International Training Centre

QUANTUM TECHNOLOGIES AND THE FUTURE OF LEARNING

March 2025

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EXECUTIVE SUMMARY

ITCILO context for this report

ITCILO has a mandate to monitor emerging technologies and investigate opportunities for innovation to enhance learning and capacity building. This mandate builds on ITCILO's track record of being early to technologies in the context of the large-scale training sector.[1] Within that mandate, our workstream has focused on refining ITCILO's taxonomy of emerging technologies as a practical tool for directing that research in general and on the potential of quantum technologies in particular. Our workstream operates with a 2030 time horizon and is mindful of broader ITCILO and ILO priorities about policies around decent work, sustainability, and social justice. Enhancing quantum readiness and quantum literacy are key themes in this report.

The report methodology comprises analysis of secondary sources and key informant interviews. The key secondary sources include 13 national government and EU strategies on quantum technologies (see appendix 3), 5 corporate roadmaps (appendix 4), 7 technology taxonomies (appendix 1), over 20 market reports, as well as selected online sources, academic papers, and sector press cited in footnotes and a dedicated scan of quantum readiness courses for section 3.2. Key informant interviews are drawn from ITCILO experts and the seven academic and corporate organisations listed in the acknowledgements. Keyword searches on academic and patent databases are also used to quantify trends and momentum in different areas of quantum technology.

Today's perspectives on quantum technologies

There is little awareness of the detail of quantum technologies outside dedicated R&D communities – and no shortage of myths (text box 1). Nonetheless, some discussions betray a general sense that quantum technologies have been long-hyped and have typically disappointed to date. For instance, "quantum computing has been on Gartner's list of emerging technologies 11 times between 2000 and 2017, each time listed in the earliest stage in the hype cycle, and each time with the categorization that commercialization is more than 10 years away".[2]

[1] This track record includes launching Zoom calls in 2013, using extended reality in 2019, and trialling live AI translation with over 100 languages for events with hundreds of participants in 2024.

[2] National Academies of Sciences, Engineering, and Medicine. 2019. Quantum Computing: Progress and Prospects. Washington, DC: The National Academies Press. https://doi.org/10.17226/25196. https://nap.nationalacademies.org/read/25196/chapter/9

A sense of scepticism is understandable in the light of previous claims and affords a helpful antidote to marketing-motivated hype, but undirected scepticism is out of date today. Quantum technologies have made enormous progress in recent years[3], are attracting commercial partnerships anticipating near-term viability, and are already being used in niche commercial settings, at least as proofs of concept. As a few examples, quantum computers are being tested in logistics optimisation challenges[4], quantum dots are used in commercially viable infrared cameras[5], and quantum simulations are being actively explored for near-term chemistry, materials design, and drug discovery[6].

Box 1: Example quantum technology myths

Myth: A Quantum Internet will allow faster-than-light communication via entangled particles

Myth: Quantum computers are so powerful because they 'calculate every possible answer simultaneously'

Myth: Quantum computers are like classical computers but faster and more powerful – they can replace classical computers for every task

See Appendices 5-6 for a glossary and sources for introductions/myth-busting for quantum tech.

Within the R&D teams working on quantum technologies and the business consultants analysing markets, there has been a shift from 'if' to 'when' quantum technologies have transformative effects in various parts of society. Such optimism is influenced by the considerable private funding, patent filings, and research output (see figures 1-3). Quantum technology is increasingly the focus of international rivalry[7], with the US focused on computing, China focused on communications, and government funding estimated at about twice the annual spend rate of private investment[8].

[3] E.g. examples in this report; see also the summary available in https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/steady-progress-in-approaching-the-quantum-advantage

[4] E.g. D-Wave 2023 case study with DENSO, in which a theoretical reduction of 30% of vehicles was identified using real-world pre-booked taxi scheduling data in Kyoto. Available via https://www.dwavesys.com/solutions-and-products/manufacturing-logistics/

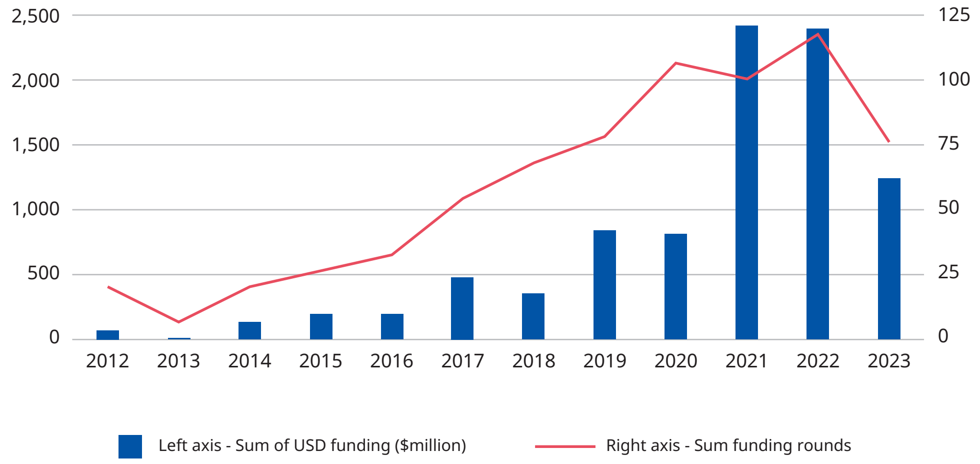
[5] E.g. the CQD technology in certain Acuros SWIR cameras, https://www.swirvisionsystems.com/, discussed at https://spectrum.ieee.org/move-over-cmos-here-come-snapshots-by-quantum-dots

[6] See survey and examples for materials science: https://www.sciencedirect.com/science/article/pii/S0167739X24002012. Example hybrid/analogue approaches for chemical simulations: https://arxiv.org/abs/2409.05835; https://arxiv.org/abs/2409.04044. For drug discovery, see the partnership between IBM and Moderna launched in 2023 https://newsroom.ibm.com/2023-04-20-Moderna-and-IBM-to-Explore-Quantum-Computing-and-Generative-AI-for-mRNA-Science, as well as other recent partnerships and patent filings reported here: https://quantumzeitgeist.com/quantum-computing-revolutionising-pharma-speeding-drug-design-and-accelerating-clinical-studies

[7] https://itif.org/publications/2024/09/09/how-innovative-is-china-in-quantum/; https://merics.org/en/report/chinas-long-view-quantum-tech-has-us-and-eu-playing-catch

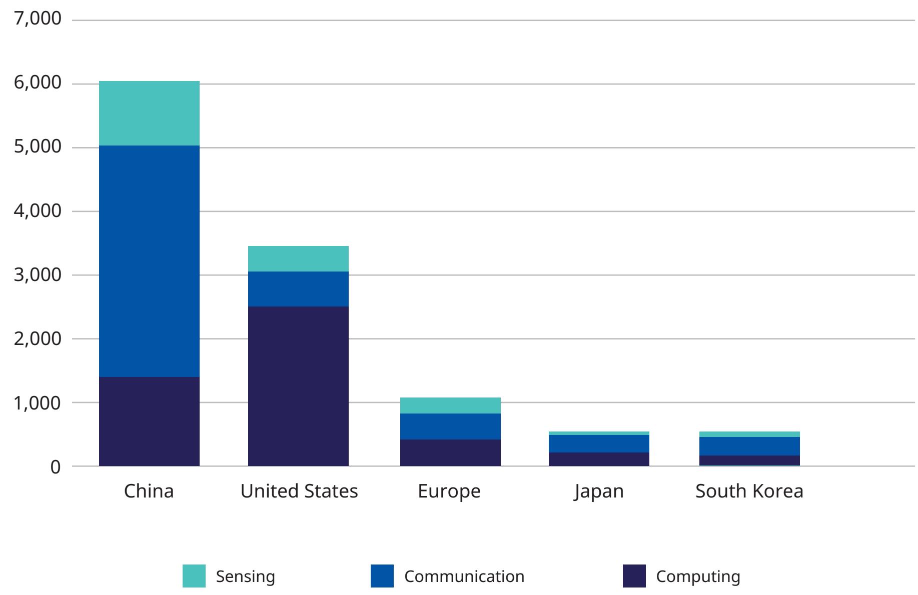
[8] IQM, State of Quantum 2024.

FIG. 1. PRIVATE INVESTMENT IN QUANTUM TECHNOLOGY



Source: Quantum Insider, updated end of Dec 2023 (IQM, State of Quantum 2024)

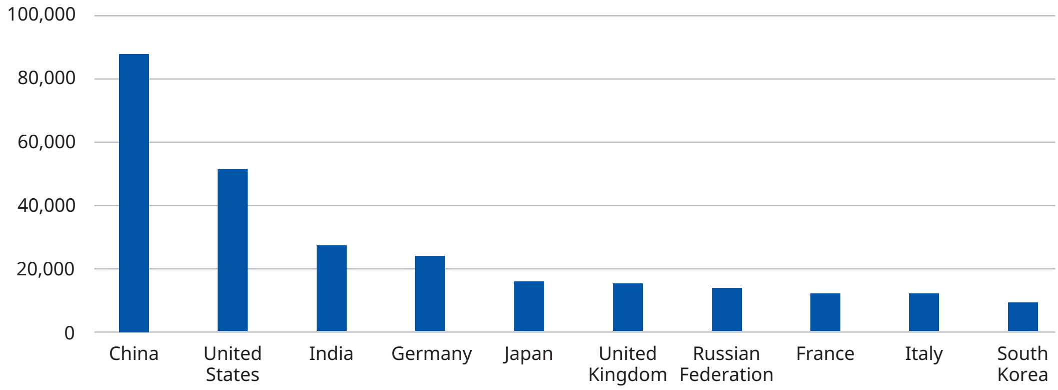
FIG. 2. NUMBER OF PATENT FAMILIES PER QUANTUM TECHNOLOGY



Source: ITIF, How Innovative Is China in Quantum? Sep 2024[9]

[9] "A Portrait of the Global Patent Landscape in Quantum Technologies" (European Quantum Industry Consortium, January 2024), https://www.euroquic.org/wp-content/uploads/2024/03/QuIC-White-Paper-IPT-January-2024.pdf.

FIG. 3. TOP 10 COUNTRIES BY ACADEMIC OUTPUT VOLUME ON QUANTUM TOPICS



Source: Scopus database search Dec 2024, all academic output featuring the word 'quantum' in title, abstract, or keywords, published since 2020

Despite this investment, it remains uncertain to what extent quantum advantage will ever prove worth its cost as a technology outside of niche applications. Opinions vary dramatically. All sides can point to example anecdotes that underpin their position, while conclusive evidence that could command a consensus remains similarly out of reach to all. While breakthroughs are coming at pace, different companies are committed to different technologies and each one relies on multiple, speculative breakthroughs before unlocking such an achievement (see section 2.4 and example company roadmaps in Appendix 4).

Quantum technologies to unlock learning applications

The future of learning is the primary focus for this report, whether that concerns the design, deployment, or delivery of learning. Several tantalising, albeit speculative use cases exist where quantum technologies *might* prove to be a key unlock, from getting the most impact out of adaptive/personalised learning and real-time, self-learning chatbot tutors through to quantum-powered neurotech and ubiquitous sensors in classrooms and about our daily lives (see text box 2). Looking to similar applications in labour market policy, a secondary area of focus for this report, other use cases *might* also exist, such as quantum-powered simulations of workforce projections for pensions or analysing the impact of decent work policy interventions on supply chains (see text box 3).

The emphasis in these use cases remains on *might* for at least three reasons. First, there is much we can do with existing and near-term classical technologies before we might need the quantum performance boost for learning applications. Second, we remain several plausible but uncertain breakthroughs away from quantum technologies providing that performance boost in a practical, cost-effective setting. Third, caution is required in taking these use cases from idea to implementation, even where the technology is powerful enough to deliver them. For instance, the role of chatbot tutors needs to be carefully considered, at least prior to evaluation evidence, to ensure they do not move beyond their brief, do not act inappropriately (such as handling nuance or conflict in learning settings or the cultural adaptability needed in working with global student cohorts), or have unintended consequences, such as reducing the resilience-building which can be a valuable element of human-led learning. As a second example, the use of individual worker or family level data in system simulations needs to be done with due care to privacy concerns and potential dataset misuse.

Box 2: The optimistic view: Example quantum technology impact in learning (speculative; pending R&D breakthroughs likely beyond 2030)

Personalised/adaptive learning

Machine learning models can be used to assemble a custom curriculum or present tailored content/questions in real-time to learners, leveraging learner preferences/goals, historical datasets of previous learner trajectories, and real-time insights from the target learner. For particularly large datasets or complex algorithms, quantum computers may become necessary or provide valuable improvements in combinatorial optimisation heuristics.

Real-time, self-learning chatbot tutors

Large language models, leveraging existing data and classical computers, are already showing potential as education aides, with several commercial ventures pursuing the vision of a 'chatbot tutor'. Current technology works in real-time by querying static models, following expensive, multi-week model training phases. However, if we want models that re-train live beyond changes that can be incorporated into the static model's input, e.g. adapting live to a learner's activities, then we need much faster (re-)training modalities, with quantum computing being one theoretical contender for rapid training. Early applications of existing LLM technology could also help generate learner-level personalised reports based on learner data/interests, including generated commentary on comparisons against norm group benchmarks, or help learners access summaries of specific reports and have dialogue with them.

Quantum-powered neurotech

We may not know exactly where quantum technology drives a breakthrough in neurotechnology, but any of several avenues might lead there. The UK's national quantum missions (2023) target quantum-enabled brain scanners by 2028, aiding surgery and leading to a better understanding of the brain, along with embedded quantum sensors. Quantum simulation may reveal key insights in brain mechanisms, given growing evidence of the important of quantum phenomena in biology. Quantum computers may improve capabilities to analyse vast amounts of data generated by the brain. Neurotech miniaturisation, enabled by quantum sensors, might enable all learners to use a wearable in the classroom, allowing learners' brain states to be observed in real-time and fuelling insights on how students respond to different activities and a group's readiness to learn topics of higher difficulty. These avenues are speculative, but early steps are being taken in these technologies and they might prove essential for the long-term visions in neurotechnology for learning, such as providing everyone with a real-time read-out of what their brain is doing and how to get more out of it (see separate report by Murielle Fabre).

› *cont. on page 7*

Quantum-powered Internet of Things

'Data as the new oil' and the exhaustion of many current data sources in training transformer-based architectures have become truisms of the modern era of AI. Ubiquitous sensors and data collection from everyday behaviours and objects via an Internet of Things provide an opportunity to replenish our collective data lakes. Quantum sensors might form part of that IoT infrastructure, providing more precise and novel data insights – or quantum computers might play supporting roles in data analysis. Such sensors/insights could tell us how to re-engineer classrooms or optimise group dynamics, as well as analysing our daily habits or social networks to identify effective, perhaps novel opportunities for learning/mutual tutoring. Systems of multiple quantum sensors might prove essential to unlock IoT benefits if concerns about privacy prevent the usage of IoT data collection at an individual learner level. Systems of multiple quantum sensors can, in principle and with further R&D, be designed so data on any individual learner is unidentifiable by design, but average data across many learners remain accessible to improve provision.

See section 3.1, esp. table 10, for more details on the top two use cases; see tables 5-7 for context on all use cases

Box 3: The optimistic view: Example impact in labour market simulations (speculative; pending R&D breakthroughs likely beyond 2030)

Supply chain reaction to 'decent work' regulations

Optimising logistics is a leading commercial use case of quantum computers today, with potential value-add even on current-scale analogue computers and near-term gated computers. As policy makers consider regulations to improve pay or reduce shift durations for factory or supply chain workers, computers could analyse the likely cost/benefit to the supply chain and the potential for substantial supply chain restructuring as opposed to the minimum manual adjustment to implement the new regulations.

Pensions forecasting

Current pensions models primarily work with a few hundred aggregated, mostly static macroeconomic variables about a country's demographics situation and trends, predicting key features like the pensions deficit at different time horizons (2030, 2050, 2100, etc). More accurate models might better reflect the underlying uncertainty with a shift to stochastic modelling or exploit person-level agent models driven by rich citizen-level administrative data to use insights from micro-economics and mechanistic theories of change that are potentially higher quality (and more interpretable) than models built on system macrovariables. Quantum computers may prove a helpful unlock as these models increase in complexity, although outperformance relative to continually-improving classical computers remains speculative.

Listed as examples but not explored further, as these are ILO-lead topics and rely on partnership working with specific governments

The importance of quantum technologies for equity, policy, and diplomacy

The high uncertainty involved in applications for learning applies in most other sectors where quantum technology has the potential for dramatic impact. Indeed, it is in other sectors where the risks/opportunities are most likely to have political implications or raise issues of social justice concern, relating to the broader priorities of the ITCILO in its capacity building work among governments, employer associations, and worker associations, including key audiences in lower and middle income countries (see text box 4).

Box 4: The case for attention: Example speculative implications that may require novel policy

Quantum Internet, the threat to e-commerce, and a potential new digital divide

If quantum computers succeed in implementing Shor's Algorithm at scale before post-quantum cryptography is in place, online communication/finance may no longer be secure. It is possible that nations will become reliant on regional-bloc Quantum Internet to maintain access to e-commerce and privacy, with no secure communication available between blocs. If so, the large costs involved in Quantum Internet infrastructure may create a dramatic new global digital divide, with lower income countries unable to build out local Quantum Internet, effectively locking their citizens out of e-commerce and related applications.

The threat to privacy and freedom from new monitoring/simulation technologies

Quantum sensors and computers may enable a step-transition in the power of data gathering, machine learning, and simulations, accelerating existing concerns about privacy and freedom from AI technologies and potential conflicts between predicted risks and human agency (e.g. see concerns in EU AI Act, which came into force in August 2024).

Reliance on a quantum cloud could ossify global power relations

Low income countries may be able to access quantum compute via a cloud hosted in high income countries, but the high cost and geographically-fixed nature of computer infrastructure may prevent locally-hosted capabilities. If quantum compute proves essential for social applications in the future, this may create a risky dependency on other nations.

The potential to support climate change and a 'just transition'

As compute becomes a larger share of global energy consumption, the potential for quantum computers to implement calculations at lower energy costs potentially mitigates carbon costs, especially where exploiting analogue mechanisms. Quantum simulations may also form part of global climate change models, increasing the importance that lower income and climate exposed nations understand the technology well enough to critique the models. More generally, quantum technologies have the potential to tackle a range of climate change factors directly, bringing possible optimism for the future.

See report tables 5-6 and section 3.2 for more details

The level of uncertainty in technology roadmaps (and subjectivity in its assessment) accentuates the importance for policy. We cannot rule out breakthroughs happening sooner than roadmaps project, just as much as we cannot assume that the necessary breakthroughs happen at all over the next few decades. While roadmaps typically place material quantum advantage for the use cases in boxes 3-5 in the 2030s and are incentivised for optimism, the reality is that no-one knows. In 2024 alone, major breakthroughs have occurred.[10]

Nor can we rule out a possible domino effect across technologies. Accelerating progress in AI for scientific innovation[11] might unlock quantum technology breakthroughs faster than expected – with quantum computers powering future generation AI in a mutually-beneficial fly-wheel. Intersections with neurotechnology, materials science, energy generation, and simulation are easy to imagine but hard to predict, as are massive R&D investments to tackle climate change or prepare for future global conflict. The speculative possibility of disruption in the future is not a reason to redirect significant resources from problems that exist today – but it is a reason for proportionate investment in readiness, at least at the strategic level, even while widespread workforce readiness remains premature.

What does this mean for the ITCILO today

At this stage - respecting a focus on practical steps for a 2030 time horizon and the inherent uncertainties/subjectivities in the technology - it is fortunate that many sensible steps to be taken for uncertain future quantum technologies line up with worthwhile steps for exploiting existing technologies. Developing quantum literacy is a precursor to any future benefits. The complexities in both quantum technology and its industrial R&D landscape point to the importance of preparing ahead of time. The possible changes from quantum technology could come suddenly and with only limited warning, making quantum readiness a worthwhile investment.

We identify two areas of opportunity for ITCILO, expanded upon in section 3 in the main report. The first area concerns quantum technology as a tool to improve the delivery of learning/training. Although we do not recommend the immediate adoption of quantum technologies for learning delivery, the potential to benefit from quantum technologies in the future can be greatly improved through certain preparatory steps. In particular, ITCILO can foster internal quantum readiness by pursuing present-day non-quantum technologies in a manner that builds the data and expertise that are precursors to unlocking future quantum use cases. The second area builds on ITCILO's expertise in capacity development, suggesting a proactive role in the design and delivery of quantum readiness courses for policymakers and strategic decision makers.

10 Examples include breakthroughs on quantum error correction by Google Research (Willow; Dec 2024; https://research.google/blog/making-quantum-error-correction-work/) and IBM/Quantinuum (Apr 2024; https://spectrum.ieee.org/microsoft-quantum-computer-quantinuum), improved stability in room temperature qubits (Japan; Jan 2024; https://www.science.org/doi/10.1126/sciadv.adi3147), progress in quantum materials (Feb 2024; https://www.nature.com/articles/s41928-024-01118-y), and many more, including those cited later in this report.

11 E.g. https://www.nature.com/articles/d41586-024-02942-0 for AI-powered engagement with academic literature; AlphaFold for protein folding; etc.

In the context of quantum technology applications for learning, our primary suggestions are to foster quantum readiness within the ITCILO by:

- **Enhancing exploratory work with current non-quantum technologies that are also en route to potential high impact quantum technology use cases beyond the 2030 time horizon**, particularly AI-enriched provision such as adaptive/personalised learning, and tutor chatbots.
- **Emphasising the design of business processes and data collection required for these high impact use cases to fulfil their potential**, being necessary regardless of whether they use present-day classical technology or potential future quantum technology. This can include introducing more automated assessment check-points during courses, more personalisation in course content, more learner choice in learning pathways, and more chatbot/hybrid approaches to facilitate learning. Such processes empower experimentation and data collection that could unlock high impact adaptive/personalised learning and tutor chatbots. See the top 3 rows in table 10 in the main report for more details.
- **Identifying points in the above exploratory work where classical compute technologies might face limitations in addressing specific use case ambitions** (such as volume of data to analyse, quality of optimisation heuristics available, speed of processing etc.) or where knock-on breakthroughs in other technologies combine to create new opportunities. Such points represent areas where quantum technologies might prove impactful, help to identify specific quantum capabilities to monitor for, and can form the basis of practical conversations with quantum computing providers.
- **Monitoring quantum technology progress and societal trends**, with a particular eye to potential developments that unlock the use cases discussed in this report, including those in text boxes 2 & 3.
- **Leveraging excitement about quantum mechanics and quantum technologies** (including the UN International Year of Quantum Science and Technology) to engage resources, partners, and pilot users in the above initiatives.

In the context of readiness for potential policy priorities, including capabilities to monitor emerging quantum technologies for further learning applications, our primary suggestions are for the ITCILO to help foster quantum readiness across the ecosystem by:

- **Developing a quantum readiness course for policymakers and strategic decision makers (potentially in partnership with the ILO or others).** Such a course could provide introduction/myth-busting for key concepts, a framework for officials to identify priority topics and early warning signs, and strategic options for how best to monitor/engage with evolving developments. See table 16 in the main report for initial ideas on the curriculum framework for such a course. As a secondary priority, ITCILO might consider quantum-readiness content aimed at other groups, such as students who might be well-placed to build skills/networks so they might support society in the future with quantum technology related transitions.

- **Identifying a dedicated quantum technologies point of contact resource, potentially in the ILO's Observatory on AI and Work in the Digital Economy.** This resource would ideally have capacity to monitor both quantum computing advancements and other quantum technologies, in order to increase in-house knowledge, support internal discussions, and help generate ideas for enriching ITCILO's course design/delivery.
- **Incorporating quantum technology related content into existing ITCILO courses.** Such integrations would typically focus on direct applications of quantum technology, such as those described in table 15 of the main report. However, integrations could also include indirect applications. For instance, playing quantum games might provide a novel, engaging method for inspiring learners to think about complex, non-linear systems with unanticipated equilibria, with a learning outcome based on a general mindset rather than the specific relevance of quantum mathematics for a given policy scenario.
- **Incorporating appropriate evaluation and updating processes into the above courses**, noting particular challenges around ensuring participant understanding of technically complex subject matter and the fast-changing technology and research/corporate landscape.
- **Promoting the exploration of requirements, constraints, and theory involved in higher quality modelling of workplaces, supply chains, and economies/populations**, both as useful activities for exploiting existing computer/supercomputer capabilities and as necessary inputs for assessing if any components of that modelling might be amenable to specific quantum computer analysis.

The collective goal across these suggestions is to leverage excitement and the intrinsic fascination with quantum technologies to initiate a shift in mindset, discussed further in section 3.3.

These suggestions reflect the necessary limitations of this report. There is significant uncertainty in our assessments, due both to the nature of the field (fast-changing, lacking in consensus, complexity of underlying technology) and to the nature of the research behind the report (a rapid generalist assessment, driven primarily by secondary sources). Given these limitations and the apparent lack of immediately-deployable use cases of relevance, the focus for learning applications is appropriately put on monitoring, preparation, and readiness. Short-term attention on learning applications is perhaps better invested in complementary technologies (e.g. personalised/adaptive learning, chatbot tutors, simulations) and other areas of the emerging technologies taxonomy (e.g. neurotech, AR/VR).

Structure of the report

Part 1 provides a brief introduction of the context for the work and ITCILO's draft taxonomy, before focusing on specific proposals for developing the taxonomy based on a comparison with seven other taxonomies and an analytical assessment. As well as adjustments in content, the primary changes suggested are a differentiation between emerging technologies in infrastructure domains as opposed to application domains and a distribution of quantum technologies across multiple domains (rather than being its own dedicated domain). The proposed revised draft is also presented on page 13 following this summary for ease of viewing.

Part II identifies and defines eight strands of quantum technology: computing hardware, materials, networking, AI/ML algorithms, cryptography, metrology, biotech, and simulations. These eight strands are prioritised based on application readiness and ITCILO relevance by 2030, to support a choice of focus areas in Part III. A summary of the prioritisation is presented on page 14 for ease of viewing.

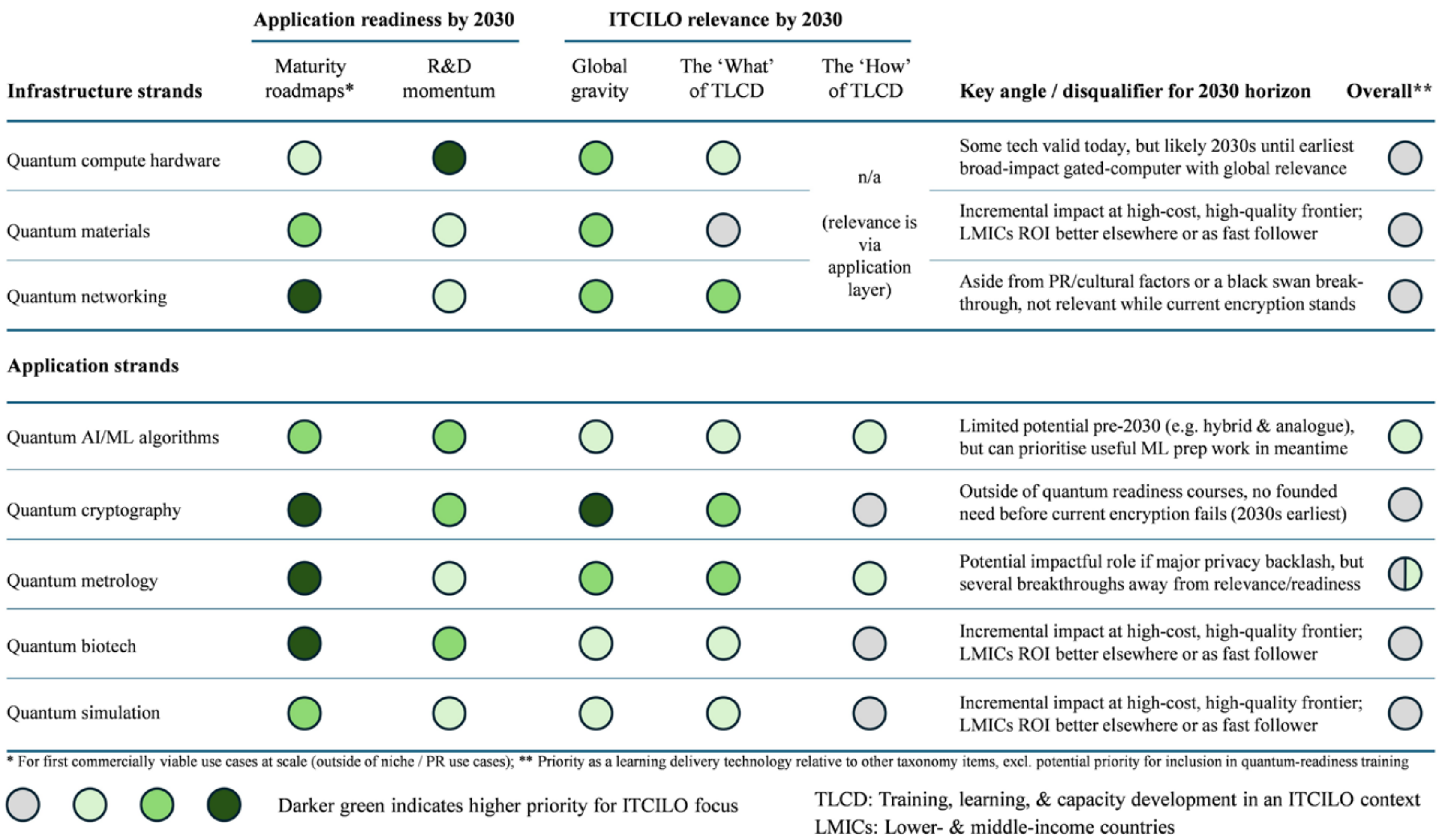
Part III provides the next level of assessment into the two areas prioritised in Part II. Firstly, the highest priority of the eight strands for a 2030 horizon, Quantum AI/ML algorithms for learning, albeit still only assessed as low priority for learning technologies overall. Secondly, the value of 'Quantum Readiness' capacity development provision, given the high uncertainty and high potential impact of quantum technologies on the future beyond 2030. We identify potential suggestions in both areas, should ITCILO wish to pursue quantum technologies further in 2025 or 2026. Appendices are included to provide supporting detail for key parts of the report.

ITCILO’s Emerging Technology Taxonomy (proposed revised draft)

Emerging technologies in infrastructure domains	
Energy • *Metrics:* energy produced per unit cost, distribution distance per unit cost, energy sustainability measures etc. • *Technology drivers:* renewable energy (solar, wind, hydro, incl. space-based solar), energy storage (batteries, supercapacitors), smart grids, hydrogen fuel cells, fusion, carbon capture, circular economy, green algorithms, etc.	**Compute** • *Metrics:* FLOPs-equivalent per unit cost, data storage per unit cost, data retrieval speeds etc. • *Technology drivers:* digital algorithm progress, transistor miniaturisation (e.g. via nanotechnologies), retrieval algorithms, superconductors, data infrastructure technologies, neuromorphic computers, DNA data storage, quantum computing hardware etc.
Materials • *Metrics:* number of unique materials/physical functions we can construct, cost for bespoke construction, ability to intervene in existing physical systems etc. • *Technology drivers:* atomic/molecular science, protein engineering, smart materials, nanotechnology, 3D & 4D printing/additive manufacturing, advanced composites, metamaterials, biomimetic materials, elastocalorics, quantum materials, etc.	**Connectivity** • *Metrics:* reliable GB/second per unit cost/energy, population connectivity coverage ratios, number of items connected to the Internet, latency, etc. • *Technology drivers:* 6G and successor technologies, fibre optic cables, infrastructure build-out, protocols and standards, high altitude platform stations, LEO satellite constellations, quantum networking etc.

