants in adopting quantum technologies could radically shape the structure of the energy markets.

Figure 4: Summary Conceptual Framework



The chapter has also argued that the value of quantum technologies in the energy sector is likely to emerge initially through complementarities with existing digital technologies, artificial intelligence and advanced data infrastructures, rather than through wholesale technological substitution. For managers, this implies that near-term strategic focus should centre on capability development, experimentation and partnership formation rather than immediate large-scale deployment. Energy firms will need to consider how quantum capabilities integrate with existing operational systems, workforce skills, cybersecurity requirements and investment horizons. For policy makers and regulators, the challenge is broader still: creating market and regulatory conditions that encourage innovation while ensuring interoperability, resilience, equitable access and consumer protection. The multi-level perspective framework helps reveal that successful adoption will depend as much on policy experimentation, institutional learning and market design as on advances in hardware scalability or algorithmic performance.

Questions therefore remain about how governments, regulators and system operators should balance long-term strategic investment with near-term commercial realities, particularly in infrastructure sectors characterised by long asset lifecycles and significant capital inertia.

More broadly, the discussion raises deeper questions about the future structure of energy markets themselves. Will quantum-enabled optimisation reinforce the position of large incumbent utilities with privileged access to data, capital and compute resources, or will it lower barriers to entry and enable more distributed and decentralised market participation? How should states govern access to strategically important quantum infrastructure in ways that preserve innovation while maintaining energy security and system resilience? And as quantum technologies mature alongside broader digitalisation of critical infrastructure, what new forms of dependency, concentration of power or geopolitical competition may emerge? These questions suggest that the future role of quantum technologies in energy systems will ultimately be determined not only by scientific progress, but also by the institutional and societal choices made during the transition itself.

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