Emerging technologies in application domains		
AI & ML • Natural Language Processing • Computer Vision • Predictive Analytics • Robotic Process Automation • Agentic AI • Generative AI / LLMs • AI TRiSM / AI alignment • Explainable AI • Quantum AI/ML algorithms	**AR & VR** • Mixed Reality • Extended Reality • Remote Assistance & Collaboration • Training and Simulation • Haptic interfaces • Holography for communication	**Cybersecurity** • Threat Intelligence • Zero Trust Security / ZKPs • Cyber Resilience • Identity and Access Management • Cybersecurity mesh architecture • Disinformation security • Homomorphic encryption • Quantum cryptography
Distributed Ledgers • Blockchain • Cryptocurrencies • Smart Contracts • Decentralized Finance • Supply Chain Management	**Sensors & Internet of Things** • Industrial IoT • Smart Homes • Wearables • Connected Vehicles • Environmental/machine sensors • VLEO satellites • Spatial computing • Quantum metrology	**Biotechnology** • Bioinformatics • Gene editing, incl. CRISPR • Synthetic biology / bioprinting Adult stem cells • mRNA therapeutics • Fluxomics • Personalised ’omics medicine • Cellular programming • Quantum biotechnology
Cloud & Edge Computing • Infrastructure as a Service • Platform as a Service • Software as a Service • Serverless Computing • Fog Computing • Edge AI / AI as a service • Real-Time Data Processing • IoT Edge • GitOps / Infrastructure as computing	**Advanced Robotics** • Collaborative Robots • Autonomous Mobile Robots/ Vehicles • Drone Technology/Swarm robotics • Robotics Process Automation • Soft robotics • Self-organising, self-healing robotics • Space manufacturing • Reconfigurable/intelligent surfaces	**Simulation** • Digital twins • Predictive Maintenance • Product Lifecycle Management • Smart Cities and Infrastructure • Virtual prototyping • Quantum simulation
Neurotechnology • Neuroimaging and Brain Mapping • Brain-Computer Interfaces (BCI) • Neurostimulation/ Neuromodulation • Neural Prosthetics • Neural Data Analysis • Neuro-pharmacology/-modulators	**Space & Transport** • Nuclear space propulsion • Hypersonics • Ion propulsion • On-orbit maintenance • Next-gen satellites • Reusable rockets	

Quantum technology strands: Part II prioritisation summary



PART I. ITCILO'S EMERGING TECHNOLOGY TAXONOMY: CONTEXT AND PROPOSAL

The ITCILO is investigating a range of emerging technologies for their possible relevance to the teaching, learning, and capacity development work of the ITCILO, where such work is primarily aimed at supporting officials across governments, employers' organisations, workers' organisations, and other partners in pursuit of decent work and sustainable development. These emerging technologies are grouped in a draft taxonomy across higher-level domains such as AI/ML, neurotechnology, and biotechnology, chosen in order to direct pragmatic research workstreams into the emerging technology applications of most likely relevance.

The ITCILO's draft Taxonomy of Foundational Technologies is intended to cover a broad range of sectors/applications, providing an up-to-date landscape of all the key foundational technologies that would be important to address in analysing the impact of future technologies on a particular topic. ITCILO's immediate topic of interest is learning and capacity development (initially up to 2030), but the taxonomy itself should be topic-neutral.

Part I of this project consisted of a review of the draft taxonomy, including an interim input to support ITCILO's attendance at the Quantum for Good conference.[12] In particular, the workshop ITCILO led on 22 November was an opportunity to discuss the broader context of technologies that includes quantum engineering. We note that 'quantum engineering' is proposed to be renamed 'quantum technologies' following the workshop and 'foundational technology' is proposed to be renamed 'emerging technology' to line up with practice elsewhere; these terms are adopted in the rest of this report.

1.1. Summary of Part I

We compared the draft ITCILO taxonomy against seven taxonomies identified from web research for diverse types of technology taxonomy. The seven taxonomies were prioritised based on recency, coverage of a broad base of technologies (i.e. not sector-specific taxonomies), and suitability for the ITCILO use case, informed by the degree of overlap with emerging technologies already included in the draft.

[12] 20-21 Nov, the Hague, Netherlands, Quantum for Good: Setting the Stage for the International Year of Quantum, hosted by the United Nations International Computing Centre (UNICC), the International Telecommunication Union (ITU) and Quantum Delta NL (QDNL).

The seven prioritised taxonomies vary widely by breadth/granularity (from 10 items to over 7,000), structure (single layer up to four layers), focus (emerging technologies, enabling technology, national security, short-term impact, all technologies etc.), and source (government body, report for government, corporate, and international networks) – see table 1 for details. They also treat quantum technologies in different ways, e.g. as a top-level domain, distributed across multiple domains, or not prioritised within their given scope/timeframe (table 2).

Reviewing these taxonomies against the ITCILO use case and considering alternative conceptual approaches to taxonomisation, we propose five main sets of revisions to the draft taxonomy:

- Split the domains into infrastructure domains (such as energy, compute) and application domains (such as AI, IoT), where the former are broad enablers for many of the latter.
- Merge certain top level domains (e.g. edge & cloud computing) and restructure others (e.g. biotechnology), to have closer alignment of granularity level, while still permitting flexibility to support ITCILO's use case.
- Add novel domains (e.g. space & transport) where highlighted as priority areas of emerging technology in the taxonomies reviewed.
- Add additional strands under specific domains, where prominent within our research so far, while noting we have not attempted extensive coverage of domains outside of quantum technologies.
- Distribute quantum technologies across domains in both the infrastructure and application layers, similar to the IEEE, InnovateUK, and EU taxonomies and better reflecting the diverse mix of quantum technologies in scope.

Our proposal maintains the short presentation (one page) and pragmatic focus of the previous ITCILO draft. We considered other possible extensions to the taxonomy, but propose these are addressed via specific workstreams and in separate reports, rather than adding complexity and length to the taxonomy. For instance:

- We maintain the current focus on hard technologies (both hardware and software innovations) and exclude soft technologies (such as business processes, governance, and social science innovations).
- We maintain the pragmatic focus on prominent emerging technologies, rather than applying a comprehensive taxonomical structure.
- We identify overlaps and structural evolution as appropriate features of the taxonomy that reflect the ITCILO use case and the reality of the research ecosystem.
- Cross-cutting themes exist throughout the taxonomy but remain implicitly presented only. For instance, user interface technologies and pedagogical technologies appear in multiple domains.

Despite being excluded from the taxonomical structure itself, these areas have potential relevance to ITCILO's broader purpose and we provide examples of where they might be picked up in future work.

Table 3 provides a version of the revised taxonomy that highlights the main additions and the quantum technologies.

1.2. Draft ITCILO taxonomy to be reviewed

ITCILO's draft taxonomy (shown overleaf) is a hierarchical taxonomy with two aligned layers: 15 top-level items (termed 'domains' in this document), with 4-7 lower-level items each (termed 'strands' in this document).

The domains primarily refer to fields of applied research, with strands referring to specific technology applications within that strand. Exceptions include the strands underneath biotechnology which refer to economic areas of possible application (marine, food, etc.) rather than specific biotechnologies (e.g. CRISPR, cloning).

The fields of applied research selected to name domains vary in granularity compared to traditional academic hierarchies (e.g. journal taxonomies; academic roles), e.g. energy technologies is a broader field of research than digital twins.

The domains typically focus on applied technologies which are attracting the most attention, e.g. emerging technologies that are more likely to have high impact, or applied fields that have traditionally attracted high-levels of funding and generated high-impact technologies (e.g. energy, biotech). This flexibility over level of granularity and selection allows more freedom to categorise items of likely ITCILO relevance over a broad range of topics.

1. Artificial Intelligence and Machine Learning • Natural Language Processing • Computer Vision • Predictive Analytics • Robotic Process Automation	**6. Augmented Reality and Virtual Reality** • Mixed Reality • Extended Reality • Remote Assistance and Collaboration Tools • Training and Simulation	**11. Cybersecurity** • Threat Intelligence • Zero Trust Security • Cyber Resilience • Identity and Access Management
2. Blockchain and Distributed Ledger Technologies • Cryptocurrencies • Smart Contracts • Decentralized Finance • Supply Chain Management	**7. Quantum Engineering** • Quantum Computing • Quantum Cryptography • Quantum Simulation • Quantum Machine Learning • Quantum Optimizatio	**12. Energy Technologies** • Renewable Energy (Solar, Wind, Hydro) • Energy Storage (Batteries, Supercapacitors) • Smart Grid Technologies • Hydrogen Fuel Cells
3. Internet of Things (IoT) • Industrial IoT • Smart Homes • Wearables • Connected Vehicles	**8. Biotechnology** • Agricultural • Industrial • Marine • Food • Bioinformatics • Environmental • Medical	**13. Edge Computing** • Fog Computing • Edge AI • Real-Time Data Processing • IoT Edge
4. 5G and Next-Generation Connectivity • Enhanced Mobile Broadband • Ultra-Reliable Low Latency Communications • Massive Machine Type Communications	**9. Advanced Robotics** • Collaborative Robots • Autonomous Mobile Robots • Drone Technology • Robotics Process Automation	**14. Digital Twins** • Simulation and Modeling • Predictive Maintenance • Product Lifecycle Management • Smart Cities and Infrastructure
5. Cloud Computing • Infrastructure as a Service • Platform as a Service • Software as a Service • Serverless Computing	**10. Advanced Manufacturing and Materials** • 3D Printing/Additive Manufacturing • Nanotechnology • Smart Materials • Advanced Composites	**15. Neurotechnology** • Neuroimaging and Brain Mapping • Brain-Computer Interfaces (BCI) • Neurostimulation and Neuromodulation • Neural Prosthetics • Neural Data Analysis and Computational Neuroscience • Neuropharmacology and Neuromodulators

1.3. Priority taxonomies identified for review

We identified seven priority taxonomies for review via a websearch methodology:

- Gartner's latest Hype Cycle for Emerging Technologies with 25 items with potential for transformational benefits over 2-10 years (published Aug 2024)
- The IEEE's latest Technology Taxonomy (published Jul 2024)
- The World Economic Forum's latest list of 10 emerging technologies (published Jun 2024)
- The US government's Critical and Emerging Technologies List (Feb, 2024)
- InnovateUK's 50 emerging technologies, used by the UK's Government Office for Science to identify priority technologies for state attention (published Dec 2023)
- The European Parliament's Key Enabling Technologies study (published Dec 2021)
- The US government's National Science Foundation key technology areas (live site)

For now, we are excluding old taxonomies (e.g. Pavitt's 1984 taxonomy) or those focused on particular sectors (e.g. NASA's 2024 taxonomy; IT-focused taxonomies like the Open Group's TRM or the TBM taxonomy).

1.4. Comparison of taxonomies

The seven prioritised taxonomies vary widely by breadth/granularity (10 items to over 7,000) and focus (emerging technologies, enabling technology, national security, short-term impact, all technologies etc.). The taxonomies, excerpts, and links for each can be found in appendix 1.

TABLE 1. COMPARISON OF PRIORITISED TAXONOMIES

Name	Structure	Organising Logic	Example Content	High-Level Methodology
Gartner's Hype Cycle for Emerging Technologies (Aug 2024)	25 items in 1 layer	Technologies grouped by hype cycle position and years to maturity (<10)	Items: Humanoid working robot, Generative AI, 6G	Reviewed over 2000 technologies from market surveys and vendor briefings
IEEE's Technology Taxonomy (Jul 2024)	Over 7,000 items in up to four hierarchy layers over 76 pages	Categorized based on technology families like AI, IoT, robotics, medical tech	*Layer 1 – 2 - 3 - 4* Magnetics - Biomagnetics – Magnetoencephalography Communications technology - Comms. systems - Comms. system security - Quantum Key Distribution	Created by IEEE to cover all technological domains, with contributions from industry experts
WEF's 10 Emerging Technologies (Jun 2024)	10 items in 1 layer	Technologies with transformational impact within 3–5 years	AI for scientific discovery, Privacy-enhancing technologies	Based on expert consultations, literature analysis, funding trends
US gov. CET list (Feb 2024)	122 items across 18 families	Advanced technologies that are potentially significant to US national security	*Family – Item:* Advanced Computing - Spatial computing Hypersonics - Propulsion Directed Energy – Lasers	Interagency deliberation with the National Science and Technology Council (NSTC) and the National Security Council (NSC), incl. subject matter experts from 18 gvnt teams
InnovateUK's 50 Emerging Technologies (Dec 2023)	50 items in 7 families	Technologies relevant to the UK economy beyond 2040	*Family – Item:* Biotechnology - Biocatalytic membranes AI, digital and computing - AGI; DNA data storage	Surveyed scientists and researchers, reviewed tech scans, analysed 30+ metrics
European Parliament's KET List (Dec 2021)	6 Key Enabling Technologies (KETs) in a single list, with major and example non-comprehensive applications	Technologies critical for European industrial leadership and sovereignty	*Family – Major application* AI – Quantum AI Advanced (nano) materials – 3D printing & design	Analysis of patents, market trends, and industrial leadership across EU
NSF Key Technology Areas (current; n.d.)	11 families in a single layer (no items)	Based on broad technological categories and focus on R&D investments	Cybersecurity, AI, Quantum Information Science	Compiled by the US government's National Science Foundation for R&D investments in the U.S. economy

1.5. Treatment of quantum technologies

The seven prioritised taxonomies treat quantum technologies in different ways, e.g. as a top-level domain, distributed across multiple domains, or not prioritised within their given scope/timeframe.

TABLE 2. TREATMENT OF QUANTUM TECHNOLOGIES – COMPARISON OF TAXONOMIES

Name	Main approach to quantum technologies
Gartner's Hype Cycle for Emerging Technologies (Aug 2024)	Explicit quantum items do not appear in the top 25, but could be underpinning technologies for others, such as AI supercomputing
IEEE's Technology Taxonomy (Jul 2024)	Distributed across multiple areas/levels in the hierarchy, e.g. Electron devices – Quantum computing – Qubit (spin qubit); Quantum advantage; Quantum algorithm; Quantum annealing; Quantum cellular automata; Quantum chemistry; Quantum circuit; Quantum networks (quantum repeaters); Quantum simulation (also logged under Computers and information processing) Geoscience & remote sensing - Remote sensing – Quantum radar (also under Electromagnetic compatibility & interference) Industry applications – Security - Cryptography – Quantum cryptography Information theory - Communication channels – Quantum channels Instrumentation and measurement - Electric variables – Capacitance – Quantum capacitance Lasers and electrooptics – Quantum well lasers – Quantum cascade lasers; Semiconductor lasers – Quantum dot/well lasers; Solid lasers – Quantum well lasers (also logged under electron devices) Materials, elements, and compounds - Quantum materials Mathematics – Optimisation - Meta-heuristics – Quantum annealing Nuclear and plasma sciences – Elementary particles - Electrons – Quantum Wells Circuits & systems - Quantum circuits Systems engineering & theory – Quantum simulation Sensors - Quantum sensing/sensors Science general - Quantum chemistry; Quantum mechanics (+ 21 subcategories[13]) Comms tech – Comms system security – Quantum key distribution Professional communication - Quantum information science – Quantum channels/ circuits (also logged under Comms tech)
WEF's 10 Emerging Technologies (Jun 2024)	Quantum information science was a BERTopic grouping reviewed, but without producing any emerging tech for the report
US gov. CET list (Feb 2024)	All items contained in one family: Quantum Information and Enabling Technologies • Quantum computing • Materials, isotopes, and fabrication techniques for quantum devices • Quantum sensing • Quantum communications and networking • Supporting systems

[13] Coherence time; Density functional theory; Proton effects; Quantum capacitance; Quantum cryptography; Quantum decoherence; Quantum entanglement; Quantum information science; Quantum key distribution; Quantum materials; Quantum optics; Quantum sensing; Quantum sensors; Quantum simulation; Quantum state; Quantum system; Relativistic quantum mechanics; Schrodinger equation; Stationary state; Teleportation; Tunnelling.

Name	Main approach to quantum technologies
InnovateUK's 50 Emerging Technologies (Dec 2023)	AI, Digital and Computing Technologies – Quantum algorithms; New computing models (quantum, but also others not based on traditional circuit technology, e.g. biological, photonic, neuromorphic computing) Electronics, Photonics and Quantum Technologies - Post-quantum cryptography; Room temperature superconductors (indirect building block; shared fundamental science); Photon generators (indirect building block)
European Parliament's KET List (Dec 2021)	Identified at the major application level and distributed across families, e.g. Under Micro/nano-electronics and photonics: • Quantum-IT • Quantum Computing • Quantum Communication and Quantum Key Distribution • Quantum Sensing • Cloud Quantum Computing • Methods and Tools for Quantum Software Development • Processes and support for handling NISQ (Noise Intermediate Scale Quantum) computing aspects • Development and application of QC to real world problems Under Security and connectivity technologies: • Quantum Key Distribution • Post-quantum cryptography Under AI: • Quantum AI and Quantum Machine Learning
NSF Key Technology Areas (current; n.d.)	Quantum Information Science is a top level family, examples on that page include quantum sensors, quantum computing, and quantum communications.

1.6. Considerations for a revised taxonomy

Organising logic for the taxonomy

Different items can always be organised and categorised in multiple, equally valid ways. The selection of approach is driven by use case, not the notional superiority of one method. For instance, rather than organise by a subset of applied research fields, we could organise by:

- field of academic study (e.g. using established journal taxonomies that cover all contemporary research, such as physics, biology, computer science, & subcategories)
- area of human/economic activity (e.g., using established sectoral taxonomies, such as entertainment, food, retail, & transport)
- underlying functional role to fit the foundational scope (e.g., hardware, software, energy, connectivity, human-interface, governance, etc.)
- time to likely first commercial non R&D purchase (e.g. current; 1-3 years; etc.)
- technology lifecycle phase (e.g. within R&D: basic science; application specification; prototyping; product design for market; market introduction etc.)
- level of foundationality (e.g. how niche it is; how much activity it affects, e.g. organic photovoltaics is a subset of solar tech which is subset of energy tech; energy tech powers almost all technology and is more foundational than VR or edge computing).

In reviewing these options, we consider them against our understanding of the ITCILO use case for this taxonomy: providing a pragmatic guide to direct research into specific technology domains, in order to understand which specific technologies might have an identified impact on learning and capacity development and other ITCILO priorities by 2030. The requirement for a pragmatic guide also helps specify taxonomy format aspects, notably maintaining a one A4 page structure, as with the current draft taxonomy.

An advantage of the first four options above is allowing for a potential 'MECE' structure, such that the categories chosen are mutually exclusive and collectively exhaustive (MECE). This way, we can be confident that every possible foundational technology would fit somewhere and we have a framework to drive an attempted comprehensive listing. However, such high-level categories do little to help direct pragmatic research:

- the first two (academic field, economic sector) would require too many subcategory layers to be both comprehensive and address our technologies of interest, i.e. they would cease to have a useable display format
- the third (functional role) has too few subcategories, so in practice does little to drive confidence in comprehensiveness
- the fourth (time to commerciality) is an output of ITCILO's planned research, so cannot structure the initial taxonomy – same with the fifth (R&D lifecycle phase).

The sixth (foundationality) can be used as a high-level guide, but precise analysis of level of foundationality would require dedicated research activity that would likely add little value.

In conclusion, given the ITCILO's use case, we recommend continuing with the current approach of selecting a subset of the most interesting applied research fields, with specific technology applications underneath them. This approach does not afford a structural guide to comprehensive completion, but this is an acceptable compromise given the benefits. Similarly, we anticipate some overlap between domains, with technology strands having closely related applications in more than one domain, but consider this a feature over the taxonomy rather than a bug, reflecting the continually evolving and interdisciplinary nature of the research ecosystem. Adequately comprehensive coverage can be gained through a research methodology. Additional items surfaced later that expand the taxonomy are to be welcomed; there is no requirement to limit to, e.g., 15 domains.

Hard vs soft technologies

The current draft taxonomy is focused on hard technologies, whereas 'softer' technologies might also be particularly relevant for the social justice implications of particular applications. For instance, such softer technologies could include organisations/business processes (which tech integrates into), user experience innovations (see also below), tech standards, governance, and broader insights from social science. However, it may be better to address such softer technologies within specific hard technology domains rather than to incorporate them into a more comprehensive taxonomy, which would be a major divergence from the current approach.

For instance, insights on quantum game theory are primarily based in the mathematical and social sciences, rather than technology innovations. Nonetheless, they become relevant as part of capacity development work helping officials explore real world strategy, i.e. where classical game theory might already be part of the curriculum. Rather than incorporate such social science into the taxonomy, we recommend it being surfaced through the investigation into individual domains, which naturally includes understanding of the underlying scientific principles and potential relevance to ITCILO topics.

Cross-cutting themes and connectivity

At the risk of adding complexity and controversy to the taxonomy, the stronger links between certain infrastructures and certain applications could be displayed visually or cross-cutting thematic links be highlighted.

An example of a cross-cutting theme is technology that improves the user interface with a particular service or function. Such 'user interface' technologies appear in multiple hard technology domains already listed, such as haptic interfaces under AR & VR, BCI under neurotechnology, explainable AI (which includes both algorithms and the interface for users to interact with results) under AI & ML, wearables under Sensors & IoT, and some applications of reconfigurable/intelligent surfaces under advanced robotics.

User interface technologies also include soft technology, such as business process or user experience innovations that do not necessarily require new scientific advances, but nonetheless exploit existing capabilities in powerful ways that can accelerate impact for end users. For instance, microlearning and education gamification innovations do not rely on emerging tech or novel basic science findings but nonetheless represent user interface innovation with existing technologies that might fit the broader ITCILO scope. Personalised and adaptive learning services can likewise be developed with existing software and data analysis technologies, with limitations in usage primarily driven by software development and provider priorities rather than a fundamental technical barrier. Nonetheless, new technologies in the taxonomy might empower such education techniques (or create excitement about them) such that uptake does progress. Examples include more powerful personalisation via new ML algorithms, potentially powered by new compute capabilities, more powerful insights via personalised 'omics or neurotechnology, or the ability to simulate a learner to test what types of education will work best.

New ways of teaching concepts, such as insights from quantum games, quantum cognition, or pedagogical research, as well as biopharmaceuticals or neurotech that might provide cognitive enhancements, could also prove relevant to teaching & learning. Nonetheless, we do not recommend grouping these technologies under a new domain of 'Teaching & Learning', because part of ITCILO's use case for the taxonomy is to explore a diverse range of emerging technology in order to identify applications that might be relevant for various teaching & learning purposes. Embedding such a domain in the taxonomy seems to assume the answer upfront and might circumscribe creativity in identifying implications from applications in other domains via research planned by ITCILO.

At present, we consider this detail is best surfaced in individual research projects and potentially summarised in a separate table (such as with quantum technologies), rather than trying to build it into the existing taxonomy. We would recommend that a later version of the taxonomy summarises the framing principles used to construct it, perhaps drawing on the discussion in this note, and explains the methodology used to populate it.

Proposed revisions

Our review identifies a number of candidate revisions to the taxonomy:

- Split the domains into infrastructure domains (such as energy, compute) and application domains (such as AI, IoT), where the former are broad enablers for many of the latter.
- Merge certain top level domains (e.g. edge & cloud computing) and split or redistribute others (e.g. biotechnology), to have closer alignment of granularity level, while still permitting flexibility to support ITCILO's use case.
- Add novel domains (e.g. space & transport) where highlighted as priority areas of emerging technology in the taxonomies identified in table 2.
- Standardise strands by technology (e.g. removing sectors from the current biotechnology domain) and add additional strands under specific domains, where prominent within our research so far.

Regarding the last point, we have not sought comprehensive listing within each domain, because this is primarily a task of specific research efforts at the domain-level and would go beyond our scope, but where items are readily available, we include them for consideration. Arguments can always be made for setting weaker or stricter inclusion criteria and usability vs coverage considerations help inform the level of depth/detail to include under each item and the level of granularity to favour. ITCILO's use case can be used to drive this in practice. For instance, strands (and domains where possible) should be chosen in a way that provides effective search terms for identifying applied R&D teams actively working on relatively near-term technology applications and their associated companies/patents. Meanwhile, granularity is limited from below by the need to maintain useability within a one A4 page limit.

Quantum-related technologies are within our scope in this respect and we have incorporated insights from table 2 and elsewhere from our research.

A revised draft taxonomy that implements these revisions can be found in table 3. As a minor point, we recommend renaming the taxonomy around emerging technologies rather than foundational technologies, aligning with the types of application already identified, the desired use case of identifying key technologies attracting R&D spend that may be impactful in the near future (the 'pathfinder' purpose of the project for ITCILO), and with the common language across the most relevant other taxonomies identified.

Our research into quantum technologies suggests specific items are best distributed across a range of domains, similar to the IEEE, InnovateUK, and EU taxonomies analysed above. This distributed approach better reflects the diverse mix of quantum technologies. The approach does not restrict our ability to analyse quantum technologies as a single group in this project, because the items can still be extracted and grouped given their common underpinning basic science, retaining visibility of their original source (see table 4).

Finally, we note that the two-layer structure of the taxonomy deliberately simplifies the multiple levels from foundational science to mature commercial operations and the separate categories deliberately elide links between areas, favouring simplicity and useability over fidelity to the research ecosystem, without seeking to imply equality of relevance across domains in the same layer. For instance, algorithmic development can be understood as part of knowledge development in foundational science and fuels various other applied technologies (such as digital twins, data analysis within neurotech applications), but is included in the application layer due to the important applied nature of today's AI/ML tools. As a second example, improved simulation technology both supports drug development in the sister domain of biotechnology, as well as materials development in the infrastructure layer.

TABLE 3. PROPOSED REVISION TO ITCILO'S EMERGING TECHNOLOGY TAXONOMY (WITH HIGHLIGHTS)

Emerging technologies in infrastructure domains*	
Energy • ***Metrics:*** energy produced per unit cost, distribution distance per unit cost, energy sustainability measures etc. • ***Technology drivers:*** Renewable Energy (Solar, Wind, hydro, incl. space-based solar), energy storage (batteries, supercapacitors), smart grids, hydrogen fuel cells, fusion, carbon capture, circular economy, green algorithms, etc.	**Compute** • ***Metrics:*** FLOPs-equivalent per unit cost, data storage per unit cost, data retrieval speeds etc. • ***Technology drivers:*** digital algorithm progress, transistor miniaturisation (e.g. via nanotechnologies), retrieval algorithms, superconductors, data infrastructure technologies, neuromorphic computers, DNA data storage, **quantum computing hardware** etc.
Materials • ***Metrics:*** number of unique materials/physical functions we can construct, cost for bespoke construction, ability to intervene in existing physical systems etc. • ***Technology drivers:*** atomic/molecular science, protein engineering, smart materials, nanotechnology, 3D & 4D printing/additive manufacturing, advanced composites, metamaterials, biomimetic materials, elastocalorics, **quantum materials**, etc.	**Connectivity** • ***Metrics:*** reliable GB/second per unit cost/energy, population connectivity coverage ratios, number of items connected to the Internet, latency, etc. • ***Technology drivers:*** 6G and successor technologies, fibre optic cables, infrastructure build-out, protocols and standards, high altitude platform stations, LEO satellite constellations, **quantum networking** etc.

Emerging technologies in application domains		
AI & ML • Natural Language Processing • Computer Vision • Predictive Analytics • Robotic Process Automation • Agentic AI • Generative AI / LLMs • AI TRiSM / AI alignment • Explainable AI • **Quantum AI/ML algorithms**	**AR & VR** • Mixed Reality • Extended Reality • Remote Assistance & Collaboration • Training and Simulation • Haptic interfaces • Holography for communication	**Cybersecurity** • Threat Intelligence • Zero Trust Security / ZKPs • Cyber Resilience • Identity and Access Management • Cybersecurity mesh architecture • Disinformation security • Homomorphic encryption • **Quantum cryptography**
Distributed Ledger Technologies • Blockchain • Cryptocurrencies • Smart Contracts • Decentralized Finance • Supply Chain Management	**Sensors & Internet of Things** • Industrial IoT • Smart Homes • Wearables • Connected Vehicles • Environmental/machine sensors • VLEO satellites • Spatial computing • **Quantum metrology**	**Biotechnology** • Bioinformatics • Gene editing, incl. CRISPR • Synthetic biology / bioprinting • Adult stem cells • mRNA therapeutics • luxomics • Personalised 'omics medicine • Cellular programming • **Quantum biotechnology**
Cloud & Edge Computing • Infrastructure as a Service • Platform as a Service • Software as a Service • Serverless Computing • Fog Computing • Edge AI / AI as a service • Real-Time Data Processing • IoT Edge • GitOps / Infrastructure as computing	**Advanced Robotics** • Collaborative Robots • Autonomous Mobile Robots/Vehicles • Drone Technology/Swarm robotics • Robotics Process Automation • Soft robotics • Self-organising, self-healing robotics • Space manufacturing • Reconfigurable/intelligent surfaces	**Simulation** • Digital twins • Predictive Maintenance • Product Lifecycle Management • Smart Cities and Infrastructure • Virtual prototyping • **Quantum simulation**
Neurotechnology • Neuroimaging and Brain Mapping • Brain-Computer Interfaces (BCI) • Neurostimulation/Neuromodulation • Neural Prosthetics • Neural Data Analysis • Neuro-pharmacology/-modulators	**Space & Transport** • Nuclear space propulsion • Hypersonics • Ion propulsion • On-orbit maintenance • Next-gen satellites • Reusable rockets	

* See Appendix 2 for other potential foundational infrastructure technologies considered but not prioritised for inclusion.

Quantum-related technologies are in **blue font**; Additions within ITCILO's original domains are in red font

PART II. QUANTUM TECHNOLOGIES ASSESSMENT

The purpose of Part II is to identify and define different strands of quantum technology and to prioritise activities for further research in Part III.

2.1. Summary of Part II

Eight strands of quantum technology are identified, allocated to eight different domains in the taxonomy:

- Quantum Computing Hardware (under Infrastructure: Compute)
- Quantum Materials (under Infrastructure: Materials)
- Quantum Networking (under Infrastructure: Connectivity)
- Quantum AI/ML Algorithms (under Applications: AI/ML)
- Quantum Cryptography (under Applications: Cybersecurity)
- Quantum Metrology (under Applications: Sensors & IoT)
- Quantum Biotech (under Applications: Biotechnology)
- Quantum Simulation (under Applications: Simulation)

Definitions of each strand and key use cases are included in table 4. These high level descriptions and the broader assessment draw on the following main sources:

- Scopus-database key-word scan for quantitative data on patent applications and academic publications
- 13 national government and EU strategies on quantum, incl. roadmaps (appendix 3)
- 5 corporate roadmaps (available in appendix 4) and various company websites
- 7 technology taxonomies (available in appendix 1)
- Over 20 consultant, industry, and market reports, including discussion of applications, use cases, roadmaps, and forecast market sizes (see table 6 notes[14])

[14] Note. Charged-for market reports have not been purchased for this report. Only summary and preview information shared publicly have been used.

- Extensive newsflow and sector commentary, prioritising well-regarded sources such as Quantum Insider and IEEE Spectrum, which report on major research progress (incl. arXiv and other pre-print sites), corporate, and government announcements
- These sources are used to drive an approximate qualitative and quantitative assessment of the eight strands against the following prioritisation framework:
- Application readiness by 2030
  - Maturity roadmaps
    Based primarily on quantitative date availability claims, commentary, and targets described in government and corporate documents, balanced against recent track record
  - R&D momentum
    Based primarily on an indicative quantitative analysis of the total volume and recent growth of patents and academic publications
- ITCILO relevance by 2030
  - Global gravity
    Based primarily on quantitative estimates of forecast 2030 market size of the different technologies and qualitative assessment of the types of labour market disruption and the types of global risks/opportunities they might bring
  - The 'What' of training, learning, and capacity development
    Based primarily on content relevant to sectors with broad global inequality, decent work, sustainable development, or social justice considerations for lower/middle income countries, i.e. likely to be important inputs/angles for ITCILO initiatives[15]
  - The 'How' of training, learning, and capacity development
    Based primarily on technologies that can be used to enhance the design or delivery of learning/ training from use case assessment across reports

The assessment should be considered preliminary, considering the modest amount of research scoped for it relative to the breadth and technicality of the quantum technologies to be addressed. Nonetheless, the current assessment is sufficient for an initial prioritisation exercise to support the ITCILO's broader objectives and to guide work for the rest of the project.

The existing interrogation of quantum technology strands drives a **prioritisation logic given the project scope, notably its 2030 time horizon**. We interpret 2030 as a time horizon within which applications should become broadly relevant to commercial applications and teaching and learning, beyond R&D, niche use cases, or PR-driven pilot projects.

The assessment must be caveated by our focus on current mid-point projections, adjusted for past levels of over-optimism, and our exclusion of black swan breakthroughs over the next 5 years. One meta-consensus in quantum technology is that there is no consensus over the likely pace of progress or which specific solutions will succeed first. We incorporate this uncertainty

[15] Note we exclude content which is primarily about training scientists working in those fields, because that is equally applicable to all research topics and is not the primary target audience for ITCILO's development work. Understanding the scientific context for a technology is nonetheless an important element of certain training programmes for policy officials or senior leaders and would be in-scope.

explicitly into a recommendation for next steps in Part III, but park it for now in assessing the most likely range of progress by 2030.

Timeline assessment summary

In the case of quantum technologies, the majority of investment and R&D capacity is focused on hardware improvements, notably the race to build functional gated quantum computers that operate at relevant scale and the race to build out quantum internet and related infrastructure. The majority of long-term economic growth is anticipated to occur via the application of sophisticated quantum algorithms on this future quantum computer infrastructure, although there is significant short-term commercial potential anticipated via quantum dot and quantum sensor technologies. The quantum internet would, if built out globally, represent an enormous investment, but its contribution to the economy beyond its own construction is primarily in defence of existing GDP, in case existing encryption technologies and post-quantum cryptography solutions in development should fail - and modern web-based financial transactions and communications cease to be secure. The failure of encryption technologies is, in turn, most likely to occur via the quantum decryption algorithms running on the aforementioned quantum computers.

Many of the other quantum applications similarly rely on algorithms running on large-scale quantum computers before they achieve a major impact. For instance, outside of small molecular simulations (which can still have value in materials or biotechnology), simulation algorithms for larger molecules, climate subsystems, or city economies will typically require a few thousand logical qubits. Large-scale gated quantum computers thus become a key consideration for several of our technology strands. In this area, it is likely to be 2030s at the earliest – likely mid-2030s rather than early 2030s. Even corporate roadmaps from IBM and Quantinuum place these achievements in the 2030s rather than before.

This assessment motivates a priority downgrade compared to various other emerging technologies in the ITCILO taxonomy, which often have the potential to have at least medium-sized impacts on training, decent work, or sustainable growth much sooner and at higher probability.

What about a sudden breakthrough in quantum computing? After all, AI was always a decade away, until suddenly it was here, primarily in the form of generative AI and the remarkable capacities of large language models (LLMs). A sudden breakthrough can never be ruled out (and several recent breakthrough candidates for quantum computing are listed in this report), but we estimate it remains unlikely relative to the 2030 time horizon. Moreover, the comparison with generative AI is inappropriate for two reasons:

- First, quantum computing is bottle-necked primarily by hardware innovations, which reduces the chance that a black-swan breakthrough will occur with both little warning and then expand rapidly. Generative AI was primarily a software/statistical breakthrough applied on top of existing data and compute resources (albeit very large volumes of both). Software-based solutions can scale and spread extremely quickly. Hardware tends to improve more incrementally and build out more gradually, as seen in the multi-year quantum computing roadmaps discussed in 2.4.

- Second, the 'sudden appearance' of generative AI was not as sudden as it might appear based solely on the explosion of interest that followed the ChatGPT public launch in November 2022. The underlying LLM technology at the same level of quality had already been released in May 2020 (GPT-3), based on a theoretical architecture described by Google researchers in 2017[16]. While public hype accelerated in 2023, hype regarding transformer technologies for next word prediction was already present since 2020 within certain ML and software engineering communities. More generally, other AI applications based on supervised and unsupervised machine learning had secured significant commercial success already in the early 2010s (e.g. CNNs for image recognition following AlexNet's 2012 success; RNNs for speech recognition in Apple's Siri and Amazon's Alexa; diverse Random Forest and XGBoost applications on tabular data, e.g. retail, banking).

We estimate that it remains very likely that large-scale quantum computers will not be commercially available at scale by 2030, locking up the majority of breakthrough application use cases.

Near-term application use cases

Application use cases in the near-term are largely focused at the high-cost, high-quality frontier of a use case served by an existing technology. The national quantum missions from the UK in December 2023[17] are illustrative of what can be achieved by the late 2020s:

- In quantum biotechnology, they target quantum-enabled brain scanners by 2028 for precision-guided surgery for children suffering severe neurological disease to improve recovery and outcomes, leading later to better research. By 2030, new quantum imaging technologies for breast cancer detection are to be in use across hospitals in the UK, significantly reducing the need for unnecessary chemotherapy.
- In quantum metrology, they target quantum navigation systems, including clocks, to be deployed on aircraft by 2030, providing next-generation accuracy for resilience that is independent of satellite signals. There are also ambitions for quantum-enabled gas sensors to accurately see and measure emissions of greenhouse and other gases.

Quantum computing hardware manufacturer D-Wave's leading edge customers as of 2024[18] also give an indication as to the use cases that will gradually become more prevalent in the coming few years, reinforcing our conclusion:

- An ecommerce auto delivery driver scheduling application, now in use at Pattison Food Group, after standard ERP solutions struggled to solve the problem of designing workforce schedules in an earlier project that was interrupted by Covid-19. The solution still requires

16 https://arxiv.org/pdf/1706.03762

17 https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

18 https://www.hpcwire.com/2024/01/30/eyes-on-the-quantum-prize-d-wave-says-its-time-is-now/

significant time investment and it is unclear how different it would be to a dedicated heuristic workflow implemented on classical computers.

- Financial portfolio optimisation in proof of concept collaborations with two major European banks, BBVA and Bankia.[19] For the largest dataset, only D-Wave's hybrid solver service and Tensor Network's classical systems could deliver solutions. The D-Wave approach took about 3 minutes while Tensor Networks took more than a day, with both producing high quality results as measured by Sharpe Ratio, a common risk-reward assessment ratio used in finance (note, however, that the classical solution performed better than the hybrid solution).
- Other examples include Davidson Technologies (radar scheduling); IPG (tour scheduling); Vinci Energies (HVAC design).
- The standard pricing for proof of concept is about $350,000 from D-Wave, although initial demonstrations (non-live) might be nearer to $70,000.

These examples and others represent premium incremental improvements for those with the highest budgets, primarily of interest only to those who are already making extensive use of computing technology to address their problems and who can anticipate significant absolute gains from small improvements at the margin.

For lower and middle income countries (LMICs), these quantum use cases are poorly suited to be high priority for national level policies in the short-term. For instance, if seeking to improve healthcare outcomes or manufacturing quality, there are other tried-and-tested methods available at lower cost to implement first. There is more reliable ROI in being a fast follower than in trying to pick a winner at the R&D frontier. If a corporate use case proves compelling in high income countries, it will likely move to lower income countries once the commercial circumstances are present.

Quantum computing itself is highly likely to be available via the cloud – following the current commercialisation track of Azure Quantum, IBM Q Experience, Google Quantum AI, Xanadu, Rigetti's Forest, Amazon's BraKet, Quantinuum, and others - ensuring that non-host countries can gain the benefits of quantum algorithms without risking the R&D investment in the unpredictable results of hardware. Although this shifts the investment case away from LMICs, there remain important factors around quantum readiness which are relevant to all countries at all levels of income – addressed later in this report.

What remains of the eight strands? One helpful approach is identifying what can be done with today's quantum technology for the most advanced users, which might become more widespread and more relevant by 2030 for ITCILO's high-impact audience of policy officials in lower and middle income countries (LMICs). The answer lies primarily in quantum annealing, other analogue computing technologies, classical-quantum hybrid algorithms, and quantum logic gate algorithms that can run on modest quantum computer stacks (e.g. a few tens up to

[19] https://www.dwavesys.com/media/5qahck2o/multiverse_case_study_v8.pdf

around 100/150 logical qubits, noting that learning sector applications are likely to be a few years behind applications in sectors like finance, logistics, and e-commerce).[20]

This reasoning results in quantum AI/ML algorithms being the top priority from our assessment for an ITCILO perspective. Focusing on that application keeps open the possibility that some short-term use cases of those algorithms might open up restricted versions of ambitions in other application layer technologies. For instance, by 2030 we are highly unlikely to simulate a whole economy with a quantum computer, run adaptive learning using all data about a student, or build a global climate change model, but it is possible there might be benefits in simulating specific markets during specific transitions, running a one-off optimisation process for an adaptive learning platform (e.g. to set a default), or modelling one particular aspect of the climate system. Even so, we remain several breakthroughs away from these partial applications, given progress needed in logical qubit scale, data encoding, algorithm design, and use case readiness among potential users.

One further consideration is niche use cases across the other strands, particularly where quantum technology provides a breakthrough capability that is simply unavailable via classical techniques. In other words, not merely an incremental improvement at the high-cost, high-quality frontier, but something sufficiently new and sufficiently impactful that it merits investment. One possibility highlighted from the ITCILO-attended conference is a quantum sensor solution that enhances our ability to detect valuable resources under the ground without needing to dig (such as LANDTEM, an Australian technology developed by CSIRO featured in Australia's 2023 government strategy for quantum).[21] However, such use cases are likely to be niche from ITCILO's perspective – they are not prominent in the literature we have reviewed to date – and would not have a direct capacity development link beyond supporting that industry. The more robust solution at a policy level is to develop capacity in quantum readiness in general, to ensure awareness of opportunities as they become available.

The Part II assessment suggests **two main activities for Part III**, prioritising insights that will support ITCILO decision-making and engagement during 2025 and 2026. First, **exploration of current and near-term quantum AI/ML algorithm capabilities** in the context of ITCILO use cases. Second, **exploration of possible 'quantum readiness' related capacity development provision**.

[20] Indeed, McKinsey market analysis focuses on chemicals, life sciences, finance and mobility, with no detailed discussion of technologies for education and training outside of teaching quantum mechanics itself. Those four sectors were considered "most likely to realize this [quantum computing] value earlier than other industries" in McKinsey's analysis of market potential by 2040. https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing

[21] Related examples follow. The RSK Gravity Pioneer project was able to identify underground tunnels in Birmingham by sensing tiny variations in gravity; https://rskgroup.com/news/gravity-pioneer-hailed-in-national-quantum-strategy/ (Mar 2023). QLM's quantum gas imaging lidar to identify greenhouse gas emissions; https://committees.parliament.uk/writtenevidence/120721/pdf/ (Apr 2023). SBQuantum and Silicon Microgravity are developing a combined magnetic and gravity sensing technology to enhance surveying for mineral deposits, https://www.mining-technology.com/features/startups-accelerate-exploration-drone-borne-quantum-sensors/ (Jun 2024).

2.2. Quantum technology assessment method

The definitions of eight quantum technology strands and example use cases are derived from the taxonomies reviewed in Part I and the roadmaps listed in Appendices 3-4. The results are provided in table 4 overleaf.

The prioritisation framework for the eight strands is based on five indicators across two topics:

Application readiness by 2030	Maturity roadmaps	Driven primarily by quantitative data on specific timelines anticipated for different technologies as assessed in government strategies, sector roadmaps, and academic, industry, and consultant analyses, incorporating accuracy of past predictions and current context
	R&D momentum	Driven primarily by quantitative analysis, using a high-level, indicative keyword search on Scopus: Number & growth of patents: 2000+, 2019-21; 2022-24 Number & growth of academic papers: 2000+, 2019-21; 2022-24
ITCILO relevance by 2030	Global gravity	Driven by quantitative estimates of forecast 2030 market size from market studies (where available), as well as qualitative assessment of the impact on society, particularly job losses or job disruption, job creation, and the quantity/quality of work
	The 'What' of TLCD (training, learning & capacity development)	Based primarily on content relevant to sectors with broad global inequality, decent work, sustainable development, or social justice considerations for lower/middle income countries, i.e. likely to be important inputs/angles for ITCILO initiatives*
	The 'How' of TLCD	i.e. technology used to enhance the design and/or delivery of learning/training Based primarily on use case assessment of government strategies, sector roadmaps, and academic, industry, and consultant analyses.

* Note we exclude content which is primarily about training scientists working in those fields, because that is equally applicable to all research topics and is not the primary target audience for ITCILO's development work. Understanding the scientific context for a technology is nonetheless an important element of certain training programmes for policy officials or senior leaders and would be in-scope.

2.3. Quantum strands – summary & definitions

TABLE 4. QUANTUM STRANDS – SUMMARY & DEFINITION

Quantum strand (home domain)	Overview*
Quantum Computing Hardware (under Compute)	**Definition**: The physical systems that enable quantum computing, exploiting quantum mechanical properties like superposition and entanglement to process information. **Importance**: Such hardware can implement algorithms to solve problems practically impossible for classical computers, with major potential in fields across, e.g., cryptography, material science, data management (e.g. Grover's Algorithm), and AI. **E.g.** Superconducting qubits; Ion trap qubits; Topological qubits and quantum error correction techniques; Single photon devices
Quantum Materials (under Materials)	**Definition**: Advanced materials manufactured and manipulated to exhibit quantum mechanical properties, often underpinned by quantum chemistry theory. **Importance**: Quantum materials could unlock new technologies in computing, communication, and energy storage by utilising unique properties such as superconductivity and topological effects. **E.g.** Topological insulators; Superconducting materials; Quantum dots for imaging and sensing applications; Quantum cryostatics; Quantum wells
Quantum Networking (under Connectivity)	**Definition**: The physical infrastructure that enables communication exploiting quantum mechanical properties. **Importance**: Certain high-impact quantum cryptography and data transfer protocols will require a quantum-capable physical infrastructure. **E.g.** Quantum optics/lasers; Low loss photon transmission channels; Quantum repeaters/routers/nodes
Quantum AI/ML Algorithms (under AI/ML)	**Definition**: Quantum algorithms which are designed to enhance machine learning models, artificial intelligence, and optimisation processes, often developed in specialised programming frameworks (e.g., Qiskit; Cirq). **Importance**: Potential to enable faster and more accurate problem-solving across various domains, including solutions to problems beyond the reach of current or anticipated next generation digital computer architectures. **E.g.** Quantum-enhanced optimisation algorithms for supply chain/finance, incl. quantum annealing; QML for pattern recognition; classical-quantum hybrid ML algorithms
Quantum Cryptography (under Cybersecurity)	**Definition**: The application of quantum mechanical principles to secure communication systems, leveraging phenomena like entanglement for highly secure networks where eavesdropping attempts can be detected. **Importance**: Potential to revolutionise cybersecurity with virtually unbreakable encryption systems, safeguarding data from future threats posed by quantum computers (e.g. Shor's algorithm threat to RSA and online commerce). **E.g.** Quantum key distribution (QKD, e.g. BB84; E91); Quantum-secured communication channels
Quantum Metrology (under Sensors & IoT)	**Definition**: Quantum-based sensors and measurement technologies that offer extreme precision. **Importance**: The potential for unprecedented sensitivity and accuracy, enabling advancements in medical diagnostics, geophysics, and precision navigation. Sometimes, quantum sensors can also bring 'form factor' benefits that provide decisive benefits over classical sensors, such as sensors small enough to use on an aircraft or in a neurotech wearables, even where any differences in sensitivity/accuracy are not essential to a given use case. Quantum sensors may also be able to meet privacy needs, such that individual data remain private even while averaged data become available to serve a given use case. **E.g.** Quantum-enhanced gyroscopes and accelerometers; Quantum metrology for precision measurements (incl. quantum lasers/optics); Quantum radar and imaging technologies

Quantum strand (home domain)	Overview*
Quantum Biotech (under Biotechnology)	**Definition**: The intersection of quantum technology and biotechnology, using quantum principles to advance medical imaging, diagnostics, genomics, gene editing, and drug discovery. **Importance**: Quantum biotech has the potential to accelerate breakthroughs in medicine, particularly in molecular-level imaging, diagnostics, and personalized treatments. **E.g.** Quantum-enhanced bioimaging; Quantum simulations for protein folding; Quantum-based diagnostics for personalized medicine
Quantum Simulation (under Simulation)	**Definition**: Quantum simulations and digital twins leverage quantum computing to simulate complex systems. **Importance**: Quantum simulations can model complex physical systems that are impossible for classical computers, enabling deeper insights into fields such as drug discovery and materials design. There may be potential in other areas of abstract modelling, such as simulating an economy or a climate, although these remain a less natural, less clearly demonstrated area of quantum advantage relative to simulating quantum systems themselves. **E.g.** Quantum-enhanced molecular dynamics simulations; Simulations for drug discovery and biological research; Advanced simulations for quantum materials and chemical reactions

Note. Quantum mechanical theory applied as an input into non-quantum technologies is out of scope for table 4 (see also appendix 2). For instance, quantum theory is important for transistor miniaturisation and improving photovoltaic cells, but these key technologies are catalogued separately. The same applies when quantum-empowered technology (e.g. quantum lasers) already listed enables precision manufacturing which might have benefits for a wide range of other technologies.

2.4. Timeline assessment of quantum computing capabilities

The analysis in the revised taxonomy and in table 4 clarifies that quantum computing capabilities are the key infrastructural unlock for many important applications, with the main exceptions being certain strands underneath quantum metrology and biotechnology. As a result, the first topic for timeline assessment is quantum computing capabilities.

The different technologies for producing quantum computers vary widely by the type of physical mechanisms they exploit and the scale they would likely need to be effective. At this stage, there is no consensus about which route is most likely to succeed (or to succeed first) and a wide range are being actively explored by R&D teams. It is not guaranteed that any method will successfully scale to cost-effective competition against classical computers, although the industry widely assumes this will be achieved at some uncertain point.

A rapid synthesis of common claims is provided below, acknowledging that there are disagreements in many areas, particularly among those invested in certain technologies. We focus first on gated or logic-gate based quantum computing, representing the digital technology that enables universal quantum programming and unlocks the most powerful use cases.

Number of logical qubits needed for commercial applications

- Quantum computers are well suited to simulating quantum systems, such as molecules or material properties. Quantum advantage is achievable with relatively modest systems, such as a few tens to a few thousand of logical qubits, depending on the set-up.[22] The low end is within reach of current technology and being used to support incremental R&D, primarily where physical qubits are sufficient due to their natural fidelity to the system being modelled.
- However, for broader optimisation problems or simulations of non-quantum systems – the most relevant use cases for broad commercial and policy impact – estimates typically require a few thousand logical qubits[23] (e.g. for logistics optimisation at scale or sophisticated materials design) or a few tens of thousand (e.g. for simulating a city economy or parts of a global climate model, or for breaking 2,048-bit RSA encryption[24]).
- Nonetheless, algorithmic advances can occur that reduce the scale needed for useful operations by several multiples. For instance, in 2019 Google researchers identified a 100x improvement in integer factorisation.[25] However, claims of rapid improvements are also

[22] https://nanoconvergencejournal.springeropen.com/articles/10.1186/s40580-024-00418-5

[23] E.g. Microsoft reported an estimate of 1m qubits in 2022, referring to physical qubits with an approximate 1:1000 conversion rate to logical qubits. See also above footnote. https://news.microsoft.com/source/features/innovation/azure-quantum-majorana-topological-qubit/

[24] 20 million noisy qubits estimated in https://arxiv.org/abs/1905.09749

[25] https://arxiv.org/abs/1905.09749

often debunked, such as a recent claim from Chinese researchers of RSA vulnerability with only 372 qubits.[26]

How many physical qubits are required for logical qubits

- Estimates vary depending on the technology, from 1000s:1 for high maturity methods and 10s:1 for experimental concept methods.
- 1000s:1. High maturity methods, i.e. where the majority of recent R&D has focused, typically require 1000+ physical qubits to create one logical qubit, although for applications that tolerate higher levels of error this can reduce to 10s or 100s (most applications cannot have very low error tolerance[27]). This includes using superconducting circuits, trapped ions, or spin qubits as qubits.
- 100s:1. Methods such as photonic qubits or neutral atom qubits can achieve higher quality ranges.[28] For instance, trapping neutral atoms and manipulating them via laser fields is potentially more robust to certain error types. These are not as mature as the superconducting circuit quantum computer methods.
- 10s:1 or less. Topological qubits[29] [30] use topological states of matter to create qubits that are inherently protected from certain types of error, potentially supporting a near 1:1 relationship for certain types of logical qubits. This is a newer route, still being explored conceptually and in small scale lab experiments.
- Nonetheless, rapid breakthrough are claimed and can occur, opening up the possibility of a rapid improvement in existing approaches. For instance, novel approaches using trapped ions were found in 2024 which might lower error correction rates 100x to 10s:1[31], along with progress in 2023/24 on cat qubits[32]. It is yet to be known whether these novel approaches will scale and apply to commercially relevant applications.
- Roadmap projections typically assume breakthroughs of one type or another, even if they cannot yet specify which breakthrough will drive the progress.

Current scale

- Operational quantum computers that operate in terms of fault-corrected logical qubits remain very small.

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[26] https://arstechnica.com/information-technology/2023/01/fear-not-rsa-encryption-wont-fall-to-quantum-computing-anytime-soon/

[27] https://spectrum.ieee.org/fault-tolerant-quantum-computing

[28] https://arxiv.org/abs/2006.12326

[29] https://news.microsoft.com/source/features/innovation/azure-quantum-majorana-topological-qubit/

[30] E.g. https://spectrum.ieee.org/microsoft-quantum-computer-quantinuum

[31] E.g., this trapped ion approach from 2024: https://spectrum.ieee.org/microsoft-quantum-computer-quantinuum

[32] https://alice-bob.com/blog/concept-cats-designing-better-qubits/ Cat qubits are superconducting qubits that offer an unequal trade off in bit flip and phase flip error rates. Whereas superconducting qubits normally experience both bit flip and phase flip errors at high rates, cat qubits trade off an exponential decrease in bit flip error rates and a linear increase in phase flip error rates. The significant benefit to bit flip error rates is perceived as justifying the modest penalty in phase flip error rates. More background at https://www.quera.com/glossary/cat-qubits

- For instance, in November 2024 Atom Computing and Microsoft claimed a world record (in terms of public, commercial availability) with 24 entangled logical qubits and error detection, correction, and computation with 28 logical qubits, using a neutral atom mechanism.[33]
- In September 2024, Microsoft and Quantinuum reported entangling 12 logical qubits with the highest fidelity ever recorded.[34]
- In December 2023, NIST researchers generated 48 logical qubits.[35]
- National security considerations result in uncertainty surrounding possible government-funded achievements in China and the US, although the scale of commercial funding from organisations like Google and Microsoft and the prestige available in academic institutions continues to support the likelihood that public commercial/academic activity remains at or near the frontier.
- In terms of physical qubits in a gated system, frontier quantum computers are typically at around 1000 qubits, with many being a few hundred or less. For instance, IBM Condor was unveiled in December 2023 with 1,121 qubits, but most machines in IBM or the Chinese Academy of Sciences have a few hundred.[36]

Example roadmap projections (see Appendix 4 for sample roadmaps)

- Several companies project 10,000 physical qubits by 2030.[37] IBM anticipate its Kookaburra quantum processor to have 4,158+ physical qubits by 2025, with plans for 150-200 logical qubits by the late 2020s. "1000s of logical qubits" is not anticipated until 2033+.[38]
- Quantinuum's latest Sept 2024 roadmap likely anticipates only 100s of logical qubits by 2029[39] (Quantinuum are partnered with Microsoft, whose primary progress comes through their partners Quantinuum and Atom Computing[40]).
- In January 2024, D-Wave described the gate model system as being at least seven years away from solving a real world problem. While D-Wave are primarily invested in a competing technology (analogue quantum computing), they also invest in gate technologies.

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33 https://azure.microsoft.com/en-us/blog/quantum/2024/11/19/microsoft-and-atom-computing-offer-a-commercial-quantum-machine-with-the-largest-number-of-entangled-logical-qubits-on-record/

34 https://thequantuminsider.com/2024/09/10/microsoft-led-team-achieves-record-for-reliable-logical-qubits-in-quantum-computing/

35 https://www.nist.gov/news-events/news/2023/12/nist-researchers-help-design-prototype-quantum-computer

36 https://en.wikipedia.org/wiki/List_of_quantum_processors

37 https://www.hpcwire.com/2024/04/15/crossing-the-quantum-threshold-the-path-to-10000-qubits/

38 https://www.ibm.com/quantum/blog/ibm-quantum-roadmap-2025; https://thequantuminsider.com/2024/10/12/ibm-quantum-roadmap-guide-scaling-and-expanding-the-usefulness-of-quantum-computing/

39 https://www.quantinuum.com/press-releases/quantinuum-unveils-accelerated-roadmap-to-achieve-universal-fault-tolerant-quantum-computing-by-2030

40 https://blogs.microsoft.com/blog/2024/09/10/microsoft-announces-the-best-performing-logical-qubits-on-record-and-will-provide-priority-access-to-reliable-quantum-hardware-in-azure-quantum/

- The UK Quantum Missions, announced in Dec 2023, reserve quantum advantage at scale until 2035, although benefits for simulating chemical processes and improving catalyst design are targeted for the late 2020s.[41]
- Google's undated roadmap builds from a relatively low base of 54 physical qubits and 1 error-corrected logical qubit as of 2023.[42]
- QuEra explains that "Most quantum computing prototypes today are small and susceptible to errors with little evidence for broad business advantage. Utility-scale gate-based quantum computers with millions of qubits are 5-10 years away."[43]

In line with the data presented here, one analyst estimates that the earliest commercial quantum applications will need several million qubits, first within reach around 2035-2040, assuming an exponential growth similar to Moore's Law.[44] We also note the history of over-optimism in quantum computing. For instance, "quantum computing has been on Gartner's list of emerging technologies 11 times between 2000 and 2017, each time listed in the earliest stage in the hype cycle, and each time with the categorization that commercialization is more than 10 years away".[45] It is notable that quantum computing is once again absent from this year's hype cycle release. In general, **we interpret these roadmap projections, particularly from commercial providers, as more likely to be over-optimistic than under-optimistic**.

With respect to the ITCILO project, we interpret the above analysis as suggesting broad-based commercially relevant quantum computing via gated computers (beyond what can be achieved with classical computers) will not be relevant until the 2030s at the earliest and likely 2035+, in the absence of a black swan breakthrough.

Alternatives to universal quantum programming computing

There are alternatives to gate-based quantum computing that offer near-term routes to viability, including some applications that are already used today: analogue and hybrid quantum computing. Proofs of concept may become viable on gated computers with a few tens of logical qubits and potentially up to 100 (or on high error systems with a few thousand physical qubits), i.e. techniques that are viable in the so-called noisy intermediate-scale quantum (NISQ) era which is likely to persist at least until 2030.[46]

Analogue quantum computing involves establishing a physical quantum system whose natural physical evolution happens to map to the algorithm you wish to solve. This greatly restricts the space of feasible algorithms relative to a universal quantum computer and requires significant

[41] https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

[42] https://quantumai.google/roadmap

[43] https://www.quera.com/our-quantum-roadmap

[44] https://quantumcomputingforbusiness.com/essentials/timelines/

[45] National Academies of Sciences, Engineering, and Medicine. 2019. Quantum Computing: Progress and Prospects. Washington, DC: The National Academies Press. https://doi.org/10.17226/25196. https://nap.nationalacademies.org/read/25196/chapter/9

[46] https://quantum-journal.org/papers/q-2018-08-06-79/

effort to map the problem and initialise the state. However, where it is possible, the problems can be solved quickly and efficiently, using technology available today.

The key commercial technique available today is quantum annealing, with gradual energy minimisation using quantum tunnelling (e.g. the D-Wave machines, with a few thousand qubits, such as D-Wave Advantage with 5,760[47]). Effectively, this restricts use cases to discrete optimisation problems that can be mapped to a few mathematical problem structures, such as travelling salesman set-ups which can be applied to financial portfolio management, logistics scheduling, or inventory / telecom network / power grid management, among others. Prototypes also exist of other analogue quantum mechanisms, such as coherent Ising machines (optical parametric oscillators) to support combinatorial optimisation (e.g. max-cut) and direct quantum simulation of a small quantum system (such as an individual molecule).

Other examples at the theoretical or early experimental stage include adiabatic computing (adiabatic evolution of Hamiltonians) which theoretically has broader simulation/optimisation potential than annealing and quantum reservoir computing for pattern recognition or time-series prediction. While these techniques are theoretically powerful, it is hard to motivate their usage outside of cases where current classical computing capabilities are not already used to achieve similar benefits.

Hybrid classical-quantum computing is also a near-term viable technology for restricted use cases, with Azure Quantum from Microsoft an example commercial access provider[48]. Essentially, the quantum computer is used for a certain, challenging component of a calculation, with the classical computer handling everything else. As Microsoft describes it in 2024: "With hybrid quantum computing, the classical and quantum architectures are tightly coupled, allowing classical computations to be performed while physical qubits are coherent. Though limited by qubit life and error correction, this allows for quantum programs to move away from just circuits. Programs can now use common programming constructs to perform mid-circuit measurements, optimize and reuse qubits, and adapt in real-time to the QPU. Examples of scenarios that can take advantage of this model are adaptive phase estimation and machine learning."

Example techniques include Variational Quantum Eigensolvers (VQE)[49] and Quantum Approximate Optimization Algorithms (QAOA)[50]. QAOA focuses on classical optimisation tasks with discrete solutions (max-cut, scheduling), whereas VQE is designed for quantum systems requiring energy minimisation and continuous solutions (chemistry, physics), modelling complex wavefunctions in polynomial time. QAOA alternates between a mixing operator and a phase operator to approximate the solution to the problem (the quantum component) with the classical component optimising parameters of the quantum circuit to find the best approximation for the classical objective function. VQE uses a parameterised quantum circuit to

47 https://arxiv.org/abs/2003.00133

48 https://learn.microsoft.com/en-us/azure/quantum/hybrid-computing-overview

49 https://arxiv.org/abs/2111.05176

50 https://ieeexplore.ieee.org/document/8939749

approximate the ground state wavefunction of the Hamiltonian (quantum component), with the classical component optimising parameters of the ansatz (trial wavefunction) to minimise the expected energy of the quantum Hamiltonian. In practice, quantum annealing applications and other analogue approaches typically require preparation and analysis on classical computing infrastructures. Quantum-assisted machine learning (e.g. for big data ML) and hybrid quantum-classical neural networks (e.g. for feature extraction, anomaly detection) are also progressing through early R&D stages.

Cost-effective commercial applications remain unclear, at least based on our research to date. Multiple breakthroughs are likely to be needed before quantum machine learning has a significant commercial impact. First, the number of useable logical qubits needs to increase by several orders of magnitude. Second, given the large volumes of data necessary to unlock the benefits of machine learning, data encoding techniques need to improve by several orders of magnitude, potentially exploiting amplitude encoding techniques. Third, the algorithms involved need to be mapped explicitly to business process workflows, datasets, and optimisation targets that relate to specific use cases, likely requiring further algorithm design progress as well.

2.5. Encryption technologies and the quantum Internet

Analogue quantum computing does not produce universal quantum computers and cannot run general quantum algorithms like Shor's or Grover's. As a result, it poses little threat to current encryption technologies, although algorithmic techniques continue to develop and we cannot be certain what capacities will be available in the future (e.g., recent progress from Chinese researchers using an adiabatic quantum algorithm[51]). In principle, adiabatic computation can simulate a quantum Turing machine with a polynomial increase in time, but this is not anticipated to be implementable for practical solutions before gated quantum computing achieves similar capabilities (translating Shor's algorithm into a suitable Hamiltonian for a given encryption is impractical, particularly given noise levels during the NISQ eta).[52]

The threat to current encryption from quantum technologies is therefore minimal over the next five years, based on the same analysis of gated quantum computers as above. For instance, current e-commerce relies on RSA (typically 2048[53] or 4096 bit) and elliptic curve cryptography, which would only become vulnerable from the mid 2030s by ambitious forecasts (1000s of logical qubits, likely 10,000+[54]). Even then, this assumes the technology can manage sufficiently close to real-time decryption to meaningfully disrupt e-commerce. It also assumes that other encryption technologies securing major investment have all failed, notably the post-quantum

51 https://onlinelibrary.wiley.com/doi/full/10.1002/que2.59

52 https://arxiv.org/abs/quant-ph/0405098v2

53 Note that the US is moving towards sunsetting RSA 2048. For instance, in Nov 2024, NIST proposed deprecating key RSA and elliptic curve techniques from 2030, disallowing them from 2035. https://csrc.nist.gov/pubs/ir/8547/ipd

54 https://alice-bob.com/blog/quantum-computers-could-be-60-times-smaller/

cryptography techniques such as lattice-based, hash-based, and code-based cryptography (see progress from NIST announced Aug 2024[55]).

It is also noteworthy that other encryption techniques are less vulnerable to quantum computing given currently known algorithms. For instance, AES and SHA algorithms can be weakened by Grover's Algorithm, but still remain out of reach from quantum computers, especially under an upgrade from AES-128 to AES-256. However, AES or SHA do not provide public-key exchange, so could not directly replace RSA/ECC in the current e-commerce infrastructure. AES/SHA would require a shared secret key, which might need to be transmitted physically (for a different type of security) or via a digital method that can be confirmed as secure. AES/SHA and related technologies provide the potential for reducing the pressure on RSA/ECC, enabling fewer, higher-bit keys to be used less often. Given the huge value of e-commerce, if quantum decryption were to pose a serious threat, there are multiple alternatives which would compete commercially with a fully upgraded quantum internet with quantum encryption. Despite much excitement about quantum internet, it is not guaranteed to be commercially necessary even if quantum computers progress at their aspirational rates. It may progress more rapidly than suggested by this analysis, given the near-term tractability of the technology (medium-scale networks already exist in China and are being built in Europe) and the potential for cultural desire for progress or an abundance of caution around encryption threats.

Quantum encryption does provide a breakthrough use case benefit that goes beyond simply safeguarding existing encryption use cases. With quantum encryption, it is possible to build in systems that guarantee the identification of an attempted eavesdrop. However, this use case is likely of value only in a national security context, with guaranteed privacy sufficient for commercial applications.

2.6. Relevance assessment of claimed application use cases

A key consideration is that use cases can be understood relative to current engagement with quantum predecessor technology. For instance, if a particular sector is not already using existing technology and machine learning to secure the kinds of benefits that quantum techniques are supposed to enhance, almost always at a higher cost-higher quality frontier, then it is unlikely in most cases that they would start doing so with quantum technology, at least with the kinds of technologies anticipated by 2030. There will be occasional exception for niche cases, edge cases, and a motivation for generating attention and PR via exciting loss-making case studies, but these are unlikely to generate large-scale industrial or policy change.

The key exception is where quantum technologies provide a breakthrough impact – something that was simply not possible before – which results in a dramatic improvement in impact-per-cost. Such cases are estimated to remain rare by 2030, barring unanticipated breakthrough which are likely best addressed today via broad-based 'quantum readiness' capacity

[55] https://www.nist.gov/news-events/news/2024/08/nist-releases-first-3-finalized-post-quantum-encryption-standards

development and systematic awareness building initiatives. The focus on already anticipated technology and use cases is also reasonable, because anything else moves into the realm of speculation and novel areas that are not currently anticipated would be unlikely to have commercial relevance in just 5 years.

Application use cases in the near-term are largely focused at the high-cost, high-quality frontier of a use case served by an existing technology. The national quantum missions from the UK in December 2023[56] are illustrative of what can be achieved by the late 2020s:

- In quantum biotechnology, they target quantum-enabled brain scanners by 2028 for precision-guided surgery for children suffering severe neurological disease to improve recovery and outcomes, leading later to better research. By 2030, new quantum imaging technologies for breast cancer detection are to be in use across hospitals in the UK, significantly reducing the need for unnecessary chemotherapy.
- In quantum metrology, they target quantum navigation systems, including clocks, to be deployed on aircraft by 2030, providing next-generation accuracy for resilience that is independent of satellite signals. There are also ambitions for quantum-enabled gas sensors to accurately see and measure emissions of greenhouse and other gases.

Quantum computing hardware manufacturer D-Wave's leading edge customers as of 2024[57] also give an indication as to the use cases that will gradually become more prevalent in the coming few years, reinforcing our conclusion:

- An ecommerce auto delivery driver scheduling application, now in use at Pattison Food Group, after standard ERP solutions struggled to solve the problem of designing workforce schedules in an earlier project that was interrupted by Covid-19. The solution still requires significant time investment and it is unclear how different it would be to a similarly dedicated workflow implemented on classical computers.
- Financial portfolio optimisation in proof of concept collaborations with two major European banks, BBVA and Bankia.[58] For the largest dataset, only D-Wave's hybrid solver service and Tensor Network's classical systems could deliver solutions. The D-Wave approach took about 3 minutes while Tensor Networks took more than a day, with both producing high quality results as measured by Sharpe Ratio, a common risk-reward assessment ratio used in finance (note, however, that the classical solution performed better than the hybrid solution).
- Other examples include Davidson Technologies (radar scheduling); IPG (tour scheduling); Vinci Energies (HVAC design).
- The standard pricing for proof of concept is about $350,000 from D-Wave, although initial demonstrations (non-live) might be nearer to $70,000.

56 https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

57 https://www.hpcwire.com/2024/01/30/eyes-on-the-quantum-prize-d-wave-says-its-time-is-now/

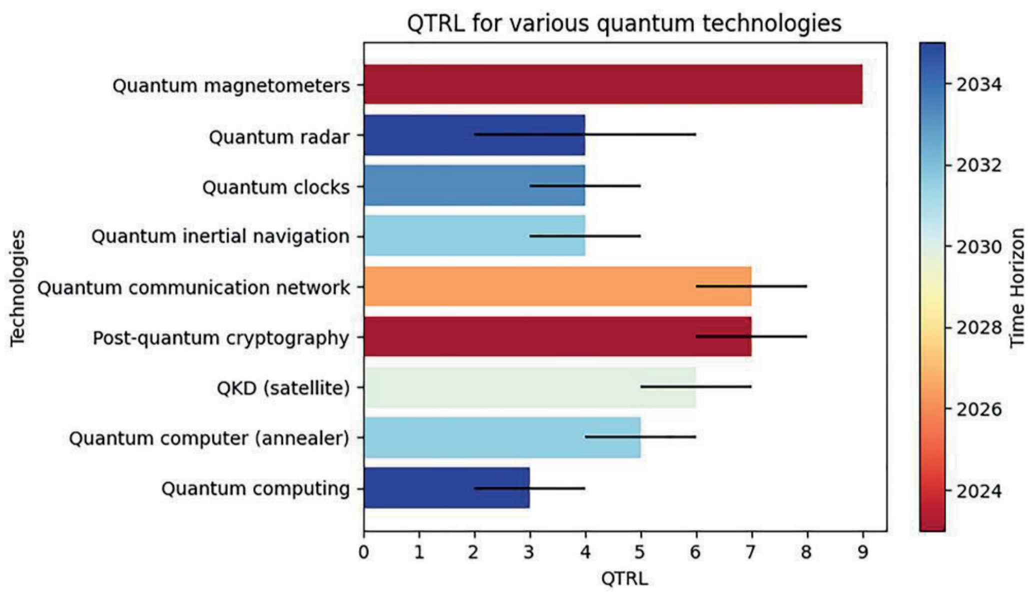
58 https://www.dwavesys.com/media/5qahck2o/multiverse_case_study_v8.pdf

These examples and others represent premium incremental improvements for those with the highest budgets, primarily of interest only to those who are already making extensive use of computing technology to address their problems and who can anticipate significant absolute gains from small improvements at the margin.

For lower and middle income countries (LMICs), these quantum use cases are poorly suited to be high priority for national level policies in the short-term. For instance, if seeking to improve healthcare outcomes or manufacturing quality, there are other tried-and-tested methods available at lower cost to implement first. There is more reliable ROI in being a fast follower than in trying to pick a winner at the R&D frontier. If a corporate use case proves compelling in high income countries, it will likely move to lower income countries once the commercial circumstances are present. Quantum computing itself is highly likely to be available via the cloud – following the current commercialisation track of Azure Quantum, IBM Q Experience, Google Quantum AI, Xanadu, Rigetti's Forest, Amazon's BraKet, Quantinuum, and others - ensuring that non-host countries can gain the benefits of quantum algorithms without risking the R&D investment in the unpredictable results of hardware.

2.7. Cross-strand timeline assessment

Our timeline assessment is based on roadmaps and use case discussions across our reports. There are relatively few cases where a single analysis provides timeline assessment across multiple strands, but we have weighted such cases highly where available (if recent), particularly where they use the standardised framework of Quantum Technology Readiness Levels (QTRL). One example is fig. 5 from Purohit et al. (2023), reproduced in full below[59]:



[59] https://doi.org/10.1049/qtc2.12072

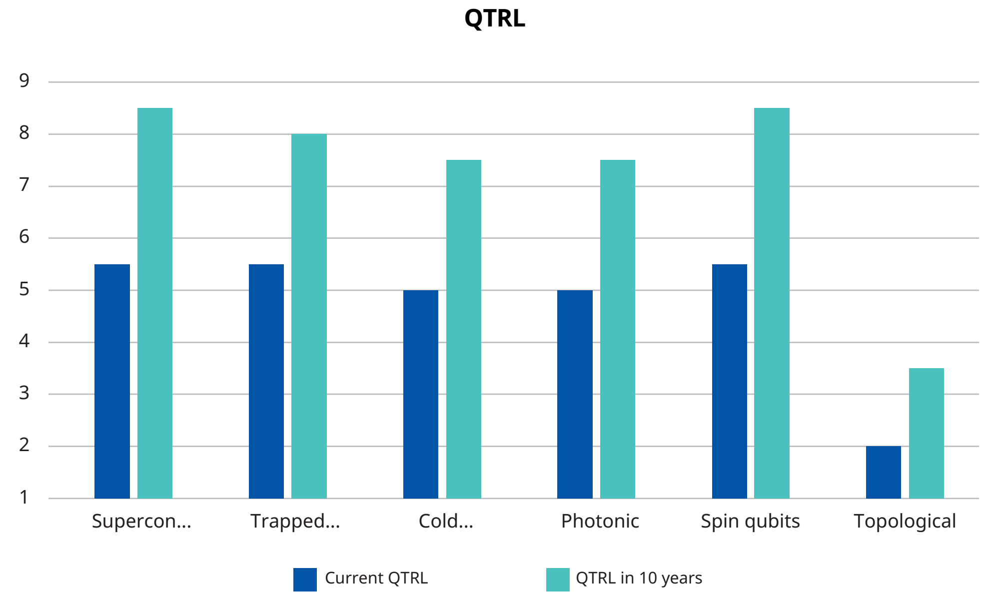
Environment	Goal	Product / Evaluation	Outputs	QTRL	Description
Laboratory	Research	Proof of concept	Research articles published on the fundamental principles of the quantum technology	QTRL 1	Basic principles observed
			Development of specific quantum technology or application based on fundamental principles	QTRL 2	Technology concept/applicatio n formulated
			Laboratory experiments and simulations to provide experimental evidence and potential advantages over classical counterpart.	QTRL 3	Analytical and Experimental proof of concept
		Prototype	Laboratory testing and integration of quantum components into larger system	QTRL 4	Quantum Technology validated in lab
Simulation	Development		Quantum technology's performance in environments that closely resemble real-world applications	QTRL 5	Quantum Technology validated in a relevant environment
			Demonstration of a functional prototype in a relevant environment	QTRL 6	Quantum Technology demonstrated in relevant environment
Operational	Implementation		Fully integrated, functional prototype level tests carried out in the operating environment	QTRL 7	Prototype demonstration in operational environment
		Commercial product/service (certified)	Rigorous testings in final configuration. Ethics and protocols taken into consideration	QTRL 8	System complete and qualified
		Deployment	Successfully deployed and used in real-world applications	QTRL 9	Successful project operations

Within a quantum computing context, a December 2023 report[60] assessed the QTRL of various methods, concluding that none of them have yet reached the level of solving small but user-relevant problems in a prototype format (QTRL-7 in their quantum computing interpretation of the overall QTRL framework). Their assessment grid is reproduced below:

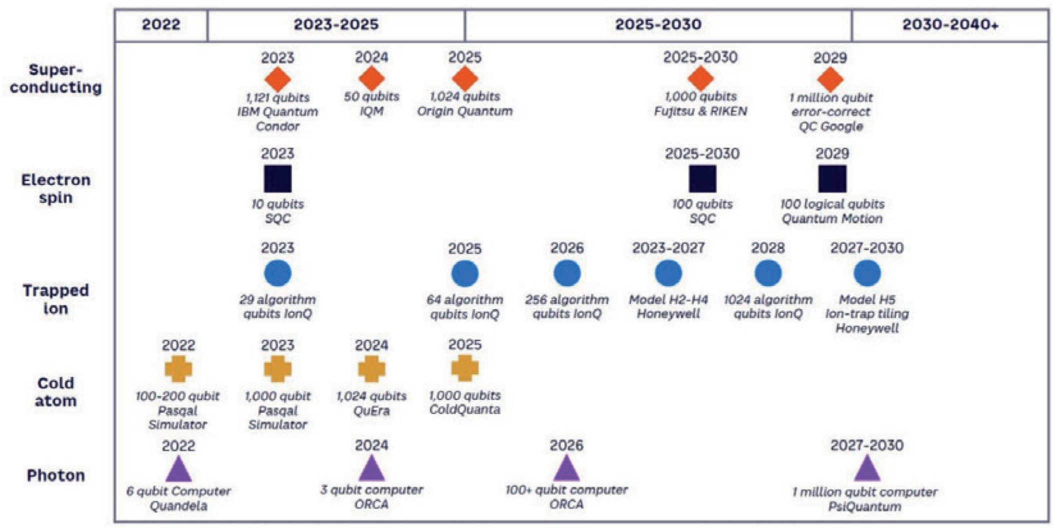
Platform	Current	Comments on evaluating
Superconducting qubits	5-6	Many companies have built small superconducting computers and papers have been published solving toy versions of user-relevant problems on them, including quantum error correction. Quantum error correction experiments on small QPUs performed successfully (see e.g. [Acharya23]).
Superconducting qubits (quantum annealing)	5	Many experiments were done on D-Wave quantum annealers, including error correction. Primitive error correction techniques available out of the box (DWave). However, QTRL6 not reached yet.
Trapped ions	5-6	Many companies have built small trapped-ion quantum computers and papers have been published solving toy versions of user-relevant problems. Quantinuum has demonstrated CNOT gates between logical qubits and has published papers solving toy-problems with error detection. Real-time quantum error correction experiments on small QPUs performed successfully (see e.g. [Ryan-Anderson22]).
Cold Rydberg atoms	5	Toy problems [Evered23] have been solved there. However, QTRL6 not reached yet.
Photonic	5	Gaussian Boson sampling performed by industrial and academic players. Universal photonic QC is at QTRL3.
Solid State Qubits (Semiconductor and NV-centers)	5-6	Small toy problems have been solved, including demonstration of QEC. Quantum Error Correction on small QPUs performed successfully (see e.g. [Takeda22]).
Topological qubits	2	Microsoft is focused on developing topological qubits.

[60] http://dx.doi.org/10.13140/RG.2.2.17822.92483/1

Even after 10 years, in 2033, the report does not envisage any of the technologies exceeding the power of classical computers (QTRL-9 in their terminology):



The same report assembles roadmaps that reinforce our conclusion that impact should be anticipated in the 2030s rather than before:



Source: Arthur D. Little, Olivier Ezratty

Collectively, these assessments lead to the strand prioritisation and summary explanations in the following tables. Application readiness is summarised in table 5. Global gravity and possible content for ITCILO training, learning and capacity development are summarised in table 6. Technology to enhance the delivery of ITCILO training, learning and capacity development is summarised in table 7. An overview grid of all factors combined and the overall prioritisation assessment can be found in the executive summary.

The overall assessment identifies **two main activities for Part III**, prioritising insights that will support ITCILO decision-making and engagement during 2025 and 2026. First, **exploration of current and near-term quantum AI/ML algorithm capabilities** in the context of ITCILO use cases. Second, **exploration of possible 'quantum readiness' related capacity development provision**.

TABLE 5. INDICATORS FOR APPLICATION READINESS BY 2030

Strand	Maturity roadmaps: Which applications might be ready by 2030	R&D Momentum
Quantum Computing Hardware (under Compute)	**Low potential** • High-profile, high-spend R&D race to improve on existing gated hardware, where quantum advantage has already been demonstrated, but only in niche areas, potentially motivated in some cases by PR considerations. • Commercial applications outside niche cases are expected to require several million physical qubits or tens of thousands of logical qubits, for which projections are nearer to 2035-2040 than 2030 (and cost-effective applications may wait longer). • Short-term potential on restricted use cases exists via hybrid or analogue set-ups.	**High potential** **High activity/high growth** 2000-now 29,283 patents 22,406 docs 2019-21 7,045 patents 4,610 docs 2022-24 15,906 patents 10,110 docs
Quantum Materials (under Materials)	**Medium potential** • Best seen as ongoing incremental progress, rather than a single breakthrough target • Quantum dots already used, QM-effects relevant in diverse small-scale technology, e.g. PV cells, computer chips. • Future potential likely to be best identified via application layer, e.g. quantum sensors, higher quality batteries, replace medical dyes. • Other more ambitious applications are likely to require a black swan breakthrough (e.g. superconductor tech) or to wait on the compute hardware progress.	**Low potential** **Med activity/low growth** 2000-now 4,540 patents 87,129 docs 2019-21 1,157 patents 16,030 docs 2022-24 1,233 patents 17,331 docs

Strand	Maturity roadmaps: Which applications might be ready by 2030	R&D Momentum
Quantum Networking (under Connectivity)	**High potential** • R&D proof of concept networks are present already (e.g. China's Beijing-Shanghai quantum network and Europe's Quantum Internet Alliance). • Large cost of deployment suggests the benefits are likely to remain a low priority outside of R&D and perhaps national defence until post-quantum cryptography is required (and only then if classical post-quantum encryption techniques prove insufficient). • However, cultural concerns about encryption and excitement around quantum systems may be enough to create an earlier-than-necessary shift to a Quantum Internet, with the UK Mission targeting 2035. • The potential to detect attempted eavesdropping (guaranteed for certain types of eavesdropping) is a breakthrough change that may motivate adoption, but is likely only relevant for national security and the premium end of applications.	**Low potential** **Low activity/medium growth** 2000-now 1,148 patents 5,122 docs 2019-21 237 patents 1,193 docs 2022-24 617 patents 1,911 docs
Quantum AI/ ML Algorithms (under AI/ML)	**Medium potential** • Progress in algorithms can help reduce the qubit-requirement of existing use cases and unlock new use cases. • Quantum ML remains primarily a theoretical claim, with several theoretical and implementation breakthroughs required to live up to the commercial potential targeted in market forecasts. However, in the short- to medium-term there is potential to support aspects of ML that can be mapped to QUBO mathematics. • Various algorithms suited to the NISQ era have potential value through to 2030, such as hybrid quantum-classical, analogue approaches (inc. annealing), applications that tolerate noise/error, or applications that can work on a small number of logical qubits.	**Medium potential** **Med activity/high growth** 2000-now 7,005 patents 11,071 docs 2019-21 1,845 patents 2,430 docs 2022-24 4,121 patents 5,411 docs
Quantum Cryptography (under Cybersecurity)	**High potential** • The earliest that existing encryption techniques come under credible threat from quantum computers is the mid-2030s, barring a black swan breakthrough. • Quantum cryptography may progress faster, with a view that it is better to be prepared or cultural preferences, but that is not driven by necessity (except for long-term secrets vulnerable to HNDL, but primarily relevant for national security). • QKD has been used in niche commercial circumstances and is available via satellite links (e.g., Micius), optical fibre networks (e.g., Beijing-Shanghai quantum backbone, Geneva-Zurich link), and physical transportation of entangled particles. However, adoption remains limited due to high costs, infrastructure challenges, and the adequacy of classical cryptographic methods for most use cases. Until large-scale quantum networks with repeater capabilities are operational, QKD's value will likely remain confined to niche applications, such as government communications or sensitive financial transactions.	**Medium potential** **Med activity/med growth** 2000-now 8,360 patents 20,069 docs 2019-21 1,744 patents 4,257 docs 2022-24 3,561 patents 6,147 docs

Strand	Maturity roadmaps: Which applications might be ready by 2030	R&D Momentum
Quantum Metrology (under Sensors & IoT)	**High potential** • Commercial use cases exist today but are more accurately seen as ongoing incremental progress, rather than a single breakthrough target. • For instance, the UK Missions target deploying quantum clocks (atomic clocks) on aircraft by 2030, providing next-generation accuracy for resilience that is independent of satellite signals. Sensors in other settings are expected to provide new situational awareness capabilities or form factor improvements, although current IoT potential remains underfulfilled. Outside military or high-end medical applications, it is unclear where sufficient value is added to merit the higher cost. • Other more ambitious applications, including privacy preserving applications, are likely to wait on hardware progress and push beyond the 2030 horizon.	**Low potential** **Low activity/med growth** 2000-now 1,367 patents 3,784 docs 2019-21 322 patents 988 docs 2022-24 744 patents 1,450 docs
Quantum Biotech (under Biotechnology)	**High potential** • Commercial use cases exist today but are more accurately seen as ongoing incremental progress, rather than a single breakthrough target. • For instance, the UK Missions identify quantum imaging technologies for breast cancer detection in NHS hospitals by 2030 and quantum-enabled brain scanners for children's neurological diseases by 2028. • Other more ambitious applications are likely to wait on the compute hardware progress and push beyond the 2030 horizon.	**Medium potential (but inferred only)** **Low activity/low growth** 2000-now 3,423 patents 53 docs 2019-21 415 patents 8 docs 2022-24 303 patents 12 docs *(applications specific keywords are likely particularly important in this domain, but given the low ITCILO priority of this use case via other factors this is not explored further)*
Quantum Simulation (under Simulation)	**Medium potential** • Some potential via the hybrid techniques (e.g. Variational Quantum Eigensolver, VQE) and annealing techniques, if the problems can be translated into the appropriate forms (e.g. QUBO optimisation; combinatorial optimisation like travelling salesman). • Some near-term potential anticipated for modelling molecular/quantum systems directly, e.g. for materials design and drug discovery. However, only limited potential anticipated for even small scale complex systems outside of quantum physics.	**Low potential** **Low activity/high growth** 2000-now 1,630 patents 4,776 docs 2019-21 489 patents 1,075 docs 2022-24 914 patents 1,632 docs

TABLE 6. INDICATORS FOR ITCILO RELEVANCE BY 2030: GLOBAL GRAVITY AND TRAINING CONTENT

Quantum strand (home domain)	**Global gravity** *e.g. quantitative estimates[61] of the market size of the different technologies and qualitative assessment of the types of labour market disruption and the types of global risks/ opportunities they might bring*	**The 'What' of training, learning, & capacity development** *e.g. prominent credible applications in sectors with broad global inequality, decent work, sustainable development, or social justice considerations for lower/middle income countries* *(relevant as content for ITCILO provision)*
Quantum Computing Hardware (under Compute)	**Medium potential** **Global market size estimates:** Forecasts tend to combine hardware and optimisation applications, with example forecasts for 2030 of US$2 bn (BCG[62]), US$2.5 bn (Grand View[63]), US$5 bn (Market.Us[64]), and US$7 bn (DHR[65]). Likely to continue attracting major investment, but with only modest commercial services purchasing by 2030, although the market is forecast to grow very fast in the 2030s as we potentially exit the NISQ era[66]. Some forecasts imply an earlier exit from NISQ, with forecasts of US$12 bn by 2030 across all quantum computing applications (Data Bridge[67]). **Other global gravity considerations:** Hardware investments attract significant public and political attention, given potential military and commercial benefits for being the first to succeed. Quantum computing hardware is the key unlock for impact, with significant uncertainty over maturity progression speed.	**Low potential** Likely that "fast follower" strategies are far more impactful for lower income countries than investing in R&D initiatives with individually low probabilities of success. While quantum hardware is likely to be highly immobile, cloud access and hybrid approaches are likely to be more than adequate through to the mid-2030s, so there is little cost-effective advantage in establishing in-country resources (beyond PR or political reasons).

[61] Estimates are highly uncertain and methodologies/technology scope vary by market report (and are often incompletely described). Nonetheless, the estimates provide a useful order-of-magnitude assessment of current enthusiasm and an indication of the wide uncertainty range across different forecasts. In some cases, the full report is publicly available, but in others only press release, summary, sample, and preview material has been reviewed.

[62] https://www.bcg.com/publications/2024/long-term-forecast-for-quantum-computing-still-looks-bright

[63] https://www.grandviewresearch.com/industry-analysis/quantum-computing-software-market-report

[64] https://market.us/report/quantum-computing-market/

[65] https://datahorizzonresearch.com/quantum-computing-market-2187

[66] E.g. McKinsey's 2024 Quantum Technology Monitor projects US$45-131 bn in market size by 2040 and US$1-2 tn in economic value; https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing

[67] https://www.openpr.com/news/3601823/quantum-computing-market-size-share-trends-growth

Quantum strand (home domain)	Global gravity	The 'What' of training, learning, & capacity development
Quantum Materials (under Materials)	**Medium potential** **Global market size estimates:** Quantum dots estimated at around US$25 bn in 2030 (Polaris[68]) and US$16 bn (CMI[69]). The market for broader materials is uncertain, but a charged-for report is available[70]. **Other global gravity considerations:** Most applications represent incremental progress, with limited scope for disruption outside of niche areas.	**Very low potential** Likely that "fast follower" strategies are far more impactful for lower income countries than investing in R&D initiatives with individually low probabilities of success. Quantum materials and applications would likely be able to travel (to add value) and hence would be accessible to lower income countries (subject to the same cost constraints that affect current technology).
Quantum Networking (Connectivity)	**Medium potential** **Global market size estimates:** US$4 bn in 2030 (Precedence Research)[71]; US$5 bn (Markets and Markets)[72]. To 2040, McKinsey estimate rapid growth to US$24-36 bn in networking & communication.[73] **Other global gravity considerations:** Significant public and political interest in the notion of a Quantum Internet. High profile ongoing Chinese and EU build-outs are likely to enhance the political salience of this topic in the face of perceived (albeit unlikely) threats to existing encryption.	**Medium potential** Relevance due to its importance for situational awareness around quantum cryptography (see below) and due to the large-scale investments taking place in China and (to a lesser extent) in other countries.
Quantum AI/ ML Algorithms (under AI/ML)	**Low potential** **Global market size estimates:** US$1 bn for 2030 (BCG[74]), although potentially higher based on interpretations of the overall quantum computing forecasts listed above, with anticipations of far higher impact between 2030 and 2040. **Other global gravity considerations:** In the forecast time horizon, the major ethical and disruption concerns are likely to remain focused on AI technologies running on classical computers. Some early niche use cases and successes may attract attention.	**Low potential** Modest value because monitoring existing algorithms, e.g. hybrid and analogue techniques, will be important for being aware of potential benefits and ensuring that use cases from higher income countries are identified/explored in a timely manner for their relevance in other countries. The broader link to both empowering AI and embedding AI in high income countries is also a credible concern, given existing LLMs and concerns over the LLM divide and training dataset bias to US/English/web-tech.

68 https://www.polarismarketresearch.com/industry-analysis/quantum-dot-market/request-for-sample

69 https://www.globenewswire.com/news-release/2024/08/21/2933681/0/en/Quantum-Dots-Market-to-hit-19-98-billion-Globally-by-2031-growing-at-18-60-CAGR-says-Coherent-Market-Insights.html

70 https://mobilityforesights.com/product/quantum-materials-market/

71 Applying 73:27 2023 hardware:services split to 2030 estimate: https://www.precedenceresearch.com/quantum-communication-market.

72 https://www.marketsandmarkets.com/Market-Reports/quantum-communication-market-143942501.html

73 https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing (third annual Quantum Technology Monitor, released Apr 2024)

74 Optimisation/ML share from 2021 applied to 2024 forecast https://www.bcg.com/publications/2024/long-term-forecast-for-quantum-computing-still-looks-bright

Quantum strand (home domain)	Global gravity	The 'What' of training, learning, & capacity development
Quantum Cryptography (under Cybersecurity)	**High potential** **Global market size estimates:** US$0.2 bn by 2029 (Yole Group[75]); US$0.2 bn in 2030 (BCG)[76]; US$0.5 bn by 2030 (Grand View[77]). Some estimate an escalating year on year growth to arrive at US$6 bn by 2030 (KBV[78] and TBR[79]) or US$8 bn by 2030 (Markets and Markets[80]). Could vary widely depending on Shor's Algorithm implementation progress and cultural concerns around encryption vulnerability. **Other global gravity considerations:** A high-profile topic with major military and national security relevance. Role as a proxy area of research and capabilities demonstration, even if immediate utility is limited.	**Medium potential** Current encryption is expected to remain valid through to 2030. However, lower income countries would benefit from monitoring this technology and assessing the time to invest in quantum networking or related cryptographic solutions, as a failure of RSA (e.g. mid/late 2030s or beyond) could mean internet commerce becomes restricted to countries with quantum internet, creating a major development threat to lower income countries, especially as novel encryption techniques may become politically restricted due to risk of being attacked, requiring countries or alliances to develop their own. Awareness around 'harvest now, decrypt later' (HNDL) schemes would also be sensible for country's safeguarding long-term sensitive information, such as national secrets, and consideration of alternatives (including traditional physical tech as well as QKD etc).
Quantum Metrology (under Sensors & IoT)	**Medium potential** **Global market size estimates:** US$0.5 bn in 2029[81] (Yole Group), US$0.8 bn in 2030 (Market Data Forecast[82]), US$1 bn by 2030 (Precedence Research[83]) , US$1-6 bn by 2040 (McKinsey[84]) **Other global gravity considerations:** This is one of the most mature quantum technologies (along with quantum dots) and with related ethical/ military aspects.[85] Nonetheless, these capabilities can often be productively analysed as part of ongoing R&D within specific application domains, rather than requiring a dedicated quantum technology focus.	**Medium potential** Applications envisaged to 2030 primarily translate into incremental, high-cost progress at the frontier of precision measurement. Lower income countries already face technology disadvantages, but progress towards closing those gaps would focus far more effectively on current technologies (e.g. IoT) rather than quantum-enhanced technologies. There may be some niche opportunities from breakthrough capabilities that are relevant sooner, such as sensing the presence of rare earths in ground without physically digging to them.

[75] https://www.eetimes.eu/slowly-but-surely-quantum-computing-will-transform-industry-and-society/

[76] Applying 2021 computational problem type breakdown from BCG to the latest BCG 2030 NISQ era forecast. https://www.bcg.com/publications/2024/long-term-forecast-for-quantum-computing-still-looks-bright

[77] https://www.grandviewresearch.com/industry-analysis/quantum-cryptography-market-report

[78] https://www.kbvresearch.com/quantum-cryptography-market/

[79] https://www.thebusinessresearchcompany.com/report/quantum-cryptography-global-market-report

[80] https://www.marketsandmarkets.com/Market-Reports/quantum-cryptography-market-45857130.html

[81] https://www.eetimes.eu/slowly-but-surely-quantum-computing-will-transform-industry-and-society/

[82] https://www.marketdataforecast.com/market-reports/quantum-sensing-market

[83] https://www.globenewswire.com/news-release/2024/11/27/2988327/0/en/Quantum-Sensor-Market-Size-Expected-to-Reach-USD-1-170-81-Million-by-2033.html

[84] https://www.mckinsey.com/featured-insights/the-rise-of-quantum-computing (third annual Quantum Technology Monitor, released Apr 2024)

[85] For instance, sensors may have invasive biometric monitoring capabilities via hard-to-detect passive monitoring, with consequences for privacy. Depending on R&D progress, potential military applications could reshape current constraints that affect military strategy and hardware design/deployment, such as accelerometers for GPS-independent navigation (critical in contested zones when satellites can be made inaccessible), quantum radars to detect stealth aircraft and submarines (e.g. via gravimeters, magnetometers, or quantum illumination), and gravimeters to locate underground bunkers.

Quantum strand (home domain)	Global gravity	The 'What' of training, learning, & capacity development
Quantum Biotech (under Biotechnology)	**Low potential** **Global market size estimates:** US$0.7 bn in drug discovery (Market.Us[86]); US$1.7 bn for healthcare overall (Markets and Markets[87]) **Other global gravity considerations:** Although this is one of the most mature quantum technologies, the related political and military applications are modest and can be considered part of ongoing R&D, rather than a specific quantum technology phenomenon.	**Low potential** The applications envisaged over the next 5 years primarily translate into incremental, high-cost progress at the medical frontier. Lower income countries already experience health inequalities, but progress towards closing those gaps would focus far more effectively on current technologies rather than quantum-enhanced technologies.
Quantum Simulation (under Simulation)	**Low potential** **Global market size estimates:** US$1 bn in 2030 (BCG[88]) **Other global gravity considerations:** Depends heavily on progress in overall quantum computing and AI/ML algorithms.	**Low potential** Where simulation tech is used for political issues closely affecting the global south, such as climate change, it will be important for state actors to be able to participate fully in discussions (even if 2030 simulations are only in minor parts of a climate model). This would not require in-country leading edge quantum hardware, but would require understanding of the technology's strengths, limitations, and potential.

TABLE 7. INDICATORS FOR ITCILO RELEVANCE BY 2030: ENHANCING THE DELIVERY OF TRAINING

Quantum strand (home domain)	The 'How' of training, learning, and capacity development by 2030 (TLCD) *(used as technology to design or deliver learning, not as the content being learned, i.e. the 'how' not the 'what' of training programmes)*
Computing Hardware	**n/a – impact on TLCD is via application layer**
Quantum Materials	**n/a – impact on TLCD is via application layer**
Quantum Networking	**n/a – impact on TLCD is via application layer**
Quantum AI/ML Algorithms (under AI/ML)	**Low potential** In principle, hybrid or annealing algorithms could provide a boost to personalised learning / adaptive learning / personalised AI tutor use cases within quantum compute/algorithm capabilities by 2030. However, initial research suggests these use cases are not currently bottlenecked by in-principle compute/algorithms for already available technologies and more bottlenecked by resource, awareness, and process inertia. Moreover, current uptake is not necessarily bottlenecked by tech capability and it is unclear that new tech in this time horizon would be so powerful to overcome current bottlenecks/barriers.

[86] https://www.rootsanalysis.com/reports/quantum-computing-in-drug-discovery.html

[87] Extending CAGR by two years from https://www.marketsandmarkets.com/Market-Reports/quantum-computing-in-healthcare-market-41524710.html

[88] Applying 2021 computational problem type breakdown from BCG to the latest BCG 2030 NISQ era forecast. https://www.bcg.com/publications/2024/long-term-forecast-for-quantum-computing-still-looks-bright

Quantum strand (home domain)	The 'How' of training, learning, and capacity development by 2030 (TLCD) *(used as technology to design or deliver learning, not as the content being learned, i.e. the 'how' not the 'what' of training programmes)*
Quantum Cryptography (under Cybersecurity)	**Very low potential** Encryption may be useful for certificates of achievement used in a training/ education context, but there exist low tech or trust-based alternatives that largely worked prior to encrypted certificates and could be returned to at relatively low cost if necessary. More general infosec considerations will be a high priority for all use cases, but likely only necessary past 2035.
Quantum Metrology (under Sensors & IoT)	**Low potential** Possible route to relevance if trust & privacy become a bottleneck to speculative IoT applications in a learning environment. Systems of multiple quantum sensors can, in principle and with further R&D, be designed so data on any individual learner is unidentifiable by design, but average data across many learners remain accessible to improve provision. However, we should expect classical IoT technologies to be used first and likely for several years to establish a use case/demand, before quantum tech would merit layering in.[89] It is also unclear whether privacy concerns prove a binding constraint.
Quantum Biotech (under Biotechnology)	**Very low potential** Applications over the target timeframe do not become relevant for the delivery of learning, although brain insights, personalised medicine or quantum-empowered neurotech[90] for learning may become relevant over a longer timeframe and would likely also have equality impacts.
Quantum Simulation (under Simulation)	**Very low potential** Simulations relevant to policy making (e.g. whole city, whole economy) rely on compute breakthroughs beyond 2030. Existing simulation tech is likely under-exploited: higher-cost, higher-quality alternatives is not currently a user priority.

[89] Classroom IoT does not appear to be a current priority, but potential examples include monitoring learner behaviour, biomarkers, and even cognitive load via neurotech wearables, to understand group dynamics, how students respond to different activities, and a group's readiness to learn topics of higher difficulty. Quantum sensor meshes could remove the need to 'trust' a school's IT systems or commitments not to use student-level data, which could prove essential if students become highly sensitive to privacy matters and refuse to participate in such IoT networks without guaranteed personal privacy.

[90] For instance, diamond quantum sensors are showing potential in non-invasive neural imaging https://www.nature.com/articles/s41598-023-39539-y

PART III. PRIORITISED QUANTUM TECHNOLOGIES: MORE DETAILED ASSESSMENT

Part II assessed eight potential strands of quantum technology, identifying one strand and one over-arching topic as most relevant for ITCILO's use cases and 2030 time horizon. The strand identified was Quantum AI/ML algorithms for learning, albeit still only assessed as low priority for learning technologies overall. The topic identified was 'Quantum Readiness' capacity development provision. Part III provides the next level of assessment into these two areas, identifying potential suggestions in case ITCILO wishes to pursue quantum technologies further in 2025 or 2026.

3.1. Quantum AI/ML algorithms for learning – Review for ITCILO near-term relevance

Relative to other quantum technologies, quantum AI/ML algorithms that can be applied within the NISQ era have the highest potential for relevance in learning design, deployment, and delivery of learning. The methodology agreed for the next level of assessment comprised: review for learning-related applications in existing sources, discussions with a small number of quantum company researchers to ask them about possible learning-related applications, a high-level search across patents and academic literature, and an analysis of existing algorithms. The analysis specifically examines quantum AI/ML technologies through the lens of ITCILO's core mission. Our assessment prioritises practical applications that enhance educational methodologies, support workforce skills development, and provide learning technology innovations.

Industry discussions and review of existing sources

Algorithmic solutions specifically for the learning domain are not prioritised in the literature – and rarely explicitly discussed at all. This assessment was further reinforced by the sparse results of a search across academic literature and patents looking for applications of quantum technology specifically for the design, deployment, and delivery of learning.

The industry-applications assessment based on company websites, sector reporting, and a literature scan was directionally confirmed in interviews with Quantinuum, IBM, D-Wave, the NL SURF Network, and an off-the-record conversation with an experienced (6+ years) member of the Google Research team (pursued following the major Willow announcement during the project[91]). Specifically, logistics optimisation, financial portfolio optimisation, and molecular/chemical simulation (and its potential applications in drug discovery, material science, and advanced manufacturing) are the most commonly promoted sector use cases for quantum algorithms outside of basic research. There is also frequent generic commentary on various potential quantum machine learning (QML) techniques, often leveraging the same underlying combinatorial optimisation techniques behind the optimisation applications mentions and similar analogue system sampling techniques as helpful in simulation. However, recent QML progress should be contextualised in the concerns about hype and lack of evidential support for relevance against classical techniques as recent as 2022 and 2023[92]. In other words, we remain at least one major breakthrough away from substantiating the possible relevance of QML.

Company sources were typically willing to explore the feasibility of quantum-empowered solutions for learning, but emphasised this would largely be a **new area of exploration** and would require particularly close collaboration with a given industry partner. For instance, work in other sectors typically requires the industry partner to provide example data structures (e.g. sample data, a data dictionary), specify a target equation/model, and indicate the scale of data required to drive an impactful solution, ideally with a classical benchmark for comparison. Proofs of concept based on such partnerships are occurring in a wide range of sectors and well before anticipated quantum advantage, such that education/training would be welcome among them. However, leading sectors are typically those already operating with very large algorithmic complexity where classical supercomputers or dedicated compute clusters are already required for well-defined mathematical problems, such as finance, logistics, pharmaceuticals, and engineering. Consultancy or full-scale proof-of-concept projects based on such approaches are likely to cost between the high-10,000's and mid-100,000s of US dollars. Several companies have research or low cost/pro bono services available, which the ITCILO may be able to access, perhaps in partnership with a university or perhaps by leveraging international interest and the opportunity for profiling in the UN International Year of Quantum (IYQ).

Such consultancy or proofs-of-concept could be pursued by ITCILO in the near future (potentially even in mid/late 2025), but initial conversations suggest such detailed analysis would be premature prior to further internal work that would likely require structuring as a dedicated project. For instance, QML has the potential to enhance adaptive/personalised learning, but existing techniques using classical techniques have not yet been sufficiently explored by the ITCILO such that colleagues can point to a specific dataset of historic learning trajectories and learner choices to fuel a specific recommender algorithm – or even specify the dataset structure that it hopes to collect in the future (discussed further in table 10).

91 https://research.google/blog/making-quantum-error-correction-work/ (Dec 2024)

92 E.g. https://www.technologyreview.com/2022/03/28/1048355/quantum-computing-has-a-hype-problem/ (Mar 2023); https://spectrum.ieee.org/quantum-computing-skeptics (Dec 2023)

Algorithm-level identification

In order to provide a more comprehensive initial assessment, we have collated some of the most commonly described quantum algorithms that might have potential relevance for learning, even if learning-related use cases are not considered a priority today relative to other industry use cases.

Table 8 provides example problems that are potentially tractable on analogue quantum computers; table 9 provides example problems that are potentially tractable on near-term gated quantum computers.[93] In general, analogue quantum computers have higher levels of commercial readiness today and there is greater feasibility for immediate proof-of-concept testing, although gated computers are developing rapidly and some immediate opportunities exist there as well. Identifying additional algorithms that can be addressed on analogue quantum computers or NISQ-era gated computers is a live area of research, so it is possible that new breakthroughs will unlock other applications of relevance to learning even if currently-anticipated use cases are limited.

TABLE 8. EXAMPLE MATHEMATICAL PROBLEMS TRACTABLE ON ANALOGUE QUANTUM COMPUTERS

Mathematical problem	Example applications
Maximum independent set Find largest subset in a graph where no two vertices are directly connected	Direct application in optimising the locations of stores in a city to have as many stores as possible but without being too close to each other
Travelling salesman and its generalisations Given a length *L* and a graph, decide whether the graph has a tour whose length is at most *L*	Given a list of locations and the distances between each pair of locations, identifying the cost-minimising set of routes for a fleet of vehicles to traverse in order to deliver to a given set of customers
Max-cut Partition the vertices of a graph into two subsets such that the number of edges between the subsets is maximized	Direct applications in circuit layout optimisation or network design
Graph colouring Assign colours to vertices of a graph such that no two adjacent vertices share the same colour, minimizing the number of colours used.	Applications in scheduling, e.g. frequency allocation in wireless networks (minimise frequencies used to preserve spectrum resources while avoiding interference, i.e. frequences that overlap for nearby/adjacent devices)
Knapsack problem Select items to maximise value while staying within a weight limit (with integer-valued variables)	Direct applications in budget allocation and financial portfolio optimisation (similar to the set cover problem, finding the smallest subset of sets that covers all elements of a universe)

[93] Note that the categorisation between problems/algorithms is fuzzy in places. We have favoured a presentation that situates a conversation about potential learning domain applications above mathematically precise distinctions.

Mathematical problem	Example applications
Kernel-based methods Calculating similarity between data points in a high-dimensional feature space	Direct applications in clustering and regression tasks in machine learning, e.g. segmenting customers in a data-driven framework, image recognition.[94]
Boltzmann sampling Taking a random sample of values from a specific distribution where classical approximations struggle in high-dimensional cases or fail to cover all regions of the probability space, whereas quantum annealers can naturally encode the Boltzmann energy landscape in their quantum states	e.g. hybrid Boltzmann Machine machine learning where dimensionality goes beyond classical heuristics for Boltzmann sampling and Boltzmann techniques add value beyond techniques like PCA, k-means clustering, and VAEs (e.g. where non-linear, non-Gaussian joint probability distributions or hierarchical feature representations are key). In a typical hybrid approach, the classical infrastructure delivers weight updates, gradient computations, and hyperparameter tuning, while the quantum infrastructure provides the sampling.

* Example list only, focusing on those of more likely relevance to learning or policy in a social science setting, e.g. not those for directly modelling physical systems of relevance to molecular simulation in areas like drug discovery and material design or complex distribution sampling with primary relevance in statistical physics. Quantum reservoir computing (QRC) not included for reasons of space, but noting potential applications for time series forecasting and anomaly detection; these applications are captured via more general discussions of QML in learning applications, noting that QRC could be reviewed along with other techniques if appropriate in the future.

The examples in table 8 are particularly relevant for classical computer comparisons, as they are typically highly mathematically complex problems, where we are confident that classical computers rapidly prove incapable of precise solutions at large input scales. These are typically NP-hard problems in the general case and mostly strong-NP hard, even if some special cases can be solved in polynomial time.[95] In an analogue quantum computer setting, however, the maximum independent set problem can sometimes be addressed by encoding the problem into a physical qubit array and annealing a quantum adiabatic algorithm via continuous physical transformations into the solution. Many problems above, as well as certain machine learning problems more generally, can be represented as quadratic unconstrained binary optimisation (QUBO) problems or Ising problems, both of which are addressable on analogue quantum computers.

[94] Illustrates the analogue/continuous vs gated/digital distinction. One analogue approach uses a continuous variable quantum system in a photonic processor, e.g. encoding information in continuous variables like the amplitude/phase of electromagnetic fields and manipulating it via operations like phase shifts and beam splitting. Certain analogue operations naturally implement kernels without requiring the formulae to be explicitly calculated via digital algorithms, which provides a computation speed-up and naturally handles continuous variables. However, physical mechanisms need to be identified for each separate kernel (e.g. Gaussian, polynomial have been identified), whereas a gated computer provides a universal solution for all algorithms, subject to its capacity limitations. E.g. https://link.aps.org/doi/10.1103/PhysRevX.14.011013

[95] NP-hard problems are at least as hard to solve as NP problems, i.e. those where a positive solution to the problem can be verified in polynomial time*, but for which we do not currently have a method to identify solutions in polynomial time (such methods likely do not exist under the unproven but broadly-accepted assumption P ≠ NP). A polynomial-time solution to any NP-hard problem encodes a polynomial-time solution to all the problems in the complexity class of NP. Strong NP-hard problems additionally do not have a pseudo-polynomial time algorithm (i.e. polynomial in the number of integers and the magnitude of the largest integer of its inputs, even if it is not polynomial in the number of integers and the number of bits in the largest integer). * Polynomial time means the algorithm time is bounded from above by a polynomial function of the problem's input size, i.e. the time to solve it is proportional to the input size, n, raised to a constant power, k: $\propto n^k$. Note that polynomial functions can still be intractably large in practice, e.g. if k is very large even though it is still a constant.

To provide a concrete example of the strengths and caveats of current techniques, we can consider QuEra's 2023 analogue computer, Aquila, which arranges up to 256 neutral atoms using laser tweezers in a 2D grid. This set-up works best for problems mappable as 2D geometric graphs with fewer than 256 nodes.[96] The set-up is inefficient for 3D graphs or arbitrary graphs, where the geometric structure might only be able to map up to tens of bits. Unlike gated computers, analogue computer assessment often relies not only on a problem's generic nature, but on the specific geometric properties of a given use-case, resulting in increased upfront consultancy costs to test whether problems can be appropriately encoded. As of February 2023, Aquila's heuristic results (i.e. not provably optimal results) would outperform a simple greedy heuristic classical algorithm for a store location problem, but be outperformed by more sophisticated classical computer applications (beyond c.50 nodes classical brute-force optimisation fails, but classical heuristics can still be high-performing).[97]

The comparison of heuristic performance is key to assessing near-term quantum computer relevance. Classical algorithms running on classical computers have been optimised over decades to deliver 'good enough' solutions on many combinatorial optimisation problems. For instance, travelling salesman problems may be formally intractable, but classical heuristics are believed to approach optimal solutions for many real world use cases sufficiently closely that most applications gain only marginally from the speed-up. Except in cases where single percentage point or basis point gains provide disproportionate benefits (such as in short-term financial trading), marginal improvements are not necessarily worth the cost. However, speed is another consideration alongside proximity to an optimal solution. For instance, even where quantum computer heuristics underperform current classical heuristics, the dramatic increase in speed may be highly profitable. For instance, one D-Wave case study may have achieved lower performance in a financial portfolio optimisation relative to high quality classical systems, but it solved the problem over 500x faster.[98]

96 In general, encoding data at scale into qubits is a key challenge for NISQ-era quantum computing and is an area of active research. Even where it is technically possible, the time and cost of encoding data can outweigh aspirational algorithmic speed-ups. Gated computers generally have more structural flexibility and potential for precision, but need to overcome error-correction barriers for larger scale inputs. Analogue computers scale more easily with today's technology (albeit still highly limited) but can only efficiently encode certain problem structures. Data encoding techniques include basis encoding, amplitude encoding, and qsample encoding, each with different pros and cons for different situations. Current and envisioned near-term quantum computers have a strict input scale cap per analysis. Fortunately, some problems are amenable to segmenting input data, analysing it in separate batches, and merging the results (e.g. Grover's Algorithm). However, others require holistic integration of all data to achieve the promised benefits (e.g. Shor's Algorithm; VQE where a global Hamiltonian does not disaggregate nicely). Hybrid approaches can sometimes tolerably mitigate the size bottlenecks, subject to caveats. For instance, classical preprocessing might identify the most complex subparts of a graph, which are then processed individually in quantum solvers. Provided the problem is adequately decomposable and a suitable ensemble algorithm available, hybrid-QML results could still be high quality (e.g. QAOA), even if not guaranteed to be optimal.

97 QuEra (Feb 2023). Optimizing store locations using QuEra's Quantum Computer. https://www.quera.com/optimization

98 https://www.dwavesys.com/media/5qahck2o/multiverse_case_study_v8.pdf

TABLE 9. EXAMPLE MATHEMATICAL PROBLEMS TRACTABLE ON NISQ GATED COMPUTERS

Mathematical problem	Example applications and caveats
Matrix multiplication e.g. using Quantum Approximate Matrix Multiplication	A central mathematical activity used in many areas of simulation and optimisation. A time-consuming and energy-consuming activity that underpins modern AI system training, such as LLMs. However, for the same reason, modern classical system are highly optimised for matrix multiplication (e.g. GPUs, TPUs, distributed systems, advanced algorithms like Strassen's). QAMM-type techniques are most likely relevant in the near-term for handling quantum native data or where processing speed is more important than exact accuracy.
Solving linear systems of equations Harrow-Hassidim-Lloyd (HHL) and related algorithms	A central mathematical activity used in many areas of simulation and optimisation, particularly relevant in differential equations as applied to modelling physical systems. In a general QML context, some algorithms (QSVM, QNN) may train more efficiently due to speedups in linear algebra tasks (e.g., matrix inversion or eigenvalue decomposition). However, relevance needs to be assessed given today's paradigm of pre-training an AI model in slow time and then leveraging input flexibility to a static, pre-trained model to generate real-time utility in deployment.
Combinatorial optimisation, e.g. max-cut, travelling salesman e.g. Quantum Approximate Optimisation Algorithm (QAOA)	See various examples from table 8. However, in addition to table 8 caveats around the quality of classical heuristics, QAOA needs to demonstrate outperformance against analogue techniques, so may only apply in the near-term to problems whose structure cannot be efficiently encoded in the available analogue quantum computer mechanisms. QAOA is generally considered most likely to be relevant against classical benchmarks where high-dimension problem matrices are particularly sparse with highly rugged solution spaces.
Unstructured search e.g. Amplitude Amplification (extension of Grover's Algorithm)	Quickly identifying the most appropriate learning material from a large content library, where that library dataset is unstructured. However, where standard methods like tagging, pre-indexing, or hash similarity are available (as they would be in most use cases), it is likely that existing techniques would be adequate even for near-real-time results generation, such as with vector similarity search or online search engines.

* Example list only and acknowledging partial links between the underlying quantum techniques that address different problems. We exclude major techniques like Variational Quantum Eigensolver (VQE) which are primarily focused on chemistry/material science.

In general, and without conceding the considerable long-term potential value if it succeeds, further work is required on table 9 problems in the context of specific learning domain use cases before we should be confident that quantum computers address a relevant bottleneck.

Algorithm comparison against ITCILO interests

The mathematical problems listed above map in principle to certain common or imaginable problems in the design, deployment, or delivery of learning. However, these learning-related problems are either not anticipated to require significant compute (e.g. course scheduling) or their current bottlenecks lie primarily outside the areas that quantum computing/algorithms would alleviate. In other words, there is limited immediate potential for quantum algorithm contribution to these use cases. Nonetheless, there may be value in exploring proofs-of-concept in these areas, in order to be ready for quantum technologies in the future. The key first steps to prepare for such proofs-of-concept include gathering data and developing specific modelling frameworks, which could then be investigated for potential quantum technology solutions.

To elaborate one high potential candidate, quantum computers may prove useful in large-scale future adaptive/personalised learning models. The core of such models is a machine learning infrastructure to assemble a custom curriculum or present tailored content/questions in real-time to learners, leveraging learner preferences/goals, historical datasets of previous learner trajectories, and real-time insights from the target learner. For particularly large datasets or to provide real-time model re-training, quantum computers may become necessary or provide valuable improvements in combinatorial optimisation heuristics. However, the immediate bottlenecks consist in fully exploring existing classical machine learning for personalised/adaptive learning, increasing learner flexibility in existing courses, and building a large dataset of learner content/question trajectories.

The example learning domain applications identified in our interviews and research are listed in table 10, along with the potential quantum computing motivation and our understanding of the priority tasks that ITCILO might progress in the short-term in order to assess the value of a putative quantum computing application.

In several cases, a proof-of-concept calculation on these use cases is feasible, although motivations would need to extend beyond short-term cost effectiveness, which is unlikely to be present. For instance, a university could schedule its classes using a quantum computer, but would not expect any materially improved result relative to its existing practice. Aside from intellectual or PR benefits, such proofs-of-concept are primarily of interest where they can be identified as part of a route towards a cost-effective or high-impact application in the future. In some cases, imaginable end points are insufficiently high impact to likely merit the costs and effort involved. For instance, a university's timetabling task would need to increase in complexity by orders of magnitude before even considering a quantum vs classical procurement decision.

For personalised/adaptive learning, however, and potentially for AI tutors, there is an imaginable high-impact end point, where learning is transformed as a result of the new technology. There may be a step along the route to that end point where a proof-of-concept quantum computer application becomes useful, but it is unlikely to be the first one or two steps that ITCILO or other sector innovators might take, e.g. the ideas as described in the 'ITCILO tasks' column of table 10. Higher value early steps would instead focus on exploring today's minimum viable products and identifying the kinds of data/optimisation desired in next generation learning. After that, the sector will be at a suitable point to ask whether classical computers and heuristic algorithms offer adequate solutions – or whether the potential quantum speed-up or optimisation quality improvement might be merited, given the prevailing view on costs/value at the time. Potential suggestions are collated in section 3.3, should ITCILO wish to pursue this form of quantum readiness.

TABLE 10. POTENTIAL LEARNING DOMAIN APPLICATIONS FOR ADVANCED ANALYTICS AND TASKS TO PRIORITISE PRIOR TO ASSESSING QUANTUM TECH POTENTIAL

Application description	Potential quantum computing contribution	Poss. ITCILO tasks to prioritise before quantum tech potential can be assessed
1. Adaptive learning for assessment and immediate content delivery Questions of different difficulty and minimal overlap are served to a learner to identify their knowledge/ability across a range of topics to a given level of confidence, while minimising the cognitive load and number of questions asked. This approach saves learner time, increases quiz diversity (so re-takes are more interesting), and enables the system to present personalised content/follow-up questions tailored to a learner's needs.	A machine learning approach to adaptive learning is powered primarily by historical datasets of question/answer trajectories to derive insights on difficulty progression, relevance to previously-answered questions, and sequence-dependent cognitive load (manual question triage approaches also exist as standalone or complementary methods where historical datasets are insufficient). It is possible that optimising such ML problems in certain contexts may push beyond classical techniques, but this is unknown without significant further investigation of a specific adaptive learning dataset/algorithm and likely also without further research into QML (which will take place outside of the learning domain, such that learning institutions might wish to be 'fast followers' rather than initial R&D investors). ***If real-time model re-training is needed,*** e.g. where learners are distinctive enough that historical datasets of past learners do not serve as good proxies for an ideal trajectory for a current learner, then the potential benefit of a QML speed-up may become relevant, so that the model is materially retrained for each individual learner following each action by the learner.	Design of existing course quiz content to incorporate & test adaptive assessments, building on the current pre/post multiple choice questions to test learning (e.g. a mid-point assessment to personalise micro-content delivery). Perhaps most relevant for courses with high levels of factual content such as public finance modules or labour market statistics. Review of commercial applications to understand product success drivers (e.g. school-age maths learning tools where adaptive learning is more widely used). Review of existing course content to identify further opportunities, potentially incorporating LLM-powered evaluations of textual answers in sufficiently constrained circumstances where approximate evaluations are good enough to tailor content (rather than for high-stakes assessment such as for credential award).
2. Personalised learning for course design A sequence of modules/ submodules is selected (and potentially revised on the fly) from a given database of modules and constraints (e.g. module initiation requirements, limited access to shared resources, limited learner time) to optimise a learner's chance of successfully completing a course, providing positive feedback, achieving their goals, and (potentially) starting a further course.	Can be mapped to graph theoretic problems once options/ consequences/ constraints are well-known. Consequences can also be learned via ML with similar considerations to (1), but with less pressure on speed of model results generation/re-training (i.e. per module stage completion rather than per question completion). For instance, given declared or inferred data on a learner's starting point, preferences, goals, and capacity and data on historic module transitions (weighted for similarity to the target learner), a sequence of modules is chosen to optimise success metrics (provided those success metrics are known for past learners in the training dataset). However, the historical dataset is harder to gather than for adaptive assessment since each learner might produce only a few transition datapoints (and only one overall goal/achievement datapoint) rather than potentially dozens or hundreds of quiz question datapoints. Moreover, there may be less learner freedom historically (the historical course design might have been 'obvious' in most cases, so it will take more creativity to identify variation worth pursuing).	Encourage and expand on existing adaptive release functionality in ITCILO courses, potentially leveraging generative AI with human oversight to increase the number/ diversity of scenario pathways that can be programmed manually (to start building a dataset that could later fuel the target optimisation algorithm). Similar to adaptive learning in principle, but with fewer commercial examples to draw on for inspiration. Likely to require greater manual design of courses to generate ML training data and greater manual design of triage strategies, at least at first when there are less training data available.

Application description	Potential quantum computing contribution	Poss. ITCILO tasks to prioritise before quantum tech potential can be assessed
3. Personal AI tutor / textbook author Rather than selecting from a curated bank of questions/ modules as above, an AI tutor generates content/questions at all levels of detail on demand (from query-by-query interactions up to a full textbook), given knowledge embedded in its neural network parameters and accessible to it by searching in real-time over a broad and potentially continuously updating domain, such as the Internet, Wikipedia, or a live internal corpus of content/ communications (e.g. millions of minutes of podcasts/internal calls).	Large language models, leveraging existing data and classical computers, are already showing potential as impressive education aides, with several commercial ventures pursuing the vision of a 'chatbot tutor'. Current technology works in real-time by querying static models, following expensive, multi-week model training phases. At this stage, it is unclear whether QML will be required to advance beyond the current LLM paradigm, but given the rate of LLM progress, it is more reasonable to assume that its ability to meet AI tutor requirements would not be materially enhanced by quantum technologies in the short or medium term. However, similar to the items above, if we want models that re-train live beyond changes that can be incorporated into the static model's input, then we need much faster (re-)training modalities, with quantum computing being one theoretical contender.	Build on ITCILO's existing RAG-powered internal LLM to build RAG-powered LLMs for specific courses to test their ability to serve as course-specific AI tutors. Enhance ITCILO understanding of the commercial domain, e.g. start-ups creating AI tutors in specific domains. Develop and test principles for incorporating pedagogic principles into existing LLMs, e.g. LLMs that know a user's level/knowledge and help them to answer the question they ask themselves, providing appropriate hints and scaffolding structure/knowledge to keep the process engaging (while maintaining enough 'friction' to support genuine learning) or tools that proactively build and apply insights from spaced repetition to embed learning. Develop an evaluation framework by which we could assess if a given AI tutor is above a threshold for being safe to use in a given context (e.g. opt-in for digital savvy users where there is access to a human trainer on demand if needed and where the tutors' responses are sampled & periodically reviewed by a human expert in hindsight).
4. Learner allocation to groups. Optimise group formation to minimise inefficiencies or conflicts among participants (e.g., overlapping roles, incompatible skill levels, or interpersonal issues).	Maps directly to the combinatorial optimisation problems described in 3.1. However, it is unclear whether organisations typically have enough flexibility in group formation options to motivate an algorithmic approach.	Invest in theory building to enable mathematical formalisation of this problem. At present, we have insufficient knowledge of efficiencies/conflicts, the features that drive them, how data on those features can be collected, and how better outcomes can be achieved.
5. Course/resource scheduling. Maximise the number of learning sessions/activities/exams given constraints on simultaneity due to facility, resource, lecturer, or participant constraints.	Maps directly to the combinatorial optimisation problems described in 3.1. However, these problems are typically limited in complexity and often need running only once per year, so a relatively slow but high performance classical algorithm heuristic would likely be sufficient. In practice, manual approaches seem to be considered sufficient.	Recommend not pursuing from a quantum tech perspective. Our understanding of provisioning constraints in education does not identify these as sufficiently challenging optimisation problems to require classical supercomputer solutions, let alone quantum optimisation.

Application description	Potential quantum computing contribution	Poss. ITCILO tasks to prioritise before quantum tech potential can be assessed
6. Mgmt. information analytics, incl. projecting learner demand Analysis of marketing/learner data.	Uncertain, potential map to QML for unsupervised clustering or other ML problems, but there is no sense that education providers are at all close to the frontier for data volume / algorithmic complexity requirements that might motivate QML, in that classical ML techniques remain little used (and perhaps appropriately so). Key issues are often based on business processes rather than compute capabilities, e.g. which questions to ask of the data and presenting existing data to best aid interpretation and mgmt. decision making.	Recommend not pursuing from a quantum tech perspective. Potential activities in this direction would focus on theory development (e.g. how to project demand) and gathering the right data to answer questions of interest.

* Table ordered in approximately descending order of likely relevance. Very low likelihood applications are excluded, such as path/route optimisation for mobile trainers and educational field trips. This optimisation can be mapped in principle to the travelling salesman problems, but these can typically be optimised manually today, without even motivating optimisation via classical algorithms, let alone near-term or potential future quantum algorithms. We also exclude applications that would apply to any large organisation with external users, because such applications are likely to become well-known following adoption in higher profit settings (e.g. e-commerce, streaming, social networks, banking) and ITCILO can follow such adoption, e.g. information security, fraud prevention, internal knowledge mgmt., performance mgmt., hiring etc.

As a precursor to the following section, we note that some of the above mathematical examples could play a role as practical exercises and entertaining simulations in 'quantum readiness' courses.

For instance, small travelling salesman problems can be easily solved by most humans using their eyes and geometric intuition. Course participants could see how their solutions quickly become very suboptimal as the problem scales. Likewise, participants could adjust a graph's complexity live to see how quickly classical algorithms solve it perfectly (including the point at which the classical algorithm can no longer solve it) vs the speed and comparative accuracy of various heuristic algorithms, both classical heuristic solvers running live and the average-anticipated performance of an illustrative quantum heuristic solver. Such an exercise could build intuitions about problem complexity, input scale, and classical/quantum heuristic trade-offs.

A more challenging but related exercise for a training course would be brainstorming to identify where travelling salesman problems occur in real-world settings. While logistics problems for companies like Amazon may be straightforward for many participants to identify, the discussion also provides an opportunity to describe less intuitive connections to QUBO-mappable problems in ML tasks, such as feature selection or clustering, and the distinctions between gated approaches for combinatorial optimisation (QAOA) and analogue approaches (e.g. annealing techniques).

3.2. 'Quantum Readiness' capacity development provision analysis

There is high confidence that political attention, investment, and technological progress will continue across a suite of quantum technologies – but low confidence over exactly what progress will unlock what use cases by when. In this context, there is significant value in ITCILO helping its core target audience become 'quantum ready', through industry-neutral, broad-based capacity development for policy-makers, organisational directors and other decision-makers.

In this section we provide an analysis of what different approaches to 'quantum readiness' might entail, with an indication of learning objectives, duration and content, and examples of existing providers to engage. We do not include a full curriculum or draft teaching materials. The intention is that the **analysis can be used as a baseline for developing customised materials for a hypothetical course** that ITCILO could develop at some point in the future. While the current significance of quantum technology is compelling on its own accord and therefore merits a dedicated course on quantum readiness, the report can also be used to guide inclusion of 'quantum readiness' content into multiple existing ITCILO courses, for instance, as part of a course on frontier technologies.

The concepts included in this section differ in one key respect to the scope of the main report: **quantum readiness should necessarily address technological impact beyond the 2030 time horizon**. As we have documented in previous sections, while there is high uncertainty surrounding the technical timeframe for many quantum technologies (especially computing-based technologies), the confidence in eventual viability is significantly higher. The current foresight is that many of these technological challenges will be solved eventually – many in the mid-term. It is therefore prudent to educate strategic decision makers on the potential impacts of the technology now.

Methodology

Our approach comprises two main components: initial research and scoping, and curriculum development framework creation.

In the first phase we conduct a desk review to understand the status quo in strategy-focused quantum readiness education. We begin by conducting an environmental scan of existing quantum readiness courses with the aim of identifying best practice and common curricula topics, including a comparison matrix of existing resources. Here we also direct specific focus to a desk review of quantum games as a pedagogical facilitator, including resources mapping and key informant interviews. Additionally, we investigate the energy implications of quantum technology in order to provide deeper background to the just transition context, as a key motivation for ITCILO's strategic support to policymakers. Simultaneously, we map ITCILO's existing course ecosystem, which involves analysing quantum-adjacent courses, identifying potential integration points for quantum content, and documenting the pedagogical approaches currently in use.

The second phase centres on developing an outline for how course development could be approached, using a curriculum framework. This begins with creating a comprehensive topic inventory covering basic quantum mechanics concepts suitable for non-technical audiences, the current quantum technology landscape, LMIC-specific opportunities and challenges, risk monitoring frameworks, and policy considerations for developing nations. We then draft learning objectives along with suggested modalities for each module. Rather than a final framework, we propose these inputs be treated as initial inspiration for course development at ITCILO, engaging suitable pedagogic and domain experts.

Quantum Readiness Courses: Market Research

The topic of quantum readiness education is reasonably well-represented online, though in the modest volumes expected of a nascent technology domain. Various educational resources are offered by national quantum programmes and other non-commercial organisations as well as commercial professional development service providers. For the purposes of this landscape analysis, we focus only on resources that are provided directly by national quantum programs, multi-lateral organisations, NGOs, and academia - or resources which are promoted by such entities. In a single exception to this rule, we include a course provided by IBM as the company is a well-established player in quantum computing and has a comprehensive online training footprint.

We further filter the course offerings to focus solely on resources that target strategy-level professionals (e.g. policy makers, organisational directors, and managers), as opposed to other introductory quantum courses (e.g. those aimed at the general public or technical professionals). The final list for review includes educational materials from seven sources. A summary is provided in table 11 below.

As noted in table 11, we include a toolkit on quantum readiness from the WEF. This white paper contrasts with the other resources not only in its format, but also in its narrow focus – i.e. quantum readiness in the domain of cyber security and risk mitigation. While this resource does not align with many of the topics covered in the courses, it is worthy of inclusion for its practical focus.

Unsurprisingly, the shortlist of courses still exhibits differentiation between various aspects including target audience, content, and geographic focus:

- **Target audience:** some resources specifically target business professionals with commercial applications and use cases; others are tailored for policymakers and government officials who need to understand regulatory and societal implications.
- **Technical depth:** course offerings range from purely strategic content to slightly deeper material delving into quantum physics principles. While most courses reflect the time constraints of working professionals in leadership positions by requiring only cursory inputs of up to four hours, one course bucks this trend by offering a 12-week course (which aims to communicate enough of the science for participants to speak authoritatively on the subject in a strategy context).
- **Geographic context:** the courses show distinct geographic orientations, with some being strongly anchored in specific regions (e.g. Quantum Delta's Netherlands-focused course or the EU's alignment with initiatives like the Quantum Flagship and EuroQCI). In contrast, resources with a global perspective emphasise generic, non-localised content or international implications/partnerships.

This course mapping demonstrates that there are multiple existing resources in the quantum readiness education space which can be used as models for an ITCILO course, or potentially for direct use in the form of procurement or partnership

TABLE 11. QUANTUM READINESS COURSE MAPPING

Provider	Resource	Duration	Format	Target	Focus Areas	Summary
European Quantum Research Centre (EQRC)	Quantum Readiness and Strategy	2-3 hours	Live course (future iterations planned)	Business leaders, managers, strategists, technology professionals	Investment trends, national/ international strategies, first/second mover strategies	Designed for business leaders, managers, and strategists to navigate quantum technologies effectively. The course focuses on differentiating quantum hype from reality and helps organisations assess whether to be first or second movers in quantum technologies.
IBM Quantum	Quantum Business Foundations	2-3 hours	Online course	Business professionals	Quantum computing business applications, industry use cases	Introductory course covering quantum computing essentials and applications specifically tailored for business audiences.
Quantum Delta	National Quantum Course	2-3 hours	Online course	Mixed technical and business audience	Technical foundations, practical applications, Dutch ecosystem	Builds from historical foundations to practical applications while incorporating expert interviews and technical content. Maintains a strong connection to the Dutch quantum technology ecosystem and includes both technical depth and broader societal implications.
Quantum Flagship	Quantum Technology Training for Policymakers	7 x 40-minute sessions	Videos + Q&A	EU and national policymakers	Policy implications, use cases across sectors	Designed specifically for EU and national policymakers. The training enables policymakers to make informed decisions and sustain meaningful conversations about quantum technology topics with experts.
QURECA	Quantum Strategy for Business	4 hours	Online course	Business strategists and leaders	Business strategy, competitive advantage	Equips participants with tools and frameworks for crafting competitive business strategies aimed at leveraging quantum technologies.
University of Queensland	Quantum Technologies for Decision Makers	12 weeks (2-12 hours / week)	Online course Instructor-led	Strategic decision makers	Sensing, communication, computing applications	Helps participants develop their own organisational quantum strategy while incorporating content from world-recognised quantum scientists and practitioners.
World Economic Forum (WEF)	Quantum Readiness Toolkit: Building a Quantum-Secure Econ.	NA	White paper / toolkit	Organisations, policymakers, business leaders	Quantum readiness principles, security transition	Framework providing organisations with guidance on quantum readiness with a focus on cyber security and risk mitigation. While not a course, this white paper serves as a relevant resource for organisations preparing for the quantum-secure economy.

Quantum Readiness Courses: Curricula Commonalities

Despite variations in delivery methods, duration, and specific focus areas, analysis of existing quantum readiness educational resources reveals a consistent core of topics. These foundational elements appear to a greater or lesser degree in the majority of courses analysed, regardless of whether they target policy makers or business leaders. This suggests a fundamental knowledge base required for strategic decision-making in the quantum era has been established in the market. Table 12 presents the foundational topics and subtopics.

TABLE 12. CURRICULA COMMONALITIES

Topic	Subtopic
Quantum Technology Fundamentals	• Basic principles and concepts in quantum mechanics • Key quantum technology categories • Current capabilities and limitations
Quantum Technology Landscape	• Current state of quantum technology development • Key players and initiatives • Investment trends and market dynamics
Business/Organisational Impact Assessment	• Use cases and applications across industries • Strategic decision-making considerations
Strategic Planning & Roadmapping	• Organisational readiness assessment • Implementation planning • Timeline considerations for adoption
Quantum Risk Management	• Security implications • Risk mitigation strategies • Transition planning for quantum security

Quantum Readiness Courses: Case Study on Quantum Delta's "National Quantum Course"

On January 8, 2025, a key informant interview was conducted with Diederick Croese to elaborate on Quantum Delta's experience with the 'National Quantum Course' as a pathfinder for a potential ITCILO quantum readiness course. Diederick leads the Center for Quantum & Society at Quantum Delta. The Center's primary focus encompasses quantum readiness across multiple domains, including law and governance, as well as societal and ethical impacts. In addition to educational outreach such as the quantum readiness course, their work includes publishing detailed vertical-specific case studies, such as energy transition applications (ref. Just Transition section below), and toolkits such as the Exploratory Quantum Technology Assessment (EQTA). The organisation operates through four primary action lines: Research and Innovation, Quantum Ecosystem, Human Capital, and Societal Impact, with Croese heading the latter. The following sub-sections detail the development plans for the quantum delta course, as well as lessons learned and advice for ITCILO with regard to developing an in-house course on quantum readiness.

Quantum Delta Course Development: Quantum Delta is currently developing an English translation of the existing (Dutch-language) quantum readiness course, scheduled for release in February 2025 accompanied by new video content. The organisation plans to expand the course's availability to four to five additional languages later in the year. The course structure is being enhanced to incorporate multiple proficiency levels, following a framework similar to the European language proficiency scale (A1-C2). The current iteration provides A1-level coverage across three primary domains: IT/Software, Basic Knowledge, and Business Applications.

Alternative Learning Modalities: While quantum games are not integrated into the primary course structure (and there are no plans to include them), Quantum Delta maintains a separate engagement track focused on experiential learning. This includes for example, the development of quantum-themed escape rooms incorporating fundamental concepts such as the double-slit experiment as interactive elements. They also explore quantum art as a medium for building intuitive understanding of quantum phenomena.

Pedagogical Approach and Digital Divide Considerations: Quantum Delta notes the inherent challenges arising from the digital divide in quantum education with particular regard to the global south. They emphasise the importance of hands-on experience with quantum hardware, asserting that theoretical knowledge alone is insufficient. To address this gap, they are exploring the possibility of establishing hardware installations in developing countries to provide tangible learning experiences.

Quantum Delta has also identified important cultural and regional variations in quantum education communication. They noted significant differences in how quantum concepts are perceived and interpreted across different regions, as evidenced by varying search engine results for quantum-related queries. For instance, the Bloch sphere representation of qubits may not be as natively accessible to learners from a non-Western background. Quantum Delta is currently preparing a white paper addressing this subject.

Target Audience Differentiation: In advice to ITCILO, Mr. Croese supported the idea of common modules addressing 'strategic decision makers'. However, he stressed the importance of including differentiation for specific modules. For instance, a tailored module relating quantum impacts within the fields of standardisation and regulation would be highly valuable for policy makers, but not necessarily for corporate decision makers. Conversely, a module focusing on specific technological applications in industry and the associated financial impacts would not be as much use for the former group.

Collaboration Opportunities: During the interview, Quantum Delta expressed strong interest in partnering with ITCILO for course delivery. Currently, they maintain an active collaboration with the United Nations International Computing Centre (UNICC) and design customised activities for various partners. If the course development roadmap is implemented as mentioned above (including differentiation in target audience and technical depth), it may be beneficial for ITCILO to consider partnering with Quantum Delta for the center's quantum readiness capacity development needs.

Quantum Games: Making Quantum Mechanics Accessible

Gamification has emerged as a powerful pedagogical methodology across disciplines, demonstrating significant success in increasing learner engagement, knowledge retention, and conceptual understanding.[99] In quantum education specifically, games and interactive tools offer compelling solutions to some of the field's most challenging pedagogical barriers. As quantum technologies continue to evolve from laboratory curiosities to industrial applications, there is an increased need to make quantum concepts accessible – even when the target audience is not technical. Traditional approaches to teaching quantum mechanics often struggle to convey its counterintuitive concepts effectively, creating barriers to entry and understanding, particularly for learners without extensive mathematical backgrounds.[100]

Quantum games address these challenges by providing engaging, intuitive environments where learners can explore quantum phenomena through direct interaction and experimentation. These tools leverage the inherent advantages of gamification - including immediate feedback, progressive difficulty scaling, and intrinsic motivation.

The value proposition is multifaceted. Quantum games can:

- Make quantum concepts more approachable by providing visual and interactive representations of otherwise abstract mathematical principles.

[99] L. Putz, F. Hofbauer, H. Treiblmaier 2020, "Can gamification help to improve education? Findings from a longitudinal study", Science Direct, Volume 110, 106392

[100] Seskir et al. 2022. "Quantum games and interactive tools for quantum technologies outreach and education." Optical Engineering 61, 081809 - 081809.

- Support different learning preferences and levels of expertise, allowing for personalised learning paths.
- Reach broader audiences through familiar gaming interfaces, helping democratise quantum education.
- Contribute to quantum research through citizen science initiatives, bridging the gap between education and scientific advancement.

Our review consists of a snapshot of leading quantum games, analysing their pedagogical approaches, effectiveness, and potential impact on quantum education and literacy. The mapping can then be used as a resource for selecting games for incorporation in a potential ITCILO quantum readiness course. We present the mapping in table 13.

Furthermore, in next subsection, we present findings from an interview with subject matter experts in the field of quantum games in the next section. These findings are included to bolster the case for the inclusion of quantum games in any curriculum emerging from this research, as well as to provide insights into best practice for training delivery and future developments in the field.

TABLE 13. QUANTUM GAMES MAPPING

Developer	Title	Release	Platform	License	Type	Key Concepts	URL	Status
Science at home	Alice Challenge	2017	Web	Proprietary, Free	Citizen science	Ultracold atoms, experimental optimisation	NA	Not Active
IBM	Hello Quantum	2018	Web / iOS / Android	Apache Proprietary,	Puzzle game	Quantum gates	NA	Not Active
LearnQM	Particle in a Box	2016	Web / MacOS / Windows	Proprietary, Free	Single player	Superposition, energy levels	https://learnqm.gatech.edu/Semiconductor-Physics-Visualization/index.html	Active
LearnQM	Psi and Delta	2018	Web / MacOS / Windows	Proprietary, Free	Multi-player	Superposition, energy levels, colour-energy relationship	https://learnqm.gatech.edu/	Active
Virtual	Quantum Game (supersedes "Quantum Game with Photons" 2014)	2022	Webapp	MIT	Puzzle game	Photons, superposition, entanglement, and quantum measurement	https://lab.quantumflytrap.com/game	Active
Quarks Interactive	Quantum Odyssey	2020	Windows (Steam)	Proprietary, Paid	Puzzle game	Quantum circuits	https://www.quarksinteractive.com/quantum-odyssey/	Active
Science at home	Quantum Moves 2	2018	Web	Proprietary, Free	Citizen science	Ultracold atoms, optimal control, wavefunctions and transport	https://www.scienceathome.org/games/quantum-moves-2/	Active
Quantum Flytrap	Virtual Lab	2019	Webapp	Proprietary, Free	Simulator / Puzzle Game	Photons, Quantum Information, Measurement	https://lab.quantumflytrap.com/lab?mode=waves	Active

Developer	Title	Release	Platform	License	Type	Key Concepts	URL	Status
QPlayLearn	Photonic Trail		Webapp	Free	Single player	Immersive quantum optics single-player game that allows anyone from beginners to seasoned pros inculcate quantum optics concepts through game play. It is a treasure hunt with six missions that span the basics of quantum optics.	https://qplaylearn.com/treasure-hunt	Active
QPlayLearn	Q|Cards	2019	Tabletop / Mobile (iOS/Android)	Free	Single player / Multi-player	Basic notions of quantum computing, such as the concept of qubit. It uses IBM's Qiskit to either simulate a quantum circuit of 2 to 5 qubits resulting from the gameplay	https://qplaylearn.com/projects/qcards	Online version currently down
Chris Cantwell	Quantum Chess	2016	NA	NA	Multi-player	Superposition	https://www.kickstarter.com/projects/507726696/quantum-chess	Not Active

Quantum Games: Deep Dive into the Current 'State of Play'

On January 23, 2025, a key informant interview was conducted with Professor Evert Von Nieuwenberg and doctoral researcher Marien Raat of Leiden University[101] to explore the general dynamics of quantum games in order to better understand how these tools can add value to a potential ITCILO quantum readiness course development. Both respondents are researchers in the field of quantum education with specific expertise in quantum games as a pedagogical tool. The discussion yielded valuable insights across several key domains, including pedagogical effectiveness, implementation considerations, and future trajectories of quantum gaming in education. We present the findings in the subsections below.

Pedagogical Value: The key question with introducing a new device or methodology into educational programming is whether it can add value. Towards this end, quantum games have demonstrated particular efficacy in building intuition around complex quantum concepts. While most empirical research has focused on high school students, the experts stated that this effect extrapolates to adult learners as quantum games typically contain very few contextual elements (e.g. tic-tac-toe).

Additionally an obvious, but perhaps underappreciated strength of quantum games lies in their ability to facilitate the acquisition of appropriate technical vocabulary and fundamental concepts. The experts noted that quantum games can be helpful simply by providing course participants with a forum within which to engage with the unintuitive terminology and concepts in quantum mechanics, in contrast to lecture-based familiarisation.

In a general sense, the value of quantum games can be characterised as special case of gamification – for which there is ample literature demonstrating the benefits vis-à-vis educational outcomes[89]. This aligns with the contemporary understanding that successful science communication must transcend the traditional "deficit model" of simply providing information – and instead engage participants through interactive and experiential learning[102].

Considerations for Training Delivery: Several critical factors emerged regarding the successful implementation of quantum games in professional development contexts. The experts strongly emphasized the importance of "first-time user experiences," recommending at a minimum very well-designed tutorials for self-directed game play – but preferably guided demonstrations to familiarize users with game mechanics and interactions. This can be helpful even in the case of seemingly simple games such as quantum tic-tac-toe.

For professional adult learners, the experts suggested tailoring the technical depth of the introduction based on the audience's background. Technically adept learners benefit from more

[101] Professor Julia Cramer of Leiden University also provided input on quantum games impact measurement with reference to relevant literature

[102] Nisbet, M. C., & Scheufele, D. A. (2009). What's next for science communication? Promising directions and lingering distractions. *American Journal of Botany*, *96*(10), 1767-1778.

detailed explanations of the underlying quantum mechanics, while non-technical professionals can effectively engage with quantum concepts without deep theoretical understanding.

Future Developments and Sustainability: Looking ahead, the experts anticipate continued growth in the gamification approach to quantum education over the next five years. They highlighted some emerging trends:

- Increasing use of quantum games as research platforms for algorithm development (i.e. citizen science applications)
- Evolution of quantum game theory as a promising area for both theoretical insights and practical applications

Regarding future-proofing, the experts noted that most quantum games focus on quantum mechanical phenomena, which remain constant despite technological advances as they represent fundamental concepts in physics. This suggests that **current educational games will maintain their relevance for the foreseeable future**, as long as the interface remains useable and appealing to learners (though some application-specific games may require updates as quantum hardware capabilities evolve).

Development Ecosystem and Resources: The experts described an active and growing development community, supported by major technology companies like Google through game development initiatives. “Game jams” – events similar to hackathons – have become productive venues for quantum game creation, often featuring collaboration between quantum experts and software developers. The experts noted that within the community, a very large number of games have been documented[103], which far exceeds the quantum games detailed in table 13.

Just Transition: Impact of Quantum Technologies

As countries strengthen their efforts to decarbonise and green their economies, the concept of “just transition” has become central to ensuring this transformation is fair and inclusive for all communities. [104] In this context, quantum technologies are emerging as powerful enablers that could help address the associated technical and socioeconomic challenges, as well as potential threats that exacerbate certain inequalities. Quantum has the potential to facilitate significant technological advancements across the energy sector – including efficiency gains in renewables development, operation, and infrastructure management. These technologies should therefore be of key consideration for policymakers and strategic decision-makers in implementing more effective and equitable transition strategies.[105]

The applications of quantum technologies span the entire energy sector, from optimising renewable energy systems to improving grid management and accelerating decarbonisation efforts. These advances can support multiple aspects of just transition: enabling more accurate

[103] The database is maintained by Laura Piispanen at Aalto University

[104] https://climatepromise.undp.org/news-and-stories/what-just-transition-and-why-it-important

[105] https://interactive.flatland.agency/nl/tno-quantumpossibilities?layerId=bf5fcdd6-d2f2-4132-822b-62d2773e380a

planning and resource allocation, creating new skilled job opportunities in green technologies, and helping ensure reliable and affordable energy access across communities. For instance, quantum computing may prove valuable in optimising district heating networks for fairer heat allocation, while quantum sensing might improve the efficiency and safety of energy infrastructure in both urban and rural areas. At the same time, it is important to acknowledge that quantum technology development will not automatically support global development. As R&D and hardware intensive technology, especially for applications with dual use potential that might be subject to export/access controls, it will be important to consider mechanisms for unlocking benefits in lower income countries.

We provide here a summary of applications across Quantum Delta's taxonomy[10] of 6 areas where quantum technologies have the potential to effect significant change.

1. **Heat Applications:** Quantum technologies have the potential to enhance geothermal energy development and district heating efficiency. For geothermal, quantum gravimeters and enhanced optical fibre sensors enable more precise identification of underground reservoirs. In district heating, quantum computing may be able to optimise the complex task of heat allocation among suppliers while minimising transportation costs, leading to more efficient heat distribution networks.
2. **Carbon Applications:** The carbon sector has the potential to benefit from quantum technologies in multiple ways: enhanced pipeline integrity monitoring through advanced fibre optic quantum sensors, improved CO2 capture through quantum computing-aided material design, and more precise CO2 measurement and monitoring systems. Additionally, quantum simulations can accelerate the development of better catalysts for direct methane conversion and improving subsurface imaging techniques.
3. **Nuclear Applications:** In nuclear energy, quantum technologies might enhance safety and efficiency through several applications: highly sensitive radiation detection using quantum magnetometers, improved solving of complex differential equations crucial for fusion research, advanced particle tracking through quantum machine learning, and enhanced understanding of nuclear physics through quantum simulations. These advances could contribute to both operational safety and fundamental research in nuclear energy.
4. **Energy Grids Applications:** Quantum technologies have the potential to revolutionise grid management through multiple innovations: improved energy storage and conversion methods, precise transformer temperature monitoring, enhanced grid monitoring capabilities, and advanced material simulations for better batteries. Additional applications include community detection for optimal grid partitioning, rare-earth metal detection, cable detection and monitoring, and improved power flow optimization. The technology also enables better contingency analysis and more accurate energy usage forecasting.
5. **Wind Applications:** For wind energy, quantum technologies could improve efficiency through enhanced turbine blade pitch fault detection, better subsurface surveys using quantum-based LiDAR, improved underwater imaging for infrastructure inspection, and optimal turbine placement optimisation. The technology could also enable more accurate

wind direction alignment and improved short-term wind speed forecasting, leading to better integration of wind energy into power grids.

6. **Solar Applications:** In solar energy, quantum technologies have the potential to advance three key areas: optimal site selection for solar plants through quantum-enhanced multi-criteria decision making, improved material characterisation and defect detection in solar cells using quantum microscopy, and enhanced material simulation for developing more efficient solar cell materials, particularly for advanced technologies like perovskite-silicon tandems.

Researchers are also exploring the potential for quantum computers to serve society's increasingly hungry appetite for compute resources at a lower energy cost. While it is uncertain how quantum computers energy requirements might change as they scale, there is suggestive evidence that workhorse calculations, such as large scale matrix multiplications, might be more energy-efficient on quantum computers, especially analogue devices.[106]

ITCILO Courses: Ecosystem

The ITCILO has developed a respectable portfolio of courses addressing frontier technologies and their implications for the world of work. This review examines the existing course offerings to identify potential integration points for quantum computing content and analyse current pedagogical approaches in technology-focused training. The review focuses particularly on ITCILO courses with topic tags covering "**artificial intelligence", "innovation",** and **"future of work" -** as the tags relevant to these topics share similar challenges to quantum in translating complex technical concepts into actionable strategic knowhow.

Our analysis covers six relevant courses from ITCILO's current catalogue, ranging from foundational technology awareness to specialised professional development programs. These courses demonstrate ITCILO's established approach to teaching emerging technologies through a combination of theoretical frameworks and practical applications, while maintaining strong connections to social impact, policy implications, and workplace transformation. By examining these existing courses, we can highlight existing pedagogical strategies and institutional capabilities that could be leveraged for a potential ITCILO quantum readiness course, while also outlining opportunities in the current course offerings where quantum content could be integrated as part of a modular approach.

[106] See, e.g., https://spectrum.ieee.org/how-much-power-will-quantum-computing-need; https://arxiv.org/abs/2205.12092; https://www.pasqal.com/news/quantum-computing-rethinking-energy-consumption

ITCILO Courses: Pedagogical Approach Mapping

For the six identified courses, the pedagogical approaches are summarised below in table 14:

TABLE 14. ITCILO PEDAGOGICAL APPROACHES AMONGST QUANTUM-ADJACENT COURSES

Learning Delivery Methods	• Live webinars combining expert-led instruction with group discussion • Self-paced digital modules with multimedia content • Video lectures and presentations • Core readings and supplementary materials
Interactive Learning Components	• Live interactive webinars combining expert-led instruction with group discussion • Self-paced digital modules with multimedia content • Video lectures and presentations • Core readings and supplementary materials
Assessment Framework	• Continuous evaluation through module completion tracking, quizzes, participation metrics • Applied learning demonstrations through individual practical assignments and application exercises • Final assessment and certification through capstone assignment demonstrating practical application and digital certificates

ITCILO Courses: Potential Integrations

Whether or not a dedicated quantum readiness course is developed for the ITCILO education portfolio, the existing ITCILO courses bordering on frontier technologies present an opportunity for integrating quantum readiness elements. In table 15 we provide an analysis of where quantum technologies modules or smaller elements could be integrated with the six existing courses, including preliminary suggestions for the modality of integration. Courses should also incorporate appropriate caveats given the early stage of technology readiness in most cases and consider a discussion of different strategic approaches (e.g. R&D leader, fast follower, slow follower) and potential early warning signs to monitor for identifying technology inflection points.

In addition to the discrete integration recommendations, several cross-cutting themes are apparent for quantum technology integration across the courses, and potentially for broader application in the ITCILO educational ecosystem. In terms of regulatory and policy frameworks, courses could incorporate quantum technology considerations in governance discussions and address quantum-specific security and privacy implications. Skills development emerges as another important area, where existing technical frameworks could be updated to identify quantum-relevant competencies and map quantum literacy requirements for different professional roles. Additionally, policy-focused courses and modules could be enhanced to include comprehensive quantum technology impact assessments.[107] There may also be

[107] We note that, while the ITCILO course database contains no courses on 'policy' using the topic tag, there are at least four courses which directly address policy while using different tags.

opportunities to incorporate insights from quantum cognition[108] and quantum game theory[109] into training which includes content on team/public psychology, cognitive biases, and classical game theory.

TABLE 15. ITCILO EXISTING QUANTUM-ADJACENT COURSES & POTENTIAL QUANTUM MODULAR INTEGRATIONS

Course Name	Summary	Example Integration Points	Example Implementation Approach
AI for Social Impact and Public Policy	Five-week course exploring AI's intersection with public policy and social impacts	• Add module on quantum-AI convergence and implications for policy maker • Include quantum computing's impact on AI bias and fairness • Explore quantum-safe cryptography in AI governance	Integrate as a dedicated week focusing on quantum-enhanced AI and its policy implications within existing course structure
Artificial Intelligence Masterclass	Free masterclass covering AI's impact on training and workforce development	• Add lesson on quantum machine learning differentiation; Include quantum-AI hybrid approaches • Address quantum computing's role in future AI development	Create a new video lesson specifically on quantum-AI convergence, following existing expert presentation format
Analytics for Learning: Leveraging Data for Effective Training	Course on using data analytics to enhance learning design and decision-making	• Introduce discussion on quantum algorithms for educational data analysis • Include quantum-inspired optimisation techniques • Add quantum computing's impact on learning analytics	Incorporate quantum concepts within existing modules, particularly in the 'Future Trends' week
Learning Analytics Fundamentals	Self-guided introduction to learning analytics and data-driven decision-making	• NA	As this is a highly focused course on understanding learning analytics, there is no significant value in integrating quantum concepts
Data Analytics and Knowledge Management for Development	Comprehensive program on leveraging data analytics and knowledge management	• Include quantum computing in technology foresight • Address quantum impacts on knowledge management systems	Integrate quantum content into existing 'Big Data and Knowledge Management Nexus' and 'Future Trends' modules
The Future of Work in the Rural Economy	Course examining innovative approaches to promoting decent work in rural settings	• Include quantum technology's potential impact on the urban-rural digital divide • Address quantum computing's role in agricultural optimisation • Explore workforce preparation for quantum technologies	Add quantum considerations to existing modules on technological transformation and skills development

[108] E.g. https://www.annualreviews.org/content/journals/10.1146/annurev-psych-033020-123501, but noting quantum cognition remains an early, contested paradigm for understanding human psychology, e.g. https://link.springer.com/article/10.1007/s11238-016-9549-9

[109] E.g. https://en.wikipedia.org/wiki/Quantum_game_theory

Curriculum Framework

Table 16 presents our proposed curriculum framework. This framework suggests a **blueprint for developing quantum readiness courses** for strategic decision-makers. It addresses the unique challenge of preparing leaders for a technology domain characterised by high certainty of future impact, but significant uncertainty around timelines and specific applications.

Development of the framework stemmed from research and analysis described in the previous section. Topics and subtopics were collated from commonalities in existing quantum readiness courses, with particular focus on seven key resources offered by national quantum initiatives, multilateral organisations, and academic institutions. This was supplemented by analysis of pedagogical approaches used in ITCILO's existing technology-focused courses, investigation of quantum games as educational tools, and research into quantum technology applications in the just transition context. The framework also incorporates findings from key informant interviews and desk research on emerging quantum technology applications.

The framework is designed to be both comprehensive and flexible. It consists of **core modules that provide valuable knowledge** for all participants, **complemented by specialised tracks** that can be deployed based on specific contextual needs. The 'core modules' could have direct applicability to other ITCILO quantum-adjacent courses (see market research above). The 'specialised track' modules likely have a more niche applicability in a dedicated quantum readiness course, but there may be additional applicability with other ITCILO programming that was not revealed in our research. The modular structure allows for customisation while maintaining consistent foundational learning outcomes across different participant groups.

The framework was designed to address the following overall **course learning objectives**, with participants able to:

1. **[Core]** Explain fundamental quantum mechanical concepts using non-technical language
2. **[Core]** Analyse current and emerging quantum technologies and their potential applications
3. **[Core]** Evaluate uncertainties in quantum technology development roadmaps
4. **[Core]** Apply quantum readiness concepts across a global context
5. **[Core]** Implement monitoring frameworks to track quantum technology developments and their implications
6. **[Specialised Track: LMICs]** Identify specific risks and opportunities that quantum technologies present for LMICs
7. **[Specialised Track: LMICs]** Compare and contrast different policy approaches for quantum technology adoption in LMICs
8. **[Specialised Track: Just Transition]** Assess the impact of quantum technologies on energy sector just transition initiatives

9. **[Specialised Track: Corporate Decision Makers]** Assess the financial risks and opportunities of various mid-term quantum technology applications
10. **[Specialised Track: Policy Makers]** Reduce risk / optimize benefits vis-à-vis societal and economic impacts of quantum technologies

It is important to note that the modules described in the curriculum framework are a starting point only. When building out this framework into a course, it is **highly likely that thematic and practical overlaps will become apparent between modules**. This is particularly the case with the specialised track modules, which already contain some degree of overlap (e.g. LMIC modules vs. modules 9 and 10).

Initial Target Audience

While policy makers and organisational decision makers may operate in different contexts, the core knowledge requirements for quantum readiness exhibit significant overlap. Both groups need to understand quantum technology's implications, assess risks and opportunities, develop strategic responses, and make informed decisions about quantum adoption and regulation. Rather than creating entirely separate courses, a **unified target audience addressed with the core modules** would likely be more efficient at this nascent stage in quantum technologies development – **with limited specialised track modules** to address target audience differentiation.

This approach aligns with the observed trend in existing quantum readiness resources, where the fundamental principles and strategic considerations remain consistent across audiences, with the main differentiation occurring in the application and context-specific examples rather than the core content. **For the first ITCILO course on quantum readiness, we therefore propose a unified target audience of** "**strategic decision makers**", which encompasses both policy makers and organisational leaders who share common needs. These needs can be characterised as:

- Understanding quantum technology impact on their domain
- Evaluating risks and opportunities
- Making informed decisions about quantum readiness
- Developing implementation strategies
- Managing organisational change

Specialised track modules can then be instantiated for specific target audiences such as LMICs, policy makers or corporate decision makers.

Potential Partners

The market research detailed above reveals several potential strategic partners for ITCILO's quantum readiness curriculum development.

The European Quantum Research Centre (EQRC) and Quantum Flagship would be valuable primary partners, as they have already demonstrated success in delivering quantum readiness training specifically designed for policy makers. EQRC's existing "Quantum Technology Training for Policymakers" program aligns well with the ITCILO target audience, and their experience with the multi-lateral EU context could help inform approaches within the ILO/UN environment. The Open Quantum Institute, hosted at CERN, may also prove a potential partner, being a multilateral governance initiative working towards inclusive access to quantum computing and the development of applications for the benefit of humanity.

Additionally, Quantum Delta could serve as a valuable partner based on their experience with the Dutch "National Quantum Course." Their success in creating content that bridges technical and business audiences while maintaining strong connections to practical applications could work as a model for the ITCILO quantum readiness course.

TABLE 16. QUANTUM READINESS COURSE: PROPOSED INITIAL CURRICULUM FRAMEWORK

Topic	Category	Subtopics	Learning Objectives (able to:)[110]	Suggested Modalities
1. Quantum Technology Fundamentals	Core module	• Key quantum mechanics principles for non-technical audiences • Core quantum phenomena (superposition entanglement interference) • Key quantum technology categories • Current capabilities and limitations • Timeline perspectives (roadmap)	• Understand basic quantum principles without mathematical complexity • Identify and differentiate quantum technology categories • Assess current technological maturity levels • Recognise development horizons	• Interactive simulations • Visual demonstrations • Quantum games • Video presentations – researchers (ref. QD course)

[110] Unless otherwise mentioned, the objectives refer to the integration of quantum technologies (QT). We leave the term 'quantum technologies' out to save space.

Topic	Category	Subtopics	Learning Objectives (able to:)[110]	Suggested Modalities
2. Global Quantum Technology Landscape	Core module	• Current state of development • Key players and initiatives • Investment trends • International collaboration frameworks • Regional initiatives • Supply chain considerations	• Map the global quantum ecosystem • Track major quantum initiatives • Analyse investment patterns • Understand international dynamics	• Video presentations - industry experts • Market analysis exercises • Interactive mapping tools • Trend analysis workshops
3. Applications & Use Cases for Quantum Technologies	Core module	• Industry applications (energy, healthcare, finance, manufacturing) • Applications across social, economic, and environmental domains	• Recognise relevant applications • Understand implementation feasibility • Assess impact potential • Prioritise use cases	• Industry case studies • Application demonstrations • Impact analysis exercises • Video presentations - industry experts
4. Strategic Planning & Implementation for Quantum Technologies	Core module	• Organisational readiness assessment • Implementation planning • Timeline considerations • Resource requirements • Capacity building • Change management • Stakeholder engagement	• Conduct readiness assessments • Develop implementation roadmaps • Design capacity building programs • Create stakeholder engagement plans	• Planning workshops • Strategy development exercises • Implementation simulations • Project planning tools
5. Quantum Risk Management	Core module	• Security implications • Risk assessment methods • Transition planning • Infrastructure protection • Data protection • Standards and compliance • Monitoring frameworks	• Identify quantum-related risks • Design risk mitigation strategies • Plan security transitions • Develop monitoring approaches	• Risk assessment exercises • Security simulations • Video presentations - industry experts • Case study analysis
6. LMIC-Specific Risks & Opportunities in the Quantum context	Specialised Track: LMICs	• Infrastructure requirements • Human capital development • Technology access considerations • Economic impact assessment • Leapfrogging opportunities • Partnership models • Resource allocation strategies	• Identify LMIC-specific constraints • Evaluate development opportunities • Assess resource requirements • Design partnership strategies	• Regional case studies • Video presentations - expert interviews • Group discussions • Scenario planning • Impact assessment exercises

Topic	Category	Subtopics	Learning Objectives (able to:)[110]	Suggested Modalities
7. LMIC Policy Considerations for Quantum Technologies	Specialised Track: LMICs	• National strategy development • Regulatory frameworks • Governance structures • Education/workforce development • International cooperation • Technology transfer; Industrial policy	• Design national quantum strategies • Develop policy frameworks • Plan workforce development • Create cooperation mechanisms	• Policy analysis workshops; • Strategy development exercises • Comparative policy studies • Stakeholder consultations
8. Just Transition Considerations for Quantum Technologies	Specialised Track: Just Transition	• Energy sector implications of QT • Workforce development • Social equity • Environmental impact • Economic transition • Policy integration	• Understand transition implications • Plan workforce adaptation • Integrate quantum in the development of equitable strategies • Integrate environmental considerations	• Transition planning workshops • Impact assessment exercises • Stakeholder engagement simulations • Policy integration exercises
9. Financial risks and opportunities of quantum technology applications	Specialised Track: Corporate Decision Makers	• Investment Landscape and Market Analysis (market size projections, trends, key players) • Risk Assessment Framework (technology readiness level, risk mitigation) • Application-Specific exploratory ROI • Strategic Positioning (build vs. buy decisions, partnership, IP) • Quantum-Ready Business Planning (budgeting, HR skills, infrastructure)	• Evaluate market dynamics and investment opportunities across different industry sectors. • Assess financial risks and develop mitigation strategies for investments. • Apply ROI analysis frameworks to implementation decisions. • Design strategic roadmaps for adoption within organisational constraints.	• Case studies • Group discussions • Scenario planning • Impact assessment exercises • Guest speakers from industry
10. Optimising the regulatory environment for quantum technologies	Specialised Track: Policy Makers	• Regulatory frameworks for frontier technologies (incl. best practice in quantum from other jurisdictions) • Innovation vs. risk management (quantifying uncertainty and potential impact) • Steering innovation via anticipatory governance	• Evaluate regulatory frameworks and mechanisms for governance • Apply structured risk assessment methods • Design adaptive governance mechanisms • Develop frameworks for international cooperation	• Policy analysis workshops; • Comparative policy studies • Guest lectures from policy experts / academics / regulators

3.3. Suggestions summary

Respecting a focus on practical steps for a 2030 time horizon and the inherent uncertainties/ subjectivities in quantum technology, it is fortunate that many sensible steps to be taken for uncertain future quantum technologies line up with worthwhile steps for exploiting existing technologies.

For instance, modern AI has the potential to help many previous learning technologies to fulfil their potential.

- The high drop-out rates of self-serve MOOC courses without human instructors might be improved with generative AI driven tutors. ITCILO's existing MOOC-type courses provide a natural entry point for testing these ideas.
- 'Just-in-time' micro-learning struggles with manual delivery of the creative and personalised process necessary to know a person's circumstances well enough to suggest/craft the relevant micro-learning at the right time; again, AI may be able to help and existing ITCILO content/customers may be available to trial such ideas.
- The promise of immersive learning and the metaverse may require next generation simulation fidelity and AI-powered co-participants, along with real-time generation of diverse scenarios. For instance, the 'bodyswap' extended reality tool helps people gain soft skills and grasp team dynamics more vividly by switching into different roles or re-living someone else's experience through their eyes.[111]
- The narrow applicability today of adaptive learning to domains that easily generate very large, computer-assessable question banks (e.g. mathematics up to age 16) may be broken open by generative AI that provides 'good enough' assessment of complex, scenario-based, text-based answers against a scoring rubric (good enough for adaptive learning trajectories, even if not used for actual end of module assessment/credentialisation).

In all of these cases, it is possible – but unknown today – whether the full pedagogic benefits will require a push beyond classical computing AI into a quantum computing domain. However, we can be confident that generic AI technologies alone will not unlock the full pedagogic benefits within a learning domain; for this, we need co-design partnerships with educators and a test & learn philosophy. For instance, off-the-shelf LLMs currently provide encyclopedia-style essays in response to technical queries. An LLM designed to help a user learn rather than simply access information would be designed differently. By knowing a user's level and knowledge, an LLM could help them to answer the question they ask themselves (or at least identify likely options, rule out certain candidates, or specify the calculation structure). By providing appropriate hints and scaffolding structure/knowledge, the LLM could keep the process engaging, while maintaining enough 'friction' to support genuine learning. LLMs could also be integrated with tools that proactively build and apply insights from spaced repetition to embed learning.

[111] See start-up https://bodyswaps.co/ using this technology to enhance interpersonal skills in healthcare to improve patient outcomes, among other use cases.

With modern AI providing a practical motivation to re-visit these technologies today with renewed pedagogical expertise, ITCILO can build the domain experience, specific datasets, use cases, and optimisation descriptions that are precursors to serious conversations about quantum computing, whether as a complementary or an alternative solution technology to classical computing in the future.

Ultimately, the most exciting impact will likely come from combining emerging technologies. Insights from personal neurotechnology wearables about what content we are best placed to learn in which circumstances; insights from an Internet of Things infrastructure helping us learn about ourselves, our learning environments, and group dynamics; real-time social network insights to curate opportunities for people to connect and topics to discuss – all of these and more will require AI to process large-scale datasets and unlock their potential.

In the context of quantum technology applications for learning, our primary suggestions are to foster quantum readiness within the ITCILO by:

- **Enhancing exploratory work with current non-quantum technologies that are also en route to potential high impact quantum technology use cases beyond the 2030 time horizon**, particularly AI-enriched provision such as adaptive/personalised learning, and tutor chatbots.
- **Emphasising the design of business processes and data collection required for these high impact use cases to fulfil their potential**, which is necessary regardless of whether they use present-day classical technology or potential future quantum technology. This can include introducing more automated assessment check-points during courses, more personalisation in course content, more learner choice in learning pathways, and more chatbot/hybrid approaches to facilitate learning. Such processes empower experimentation and data collection that could unlock high impact adaptive/personalised learning and tutor chatbots. See the top 3 rows in table 10 for more details.
- **Identifying points in the above exploratory work where classical compute technologies might face limitations in addressing specific use case ambitions** (such as volume of data to analyse, quality of optimisation heuristics available, speed of processing etc.) or where knock-on breakthroughs in other technologies combine to create new opportunities. Such points represent areas where quantum technologies might prove impactful, help to identify specific quantum capabilities to monitor for, and can form the basis of practical conversations with quantum computing providers.
- **Monitoring quantum technology progress and societal trends**, with a particular eye to potential developments that unlock the use cases discussed in this report, including those in text boxes 2 & 3 in the executive summary.
- **Leveraging excitement about quantum mechanics and quantum technologies** (including the UN International Year of Quantum Science and Technology) to engage resources, partners, and pilot users in the above initiatives.

Regarding the potential to accelerate work and capitalise in IYQ 2025, ITCILO may wish to develop synthetic datasets and example optimisation problem descriptions for testing proof-of-concept algorithms for high interest learning use cases (e.g. table 10). Such material can form the basis for initiating a conversation and potential consultancy support with quantum computing providers, to understand where existing quantum techniques might contribute to the overall optimisation problem (as proof-of-concept as part of quantum readiness, rather than pursuing quantum advantage or cost-effectiveness vs classical supercomputers). The material can similarly be used to engage potential ITCILO partners to provide access to a quantum computer in 2025 or 2026. For instance, ITCILO might consider resources in Europe, such as the Barcelona cluster (BSC-CNS, anticipating 30 superconducting transmon qubits by end 2025), other sites in Czechia, Germany, France, Italy, and Poland[112], the IBM clusters in London, Dublin, Paris, Rome, and elsewhere, as well as other locations, to be advised and prioritised based on ITCILO accessibility.

In the context of readiness for potential policy priorities, including capabilities to monitor emerging quantum technologies for further learning applications, our primary suggestions are for the ITCILO to help foster quantum readiness across the ecosystem by:

- **Developing a quantum readiness course for policymakers and strategic decision makers (potentially in partnership with the ILO or others).** Such a course could provide introduction/myth-busting for key concepts, a framework for officials to identify priority topics and early warning signs, and strategic options for how best to monitor/engage with evolving developments. See table 16 for initial ideas on the curriculum framework for such a course. As a secondary priority, ITCILO might consider quantum-readiness content aimed at other groups, such as students who might be well-placed to build skills/networks so they might support society in the future with quantum technology related transitions.
- **Identifying a dedicated quantum technologies point of contact resource, potentially in the ILO's Observatory on AI and Work in the Digital Economy.** This resource would ideally have capacity to monitor both quantum computing advancements and other quantum technologies, in order to increase in-house knowledge, support internal discussions, and help generate ideas for enriching ITCILO's course design/delivery.
- **Incorporating quantum technology related content into existing ITCILO courses.** Such integrations would typically focus on direct applications of quantum technology, such as those described in table 15. However, integrations could also include indirect applications. For instance, playing quantum games might provide a novel, engaging method for inspiring learners to think about complex, non-linear systems with unanticipated equilibria, with a learning outcome based on a general mindset rather than the specific relevance of quantum mathematics for a given policy scenario.
- **Incorporating appropriate evaluation and updating processes into the above courses**, noting particular challenges around ensuring participant understanding of technically complex subject matter and the fast-changing technology and research/corporate landscape.

[112] https://digital-strategy.ec.europa.eu/en/policies/quantum

- **Promoting the exploration of requirements, constraints, and theory involved in higher quality modelling of workplaces, supply chains, and economies/populations**, both as useful activities for exploiting existing computer/supercomputer capabilities and as necessary inputs for assessing if any components of that modelling might be amenable to specific quantum computer analysis.
- **Leveraging excitement about quantum mechanics and quantum technologies** (including the UN International Year of Quantum Science and Technology) to engage resources, partners, and pilot users in the above initiatives.

We see significant benefit in quantum content being streamlined into multiple courses, rather than silo'ed in specific 'quantum technology' modules. Small, non-technical references to quantum technology in appropriate context and based on concrete examples will help raise quantum literacy across the board and help channel interest into more detailed, dedicated quantum readiness courses, which otherwise risk being seen as the domain of experts only.

These suggestions also reflect the necessary limitations of this report. There is significant uncertainty in our assessments, due both to the nature of the field (fast-changing, lacking in consensus, complexity of underlying technology) and to the nature of the research (a rapid, generalist assessment, driven primarily by secondary sources[113]). Given these limitations and the apparent lack of immediately-deployable use cases of relevance to learning delivery, the focus is appropriately put on monitoring, preparation, and readiness. Short-term attention on learning applications is better invested in complementary technologies (e.g. personalised/adaptive learning, chatbot tutors, simulations) and other areas of the emerging technologies taxonomy (e.g. neurotech, AR/VR).

The collective goal across these suggestions is to leverage excitement and the intrinsic fascination with quantum technologies to initiate a shift in mindset.

For instance, regarding technologies for learning, we might provoke a mindset shift from "what data can we analyse today" or "what learning software can we purchase today" to "how can we change business processes to gather new types of data that unlock impact pathways for current and future technologies (including but not limited to quantum technologies)" and "who can we partner with to trial minimum viable products en route to a possible future goal".

Regarding quantum readiness for officials, we might provoke a mindset shift from seeing quantum technologies as impenetrable mathematics of interest only to physicists, to seeing themselves as active participants able to choose from diverse strategies to suit their needs in the context of an evolving ecosystem of emerging technologies (including but not limited to quantum technologies).

[113] See methodology sections for more detail. Indicatively, the eight quantum strands have had 1-2 days of assessment each in Part II, with 4-5 days dedicated to each of the two priority areas for Part III (AI/ML algorithms; quantum readiness courses) and enriching earlier work with Part III insights, with remaining time focused on Part I.

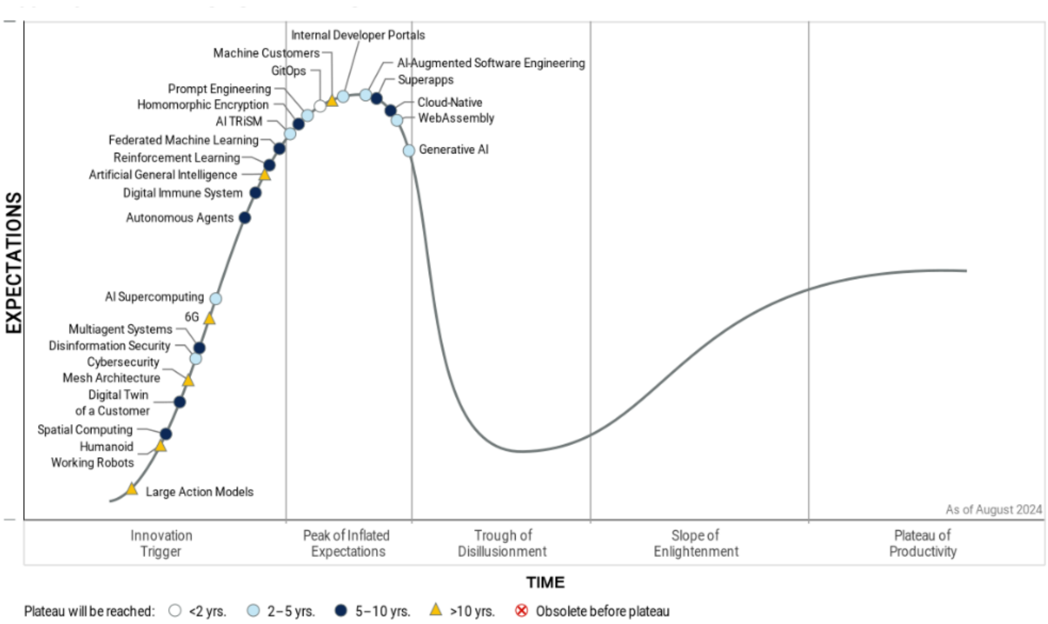
The overarching mindset shift to which these approaches might make a modest contribution is moving away from 'blue sky' brainstorming sessions limited to half-day off-sites towards one where technology-related ideas for creativity, innovation, and disruption are explored as part of day-to-day working life. A mindset in which the future has already started – and we seize its opportunities today.

APPENDIX 1 – PRIORITISED TAXONOMIES FOR COMPARISON

Gartner's Hype Cycle for Emerging Technologies (published Aug 2024)

Link:

https://www.gartner.com/en/newsroom/press-releases/2024-08-21-gartner-2024-hype-cycle-for-emerging-technologies-highlights-developer-productivity-total-experience-ai-and security



The IEEE's Technology Taxonomy (published Jul 2024)

Link: https://www.ieee.org/publications/services/thesaurus-thank-you.html

This four-layer taxonomy takes 78 A4 pages to be specified in full. The first page provides a representative view of the level of detail and type of item included:

Aerospace and electronic systems

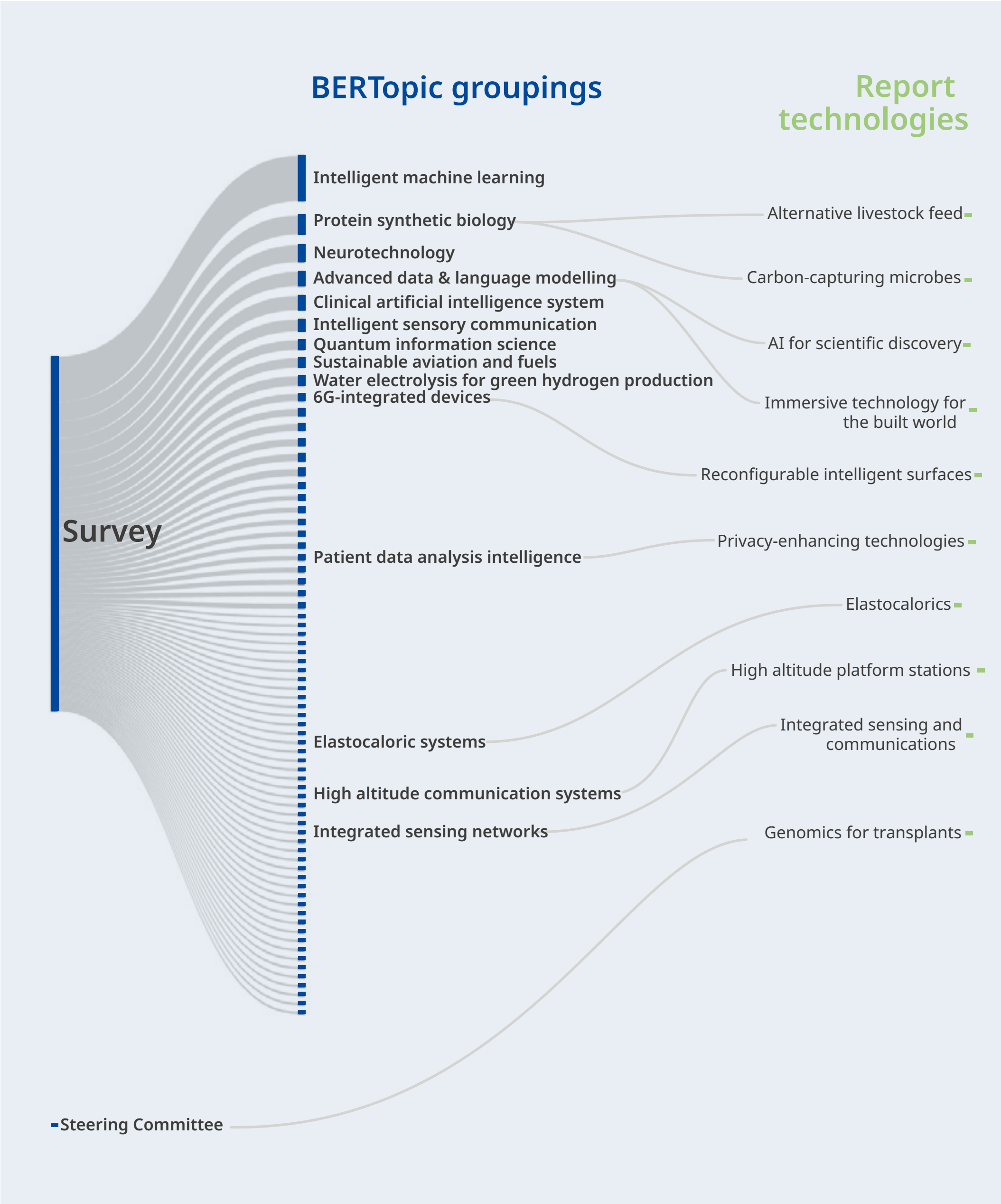
....Aerospace control
........Air traffic control
........Attitude control
........Ground support
....Aerospace engineering
........Aerospace biophysics
........Aerospace electronics
........Aerospace safety
............Air safety
........Aerospace simulation
........Aerospace testing
............Wind tunnels
........Artificial satellites
............Earth Observing System
............Low earth orbit satellites
............Military satellites
............Space stations
........Space technology
............Payloads
............Space debris
............Space exploration
....Aerospace materials
........Aerospace components
....Aircraft manufacture
....Aircraft navigation
....Aircraft propulsion
........Propellers
....Command and control systems
....Electronic warfare
........Electronic countermeasures
........Jamming
........Radar countermeasures
....Military equipment
........Military aircraft
............Payloads
........Military satellites
........Military vehicles
........Weapons
............Biological weapons
............Chemical weapons
............Guns
............Missiles
............Nuclear weapons
............Projectiles
............Weapons of mass destruction
....Sensor systems
........Activity recognition
............Human activity recognition
........Gunshot detection systems
....Sonar
........Side-scan sonar
........Sonar applications
............Sonar detection
............Sonar measurements
........Sonar equipment
............Echo sounders
........Synthetic aperture sonar
....Telemetry
........Biomedical telemetry

Antennas and propagation

....Antennas
........Antenna accessories
............Radomes
........Antenna arrays
............Adaptive arrays
............Butler matrices
............Linear antenna arrays
............Log periodic antennas
............Microstrip antenna arrays
............Microwave antenna arrays
............Phased arrays
............Planar arrays
........Antenna radiation patterns
............Near-field radiation pattern
........Antenna theory
............Frequency selective surfaces

The World Economic Forum's 10 emerging technologies (published Jun 2024)

Link: https://www.weforum.org/publications/top-10-emerging-technologies-2024/



US government 2024 Critical and Emerging Technologies List (Feb, 2024)

Link: https://www.whitehouse.gov/ostp/news-updates/2024/02/12/white-house-office-of-science-and-technology-policy-releases-updated-critical-and-emerging-technologies-list/

CRITICAL AND EMERGING TECHNOLOGIES LIST UPDATE

Critical and Emerging Technologies List

The following critical and emerging technology areas are of particular importance to the national security of the United States:

- Advanced Computing
- Advanced Engineering Materials
- Advanced Gas Turbine Engine Technologies
- Advanced and Networked Sensing and Signature Management
- Advanced Manufacturing
- Artificial Intelligence
- Biotechnologies
- Clean Energy Generation and Storage
- Data Privacy, Data Security, and Cybersecurity Technologies
- Directed Energy
- Highly Automated, Autonomous, and Uncrewed Systems (UxS), and Robotics
- Human-Machine Interfaces
- Hypersonics
- Integrated Communication and Networking Technologies
- Positioning, Navigation, and Timing (PNT) Technologies
- Quantum Information and Enabling Technologies
- Semiconductors and Microelectronics
- Space Technologies and Systems

CRITICAL AND EMERGING TECHNOLOGIES LIST UPDATE

Critical and Emerging Technology Subfields

Each identified CET area includes a set of key subfields that describe its scope in more detail.

Advanced Computing

- Advanced supercomputing, including for AI applications
- Edge computing and devices
- Advanced cloud services
- High-performance data storage and data centers
- Advanced computing architectures
- Advanced modeling and simulation
- Data processing and analysis techniques
- Spatial computing

Advanced Engineering Materials

- Materials by design and material genomics
- Materials with novel properties to include substantial improvements to existing properties
- Novel and emerging techniques for material property characterization and lifecycle assessment

Advanced Gas Turbine Engine Technologies

- Aerospace, maritime, and industrial development and production technologies
- Full-authority digital engine control, hot-section manufacturing, and associated technologies

Advanced and Networked Sensing and Signature Management

- Payloads, sensors, and instruments
- Sensor processing and data fusion
- Adaptive optics
- Remote sensing of the Earth
- Geophysical sensing
- Signature management
- Detection and characterization of pathogens and of chemical, biological, radiological and nuclear weapons and materials
- Transportation-sector sensing
- Security-sector sensing
- Health-sector sensing
- Energy-sector sensing
- Manufacturing-sector sensing
- Building-sector sensing
- Environmental-sector sensing

+ 3 similar pages

InnovateUK's 50 emerging technologies (published Dec 2023)

Link: https://www.ukri.org/publications/insights-report-innovate-uks-50-emerging-technologies/

The results are not explicitly presented in a taxonomic grid, but the table of contents provides visibility of the two layer hierarchy, with seven top level categories and 4-9 second level items organised by top-level category.

Our showcase technologies are highlighted in bold.

The European Parliament's Key Enabling Technologies study (published Dec 2021)

Link: https://www.europarl.europa.eu/thinktank/en/document/EPRS_STU(2021)697184

The body of the report provides further example applications under each KET, but does not claim comprehensive listing.

Six KET and their major applications

NSF Key technology areas (current; no date)

Link: https://new.nsf.gov/focus-areas/technology

Key technology areas

- Advanced Manufacturing
- Advanced Materials
- Artificial Intelligence
- Biotechnology
- Communications and Wireless
- Cyberinfrastructure and Advanced Computing
- Cybersecurity
- Disaster Risk and Resilience
- Energy Technology
- Quantum Information Science
- Semiconductors and Microelectronics

APPENDIX 2 – POTENTIAL ADDITIONAL INFRASTRUCTURE DOMAINS

We do not currently include domains which could be considered either inputs to these technologies (e.g. R&D spend, education levels, collaboration technologies) or soft technologies adjacent to the current domains (e.g. governance, standards/protocols, ethics infrastructures).

Borderline candidates for inclusion include:

- **Mathematics/algorithms**, where the number of mathematical systems we can develop, the bounds on various mathematical claims, the diversity & computational efficiency of functions we can implement algorithmically, and the proofs we demonstrate are powerful inputs for the four infrastructure domains as well as the application layer. This would include foundational research into new quantum algorithms which might then lead to specific technologies for a future version of this taxonomy.
- **Data/knowledge**, where the amount of information we have as a society and our understanding of how the world works forms the base on which contemporary science builds, the resource we have available to train AI, and the content for educating the next generation. This would include foundational knowledge about quantum mechanics that might lead to specific technologies, but would not yet have led to additional items in our foundational technology taxonomy.

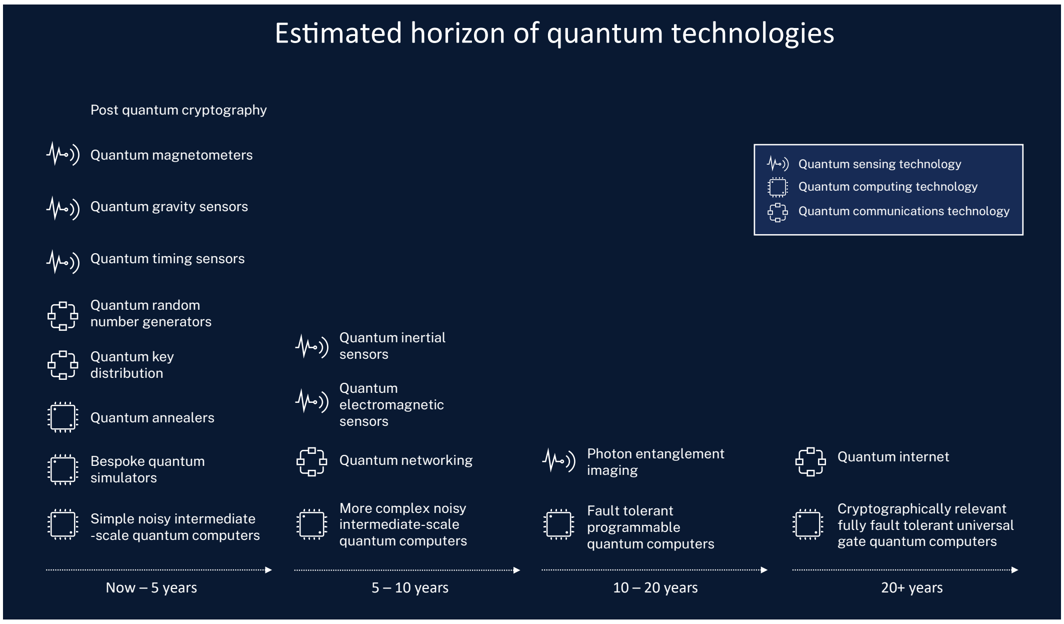
Both are excluded as they are nearer to foundational intellectual research, rather than the current infrastructural items whose metrics and technologies are closely related to the physical world.

APPENDIX 3 – EXAMPLE GOVERNMENT STRATEGIES AND ROADMAPS

Australia

National Quantum Strategy. (2023). Australian Government, Department of Industry, Science and Resources. https://www.industry.gov.au/publications/national-quantum-strategy

Provides an estimated horizon for technologies, copied below



Canada

National Quantum Strategy. (2022). Innovation, Science and Economic Development (ISED). https://ised-isde.canada.ca/site/national-quantum-strategy/sites/default/files/attachments/2022/NQS-SQN-eng.pdf

Public document focuses on spend and strategy over roadmap date targets for specific technologies

China

New Generation Artificial Intelligence Development Plan. (2017). China State Council. https://digichina.stanford.edu/work/full-translation-chinas-new-generation-artificial-intelligence-development-plan-2017/

European Union

European Quantum Communication Infrastructure Initiative (EuroQCI). (launched 2019, first implementation in 2023). European Commission, Directorate-General for Communications Networks, Content and Technology

https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci

Quantum Technologies Flagship Report. (launched 2018, major report in 2023). European Commission, Directorate-General for Communications Networks, Content and Technology (DG CONNECT).

https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship

Digital Decade. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en

https://digital-strategy.ec.europa.eu/en/policies/quantum

Summary site, including ambitions for its "first supercomputer with quantum acceleration by 2025, paving the way to being at the cutting edge of quantum capabilities by 2030."

France

France 2030: National strategy for quantum technologies. (2023; earlier strategy launched 2021)

https://www.entreprises.gouv.fr/priorites-et-actions/autonomie-strategique/soutenir-linnovation-dans-les-secteurs-strategiques-14

France National Quantum Strategy: Annual report, March 2023.

https://www.info.gouv.fr/upload/media/organization/0001/01/sites_default_files_contenu_piece-jointe_2023_04_france2030_quantique_rapport_activite_2022_vdef2.pdf

Germany

Quantum Technologies: Conceptual Framework Programme of the Federal Government. (2023). Federal Ministry of Education and Research.

https://www.quantentechnologien.de/fileadmin/public/Redaktion/Dokumente/PDF/Publikationen/Quantum-Technologies-Conceptual-Framework-2023_english_bf_C1.pdf

https://qbn.world/wp-content/uploads/2023/04/Action-Plan-Quantum-Technologies-by-German-Government-2023-2026.pdf

https://thequantuminsider.com/2023/05/03/germany-announces-3-billion-euro-action-plan-for-a-universal-quantum-computer/

By 2026, expecting around 100 qubits - and eventually reach 500 qubits "in the medium term"

By 2026, five new products in quantum sensor technology on the market and optical clocks that meet the requirements of the next generation of Galileo clocks.

By 2026, tap-proof quantum communication between selected authority locations and demonstration of first quantum repeater test tracks

India

National Quantum Mission. (2023). Indian Department of Science and Technology (DST).

https://dst.gov.in/national-quantum-mission-nqm

From 2023/24 to 2030/31, ambitions include:

- Develop intermediate scale quantum computers with 20-50 physical qubits (3 years), 50-100 physical qubits (5 years) and 50-1000 physical qubits (8 years) in various platforms like superconducting and photonic technology.
- Develop satellite based secure quantum communications between two ground stations over a range of 2000 kilometers within India as well as long distance secure quantum communications with other countries.
- Develop inter-city quantum key distribution over 2000 km with trusted nodes using wavelength division multiplexing on existing optical fibre.
- Develop multi-node quantum network with quantum memories, entanglement swapping and synchronized quantum repeaters at each node (2-3 nodes).
- Develop magnetometers with 1 femto-Tesla/sqrt(Hz) sensitivity in atomic systems and better than 1 pico-Tesla/sqrt(Hz) sensitivity in Nitrogen Vacancy-centers; gravity measurements having sensitivity better than 100 nano-meter/second2 using atoms and atomic clocks with 10-19 fractional instability for precision timing, communications and navigation.
- Design and synthesis of quantum materials such as superconductors, novel semiconductor structures and topological materials for fabrication of quantum devices for development of qubits for quantum computing and quantum communication applications, single photon sources/detectors, entangled photon sources for quantum communications, sensing and metrological applications.

Mission details available via, e.g.,: https://onlinedst.gov.in/Documents/ProjectProposalFormat/SchemeId_2332_NQMCallDocumentforPre_Proposals.docx; https://www.shankariasparliament.com/blogs/pdf/national-quantum-mission

Italy

National Quantum Science and Technology Institute (NQSTI). (2023). Italian Ministry of University and Research.

https://www.mur.gov.it/sites/default/files/2023-02/D.D.%20341%20_PE0000023_rev131022NF.pdf

Quantum Italy Deployment (QUID): Implementation of Quantum Communication Network. (2023). Italian Ministry of Innovation.

https://www.inrim.it/sites/default/files/2023-06/Press%20Release%20QUID_DEF_ENG_20230606_2.pdf

Japan

Quantum Technology Innovation Strategy. (2022). Japanese Cabinet Office.

https://www8.cao.go.jp/cstp/english/quantum/index.html; https://www8.cao.go.jp/cstp/english/strategy_r08.pdf

“10s to 100s of logical qubits by 2030”; “10 million quantum technology users in Japan by 2030”

Singapore

National Quantum Strategy. (2024). https://nqo.sg/nqs/

5 year strategy; public material focuses on spending and strategy rather than a specific technology roadmap

Singapore’s Quantum Engineering Programme (QEP) launched in 2018 https://qepsg.org/

South Korea

South Korea’s Quantum Science and Technology Strategy. (2023). Ministry of Science and ICT (MSIT)

https://www.msit.go.kr/eng/bbs/view.do?bbsSeqNo=42&mId=4&mPid=2&nttSeqNo=828&sCode=eng&searchOpt=ALL

By 2035: Develop a 1,000-qubit quantum computer with South Korean technology; initiate an intercity quantum network; develop state-of-the-art quantum sensors

UK

National Quantum Strategy. (2023). UK Government, Department for Science, Innovation and Technology.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1142942/national_quantum_strategy.pdf

See also example roadmap dates in the national quantum strategy missions (updated Dec 2023):
https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions

- 2028 extend beyond the NISQ-era with a million quantum operations, for applications associated with the simulation of chemical processes, helping to improve catalyst design for example.
- 2028 quantum-enabled brain scanners will enable precision-guided surgery for children suffering severe neurological disease
- 2030 mobile, networked quantum sensors will have unlocked new situational awareness capabilities, exploited across critical infrastructure in the transport, telecoms, energy, and defence sectors

- 2032 demonstrate large-scale error correction capabilities with a billion quantum operations, with applications including accelerated drug discovery.
- 2035 achieve quantum advantage at scale through reaching a trillion quantum operations, enabling applications such as optimising the production of clean hydrogen.
- 2035 a quantum network, to be known as 'year 0' of the quantum internet

US

National Quantum Initiative Act. (2018). United States Congress.

https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf

A National Strategic Overview for Quantum Information Science. (2018). NSTC.

https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

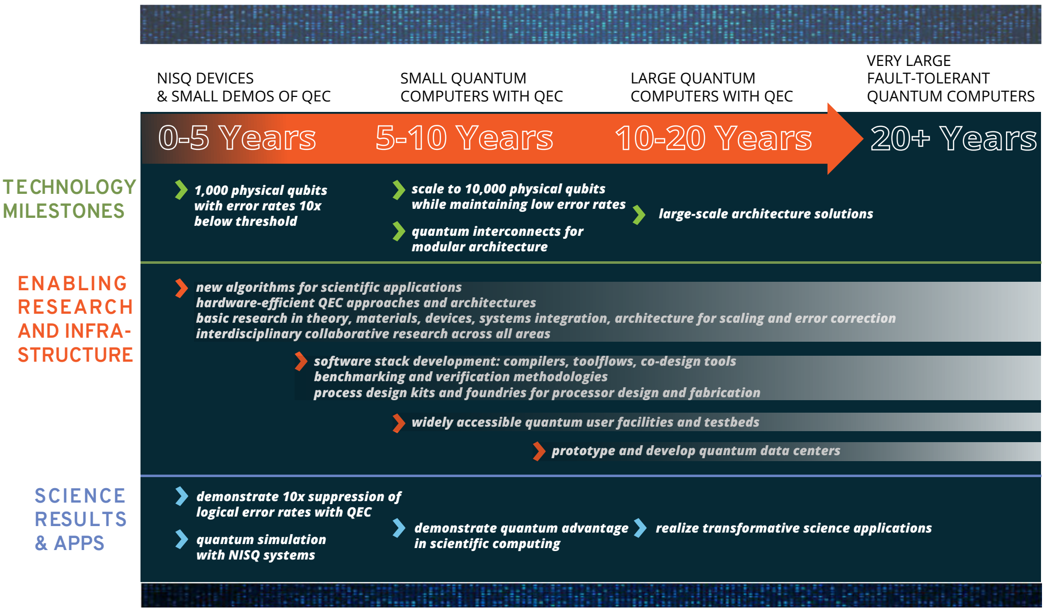
https://www.quantum.gov/strategy/ (provides annual reports on the National Quantum Initiative Program)

2024 Quantum Information Science Applications Roadmap. (2024). US Dept of Energy (technical report).

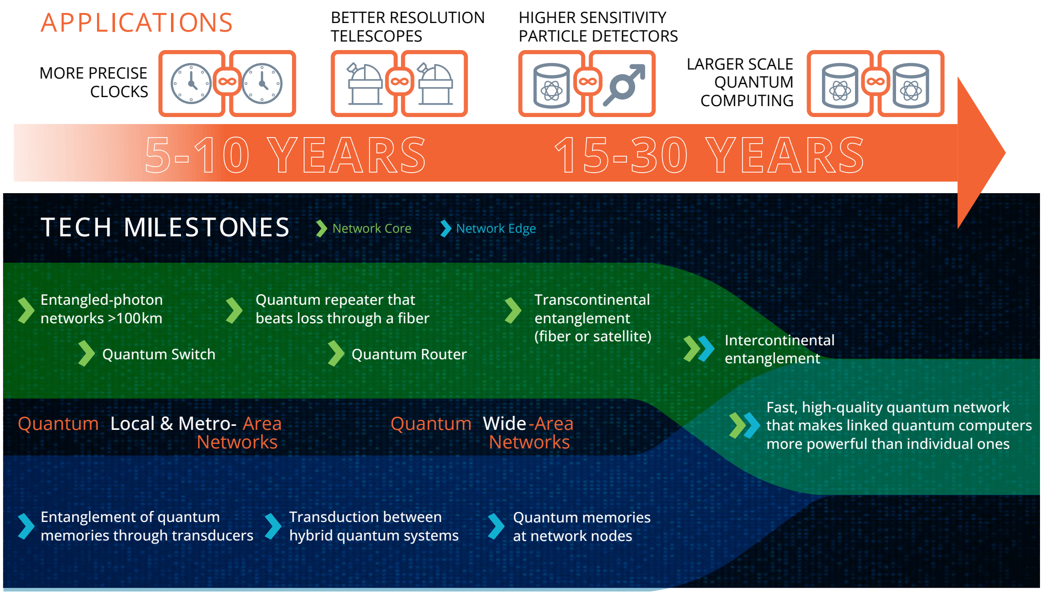
https://www.quantum.gov/wp-content/uploads/2024/12/DOE_QIS_Roadmap_Final.pdf

See also the National Quantum Initiative Supplement To The President's FY 2025 Budget. A report by the Subcommittee on Quantum Information Science (Committee on Science of the National Science & Technology Council). (Dec 2024). https://www.quantum.gov/wp-content/uploads/2024/12/NQI-Annual-Report-FY2025.pdf

The 2018 public documents mostly focus on spend and strategy over roadmap date targets for specific technologies; noting that post-quantum cryptography timelines are discussed elsewhere in the main report. The 2024 technical roadmap includes various timelines, copied in full below:



Development of quantum computing capabilities relevant to the DOE mission.
Over the next 20 years, the capabilities of quantum computing systems to tackle scientific problems relevant to the DOE will increase substantially. During this period, the role of quantum computers in accelerating scientific discovery will be fully established. Achieving the transitions between the eras noted requires innovations across the hardware, software, and systems stacks. Each era will unlock new scientific results, starting with modest beyond-classical computations, growing into problem-specific quantum advantages, and maturing into large-scale, scientifically relevant applications.



Timeline for developing quantum network applications.
Applications appear at the top of the timeline with corresponding technological developments shown below, categorized into "network core" and "network edge."

	1-5 Years	5-10 Years	10+ Years
PRECISION MEASUREMENT FOR NEW PHYSICS	Quantum control techniques to extend searches for new physics with quantum sensors Develop new precision measurement platforms for next-gen searches for new physics	Next-gen quantum sensing searches for new physics, targeting parameter space with highest potential for new discoveries Entanglement enhanced searches for new physics with beyond-classical capabilities	Quantum sensors and sensor networks for axion and ultralight dark matter search over large parameter space. Use quantum sensors to explore interface between relativity and quantum mechanics. Integrate quantum sensors with particle accelerators and detectors to enhance their performance.
SENSITIVE HIGH-RESOLUTION PROBES FOR MATERIALS ANALYSIS AND DESIGN	Ultrahigh sensitivity magnetometers near the quantum noise limit, Discovery of new qubits for sensing Nanometer resolution magnetic imaging of currents, magnetic phases Noise sensing for dynamics	Integrated probes and instruments for high-throughput materials science Measure correlation functions in materials Exploit many-body physics, squeezing, entanglement for better sensitivity	User facilities with quantum sensors Commercial deployment of materials analysis tools Nanoscale sensors with quantum advantage
ROBUST AND DEPLOYED SENSING RESULTS	Improvements in size, weight & power, component integration, robustness to bring state-of-the-art quantum sensors into the field Materials development for radiation, thermal, and chemical resilience	Demonstrate prototypes in the field Demonstrate sensors in fusion environments	Mid-scale and large-scale manufacturing and deployment for scientific applications Technology translation to commercial partners
BIOLOGICAL, CHEMICAL, AND BIOMEDICAL SENSING	Sensor integration with relevant geometry for biological and chemical sensing and imaging, materials development and surface functionalization New protocols for measuring dynamics and small signals	Translation to bioenergy, capture of CO_2, biomedical and clinical applications Quantum sensing and imaging in physiologically relevant conditions Demonstrate high-throughput, high-sensitivity chemical sensing	Technology transfer to clinical settings, bioenergy and a bioeconomy Wide-scale deployment of biological and chemical assays

Key activities and milestones for quantum sensors in each of the four application areas over 1–5 years, 5–10 years, and for the 10+ year time frame, assuming significant investments over this time period.

Note. Example roadmap dates for specific technologies included from selected documents; not intended to be comprehensive. Government strategies may have developed or altered since the documents published above. The listed documents do not necessarily capture all elements of a given government's focus on quantum technologies. Roadmaps typically incorporate a significant level of uncertainty and vary across countries in their levels of ambition and feasibility.

APPENDIX 4 – SAMPLE PUBLIC QUANTUM COMPUTING ROADMAPS

IBM

https://www.ibm.com/roadmaps/quantum/

IBM Technology Atlas

Quantum roadmap

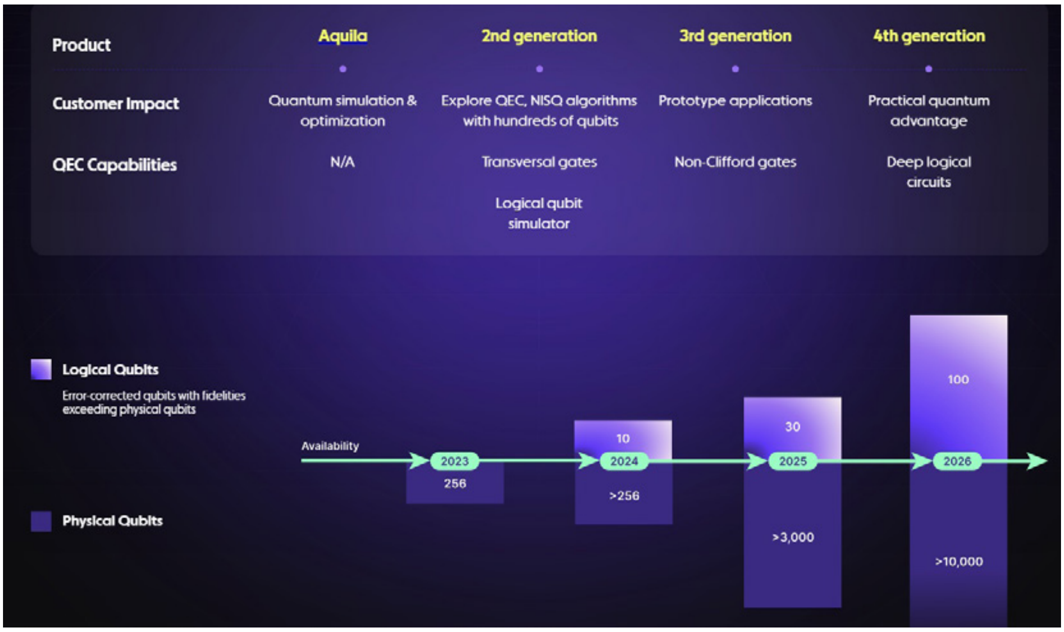
The future of computing is quantum-centric.

Updated October 2024
completed
pushed to next year
on target

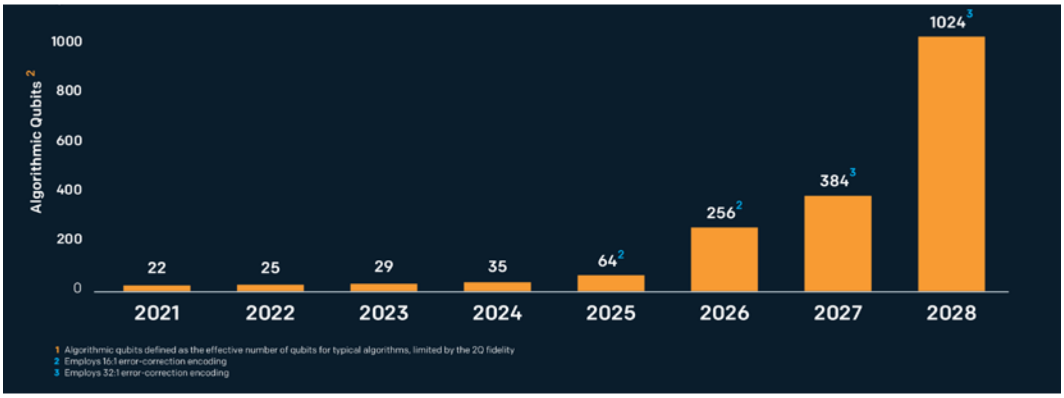
	2024	2025	2026	2027	2029	2033+
Quantum journey	*Introduce parallelization of quantum computations.*	*Demonstrate quantum-centric supercomputing.*	*Automate and increase the depth of quantum circuits.*	*Scale quantum computing.*	*Deliver a fully error-corrected system.*	*Deliver quantum-centric supercomputers with 1,000's of logical qubits.*
Strategy overview	We will improve the quality and speed of quantum circuits to allow running 5,000 gates with parametric circuits.	In 2025, we will demonstrate the first quantum-centric supercomputer by integrating modular processors, middleware, and quantum communication. We will also enhance the quality, execution, speed, and parallelization of quantum circuits.	We will enable quantum circuits with 7,500 gates through circuit quality improvement.	We will scale qubits, electronics, infrastructure, and software to reduce footprint, cost, and energy usage. The quality of quantum circuits will improve to allow running 10,000 gates.	We will bring users a quantum system with 200 qubits capable of running 100 million gates.	Beyond 2033, quantum-centric supercomputers will include thousands of qubits capable of running 1 billion gates, unlocking the full power of quantum computing.
Why this matters to our clients and the world	Qiskit Primitives with error mitigation will provide the foundation platform where algorithm and application developers can focus on the workflows and get the best quality out of the quantum hardware.	We will make quantum computing easier to use by abstracting quantum circuits into quantum functions and Qiskit patterns, opening the way for domain libraries.	By running circuits with more gates, clients can expand their use case exploration. Circuit mapping collections will simplify mapping use cases to quantum circuits.	Scaled quantum systems will allow users to run larger computations. Multiple computing resources will be seamlessly combined to optimally handle workflows and extend the computational reach of quantum systems.	Users will be able to run large-scale problems using high-rate quantum error correction.	Quantum computers running algorithms using thousands of logical qubits are expected to enable general applications in security, chemistry, machine learning, and optimization.
The technology or innovations that will make this possible	Built-in error mitigation will automatically determine the best method to reduce the effect of noise. Transpiler services will optimally rewrite circuits for hardware, taking advantage of AI. Watson Code Assistant will help users write Qiskit code to program quantum systems.	We will demonstrate a quantum node as part of a network that incorporates classical and quantum communication. Resource management tools will enable system partitioning, manage quantum and classical workflows, and parallel execution. Qiskit will provide libraries of quantum functions and higher-level APIs for faster algorithm and application development.	To improve performance and allow running more complex algorithms, we will enable the decomposition of quantum circuits into shorter circuits, run these in parallel using multiple quantum chip processors, stitch these circuits back together with classical hardware, and automate the process of mapping use cases to quantum circuits.	Intelligent orchestration will analyze workflows to identify the optimal resource allocation (QPUs, communication, and classical resources) for the task. Qiskit will orchestrate approaches to handle errors to provide noise-free outputs to the users. Working alongside clients, we will build and make available use-case-specific libraries in Qiskit.	A novel and efficient error correction code will extend the computational reach of quantum resources. The system will have low-level dedicated classical hardware and a compiler for quantum-centric supercomputing.	Efficient logical decoding will enable 2,000 qubits working in a distributed 100,000-qubit machine. The middleware will include distributed software tools to manage noise-free quantum computations working seamlessly with classical computations. Qiskit will include general purpose quantum computing libraries to simplify the work of developers.
How these advancements will be delivered to IBM clients and partners	Multiple higher-quality 100+ qubit Heron processors will be connected using classical communication.	Pre-built Qiskit functions and optimized libraries will become available. Our multi-quantum-chip Flamingo system, comprised of processors each made from multiple chips, will be demonstrated.	These achievements in 2026 are slated to be integrated with our modular Flamingo systems to allow users to run circuits with up to 7,500 gates and 1,000+ qubits.	The performance of our Flamingo systems will improve to allow users to run circuits with up to 10,000 gates and 1,000+ qubits.	The Starling system will be available to clients. It will be a modular, error-corrected quantum-centric supercomputer with 200 qubits capable of running a total of 100 million gates.	Our 100,000-qubit Blue Jay system will define 2,000 qubits capable of running a total of 1 billion gates. The middleware will integrate this system into ever more powerful quantum-centric supercomputers.

QuEra

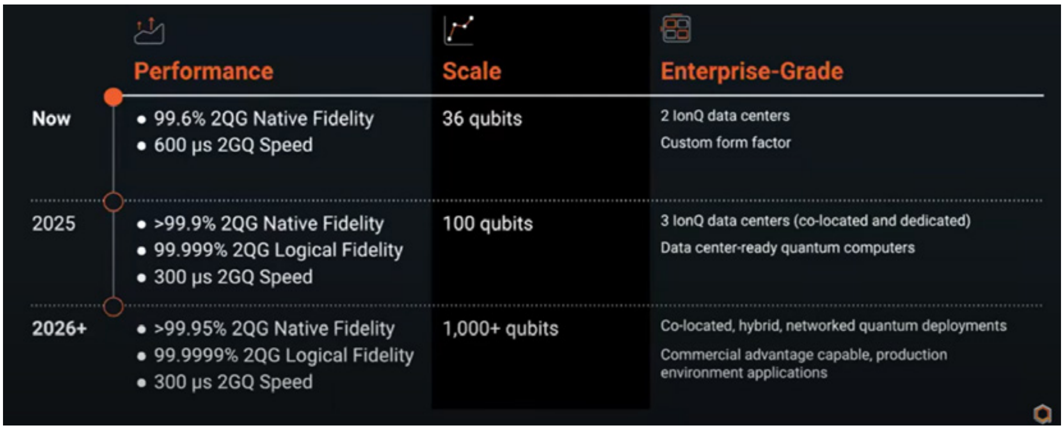
https://www.quera.com/qec



IonQ

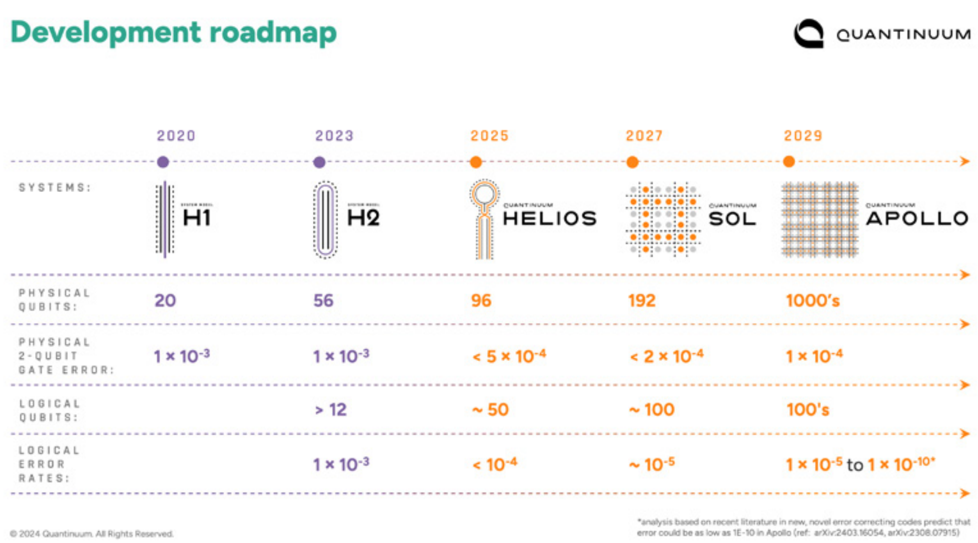


https://ionq.com/blog/december-09-2020-scaling-quantum-computer-roadmap (Dec 2020); definition at https://ionq.com/algorithmic-qubits



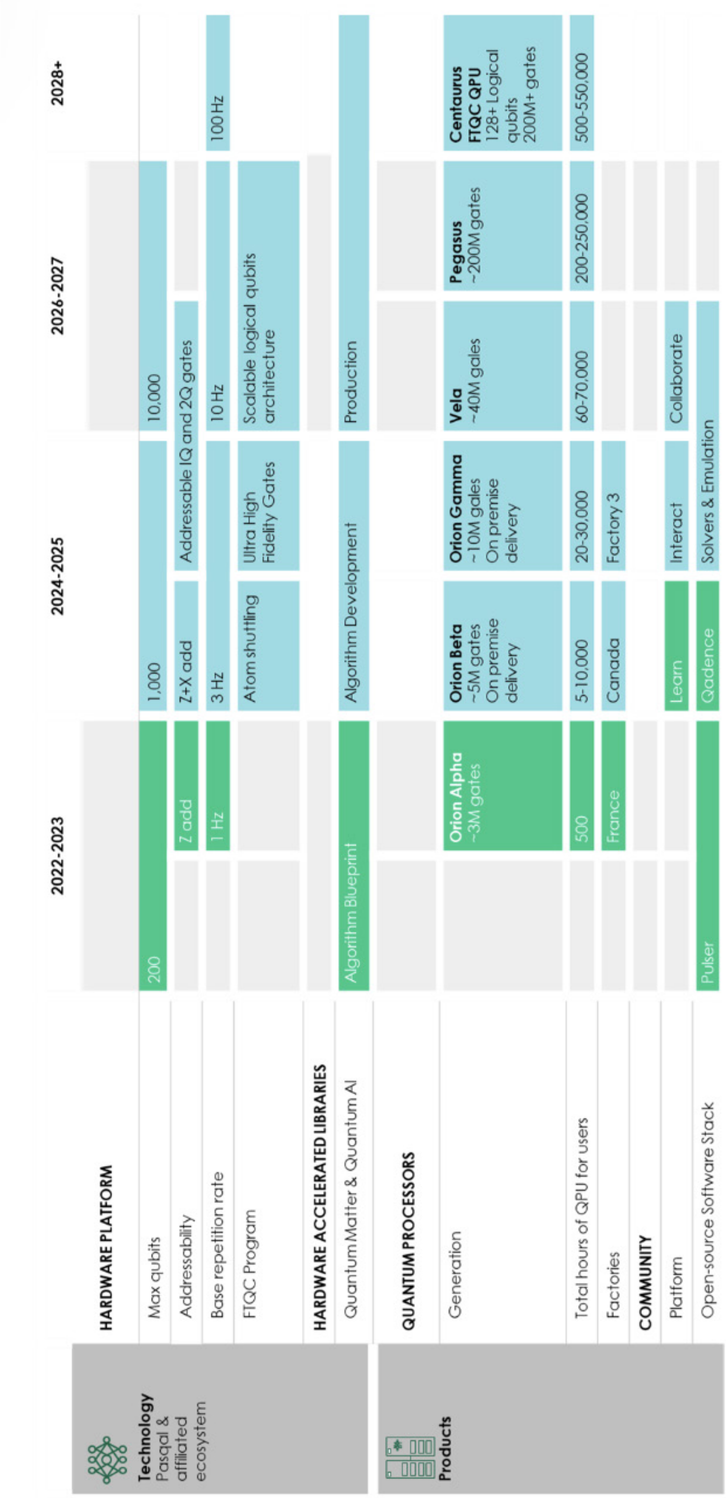
https://ionq.com/resources/ionq-technology-and-performance-updates-milestones-commercial-advantage (Jun 2024)

Quantinuum



https://www.quantinuum.com/press-releases/quantinuum-unveils-accelerated-roadmap-to-achieve-universal-fault-tolerant-quantum-computing-by-2030

Pasqal



https://www.pasqal.com/our-technology/our-roadmap/

APPENDIX 5 – GLOSSARY OF TERMS

Term	Definition
Adaptive Learning	An educational approach that uses data and algorithms to automatically adjust the level or type of instruction based on individual learner performance and needs.
Adiabatic Quantum Computing	A type of quantum computing that leverages the adiabatic theorem of quantum mechanics, where a system is kept in its ground state while being gradually transformed from a simple initial configuration to a final configuration that encodes the solution to a computational problem. This approach is particularly effective for optimisation problems and maintains the system in its lowest energy state throughout the computation process.
Artificial General Intelligence (AGI)	Hypothetical artificial intelligence that can understand, learn, and apply knowledge and generalise across different domains similar to human intelligence.
Algorithm	A set of step-by-step instructions or rules for solving a problem or performing a task, especially in computing.
Amplitude Amplification	A quantum algorithm technique (extending Grover's Algorithm) used for searching through unstructured data more efficiently than classical computers.
Analogue Quantum Computing	A type of quantum computing where physical quantum systems are set up to naturally evolve in ways that solve specific problems, rather than using discrete quantum gates.
Artificial Intelligence (AI)	Technology that enables computers to perform tasks that typically require human intelligence, such as visual perception, speech recognition, and decision-making.
Blockchain	A distributed, decentralized ledger technology that records transactions across a network of computers securely and transparently.
Cat Qubits	A type of quantum bit that uses 'cat states' (named after Schrödinger's cat thought experiment), which are quantum superpositions of multiple coherent states. These states are typically implemented using superconducting circuits or optical systems and are designed to be more robust against decoherence and errors than traditional qubit implementations.
Cloud Computing	The delivery of computing services including servers, storage, databases, networking, software, and analytics over the Internet.
Combinatorial Optimisation	A class of problems that involve finding the best possible solution from a finite set of possibilities.
Cryptography	The practice and study of techniques for secure communication in the presence of adversaries or third parties.
Decentralized Finance (DeFi)	Financial services and products built on blockchain technology that operate without traditional financial intermediaries.
Digital Twin	A comprehensive virtual representation that serves as a real-time digital counterpart of a physical object, process, or system. It combines real-time data, historical data, and simulation capabilities to monitor, analyse, and predict the behaviour of its physical counterpart. While it can be enhanced by quantum simulation capabilities, its core functionality relies on creating an accurate digital model that can be used for testing, optimisation, and predictive maintenance.
Edge Computing	A distributed computing paradigm that brings computation and data storage closer to the location where it is needed.
Entanglement	A quantum mechanical phenomenon where two or more particles become correlated in such a way that the quantum state of each particle cannot be described independently.
Fog Computing	An extension of cloud computing that brings processing closer to data sources, similar to edge computing but with a more hierarchical structure.

Term	Definition
Gated (Logic-Gate) Quantum Computing	A type of quantum computing that uses quantum logic gates to manipulate qubits, similar to how classical computers use logic gates to manipulate bits. This is considered the most versatile approach to quantum computing.
GitOps	A way of implementing continuous deployment for cloud native applications using Git as the single source of truth.
Gradient	A vector of partial derivatives that indicates the direction of steepest increase in a function, commonly used in machine learning optimisation to steer the training algorithm to minimise a given loss function.
Graph Theory	A mathematical study of structures used to model pairwise relations between objects. A graph is made up of vertices (or nodes) connected by edges.
Grover's Algorithm	A quantum algorithm for searching an unsorted database quadratically faster than classical algorithms.
Hamiltonian	A mathematical operator representing the total energy of a system, including both kinetic and potential energies.
Heuristic	A practical method or approach to problem solving that may not be optimal but is sufficient for immediate goals.
Homomorphic Encryption	A form of encryption that allows computations to be performed on encrypted data without decrypting it.
Hybrid Quantum-Classical Computing	An approach that combines quantum and classical computers, using each for the tasks they do best. The quantum computer handles specific, challenging components while the classical computer manages everything else.
Infrastructure as a Service (IaaS)	A form of cloud computing that provides virtualised computing resources over the internet.
Internet of Things (IoT)	A network of physical objects embedded with sensors, software, and other technologies for exchanging data with other devices over the internet.
Large Language Model (LLM)	An AI model trained on vast amounts of text data that can understand, generate, and manipulate human language.
Linear Algebra	A branch of mathematics dealing with linear equations and linear functions, fundamental to many quantum computing operations.
Logical Qubit	A more stable form of qubit created using multiple physical qubits and error correction techniques to achieve reliable quantum operations.
Machine Learning (ML)	A technique of AI that provides systems the ability to automatically learn and improve from experience without being explicitly programmed.
Matrix	A rectangular array of numbers, symbols, or expressions arranged in rows and columns, used extensively in AI and quantum computations.
Mutually Exclusive Collectively Exhaustive (MECE)	A principle where a group of categories or options are both non-overlapping and complete in covering all possibilities in a specific domain.
Natural Language Processing (NLP)	A branch of AI that helps computers understand, interpret, and manipulate human language.
Neural Network	A computer system modelled on the human brain and nervous system, used in machine learning / deep learning.
Noisy Intermediate-Scale Quantum (NISQ)	Refers to current and near-term quantum computers that have limited numbers of qubits and are subject to noise and errors. This term describes the current era of quantum computing technology.
Non-deterministic Polynomial time (NP)	A complexity class of decision problems for which a solution can be verified in polynomial time, even if a guarantee of finding the solution would tale longer than polynomial time on a deterministic system.

Term	Definition
NP-Hard	A class of problems at least as hard as the hardest problems in NP. A problem is NP-hard if solving it efficiently would make it possible to solve all problems in NP efficiently.
Physical Qubit	The actual physical implementation of a quantum bit in hardware, which may be subject to errors and decoherence. A qubit can be any two-level quantum mechanical system, i.e. it can be interpreted as being in one of two states once measured, e.g. whether an electron is spin-up or spin-down.
Platform as a Service (PaaS)	A cloud computing model where a third-party provider delivers hardware and software tools over the internet.
Polynomial Time	An algorithm runs in polynomial time if its running time is upper bounded by a polynomial expression in the size of the input. Generally considered 'efficient' in complexity theory.
Post-Quantum Cryptography (PQC)	Cryptographic algorithms thought to be secure against an attack by a quantum computer.
Quantum Approximate Optimisation Algorithm (QAOA)	An algorithm designed for running on NISQ devices to solve optimisation problems, particularly useful for combinatorial optimisation tasks.
Quantum Key Distribution (QKD)	A secure communication method that uses quantum mechanics principles to generate and distribute encryption keys between parties.
Quantum Technology Readiness Level (QTRL)	A framework for assessing the maturity of quantum technologies, similar to Technology Readiness Levels used in other fields.
Quantum Advantage	The demonstrable threshold at which a quantum computer solves a practically relevant problem faster, more efficiently, or more effectively than any classical computer using the best known classical algorithms. This advantage must be verifiable and significant enough to have practical value, not just theoretical interest. Also known as 'quantum supremacy' in some contexts, though this term is becoming less favoured.
Quantum Annealing	A type of optimisation technique using quantum effects to find the lowest energy state of a system, useful for solving certain types of optimisation problems.
Quantum Biotech	The application of quantum technology to biological systems and medical applications, including imaging, diagnostics, and drug discovery.
Quantum Cryptography	The use of quantum mechanical principles to create theoretically unbreakable encryption systems.
Quantum Dots	Nanoscale semiconductor particles that can be precisely controlled for various applications, including imaging and sensing.
Quantum Internet	A network that can transmit quantum information between distant locations, enabling secure communication and distributed quantum computing.
Quantum Materials	Materials that exhibit quantum mechanical properties that can be manipulated for technological applications.
Quantum Metrology	The science of extremely precise measurements using quantum effects, including quantum sensors and measurement devices.
Quantum Networking	The infrastructure and protocols needed to transmit quantum information between different locations.
Quantum Radar	A sensing technology that combines quantum illumination techniques with traditional radar principles to achieve superior detection capabilities, particularly in high-noise environments. By using entangled photons and quantum correlation measurements, it can achieve better signal-to-noise ratios than conventional radar systems and is more resistant to jamming and environmental interference.
Quantum Readiness	The state of being prepared to understand, implement, and adapt to quantum technologies as they become available.

Term	Definition
Quantum Simulation	The use of quantum computers to model and understand complex quantum systems that are difficult to simulate on classical computers.
Qubit	The fundamental unit of quantum information, analogous to a classical bit but capable of manifesting exclusively quantum mechanical phenomena, such as existing in two states simultaneously through superposition.
Quadratic Unconstrained Binary Optimisation (QUBO)	A mathematical formulation where problems are expressed as optimising a quadratic function of binary variables without constraints.
Shor's Algorithm	A quantum algorithm capable of efficiently factoring large numbers, which could potentially break certain current encryption systems, e.g. RSA.
Software as a Service (SaaS)	A software licensing and delivery model in which software is licensed on a subscription basis and centrally hosted.
Spatial Computing	Technology that enables humans and machines to interact with the digital world in three dimensions and overlays on the physical world.
Superposition	A fundamental principle of quantum mechanics where a quantum system can exist in multiple states simultaneously until measured.
Swarm Robotics	The study of how to design many simple robots and merge their behaviour into a desired collective behaviour.
Tensor	A mathematical object that generalises vectors and matrices to higher dimensions, commonly used in quantum computing and machine learning.
Trust Risk and Security Management (TRiSM)	A framework for managing AI systems focusing on trustworthiness, risk assessment, and security.
Vector	A mathematical object with both magnitude and direction, often used in machine learning for representing data.
Variational Quantum Eigensolver (VQE)	A hybrid quantum-classical algorithm used primarily for simulating quantum systems and solving optimisation problems.
Zero Knowledge Proof (ZKP)	A method by which one party can prove to another party that a statement is true without conveying any additional information, including the specific content of the proof which might be commercially sensitive or personal.

APPENDIX 6 – QUANTUM 101

While this report has been constructed with a general but technically aware audience in mind, we recognise the inherent comprehension challenges for readers less familiar with quantum technologies, their underlying mechanics and the associated technical terminology used to describe them. In addition to the glossary, we provide here three educational resources targeted at individuals with only cursory knowledge of the quantum domain. The resources are presented in order of time commitment.

MinutePhysics – Quantum Mechanics:[114] Educational video series (YouTube) providing a 1.5 hour introductory exploration of quantum mechanics through 20 short lessons (between 1 to 17 minutes), covering fundamental concepts like wave-particle duality and quantum tunnelling alongside advanced topics such as quantum computing and encryption. The curriculum progresses from basic principles like the uncertainty principle and Schrödinger's cat to more complex subjects including quantum teleportation, Hardy's paradox, and Shor's algorithm, offering viewers a structured path to understanding both theoretical quantum physics and its practical applications in modern technology in a short period of time.

Ars Technica – Guide to Modern Quantum Mechanics:[115] Series of 7 articles (approximately 2-3 hours) offering a non-mathematical exploration of quantum mechanics and its growing influence on modern technology, presented as a guided tour through quantum phenomena. The articles employ accessible text, images and videos focusing on experimentally verified quantum effects and their practical applications, with the goal of helping readers understand both current technological implementations and emerging innovations that utilise quantum mechanical principles in our everyday world.

QURECA[116] **- Quantum For Everyone 2.0:**[117] 15-hour beginner-level online course offering a non-technical introduction to quantum technologies and their industrial applications, designed to help participants understand and navigate the emerging quantum revolution. The course is structured into four lessons covering quantum computing basics, use cases, quantum-safe security, and industry insights, aiming to develop participants' technical, business, and management skills through topics like cloud quantum computing, quantum cryptography, and practical business applications.

[114] https://www.youtube.com/watch?v=Q_h4IoPJXZw&list=PL0E2ABD1D84697428

[115] https://arstechnica.com/science/2021/01/the-curious-observers-guide-to-quantum-mechanics/

[116] Cf. Qureca's Quantum Strategy for Business course analysed in section 3.2

[117] https://lms.qureca.com/product/quantum-for-everyone-2-0/?v=1fdc0f893412

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INFO

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