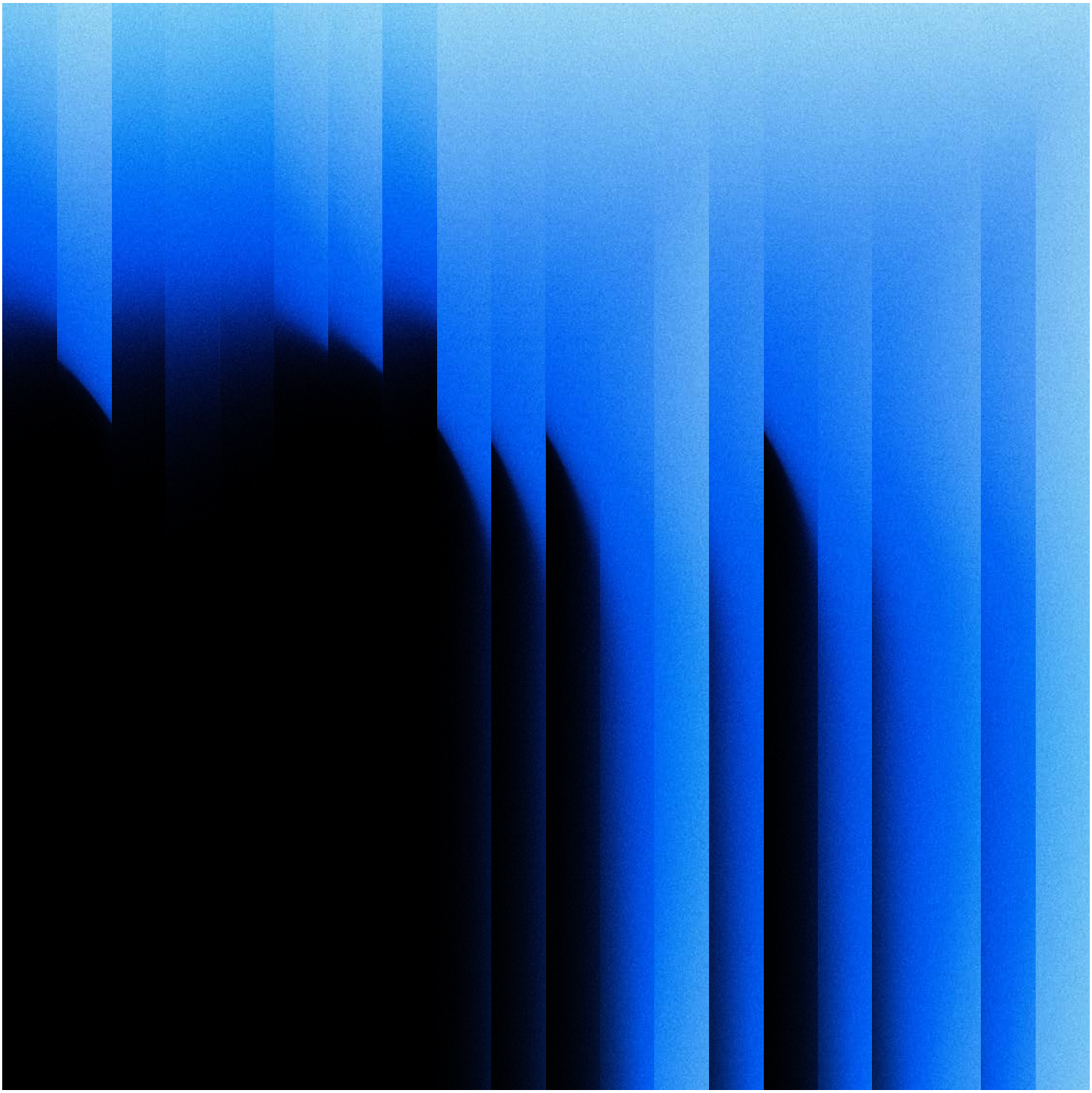
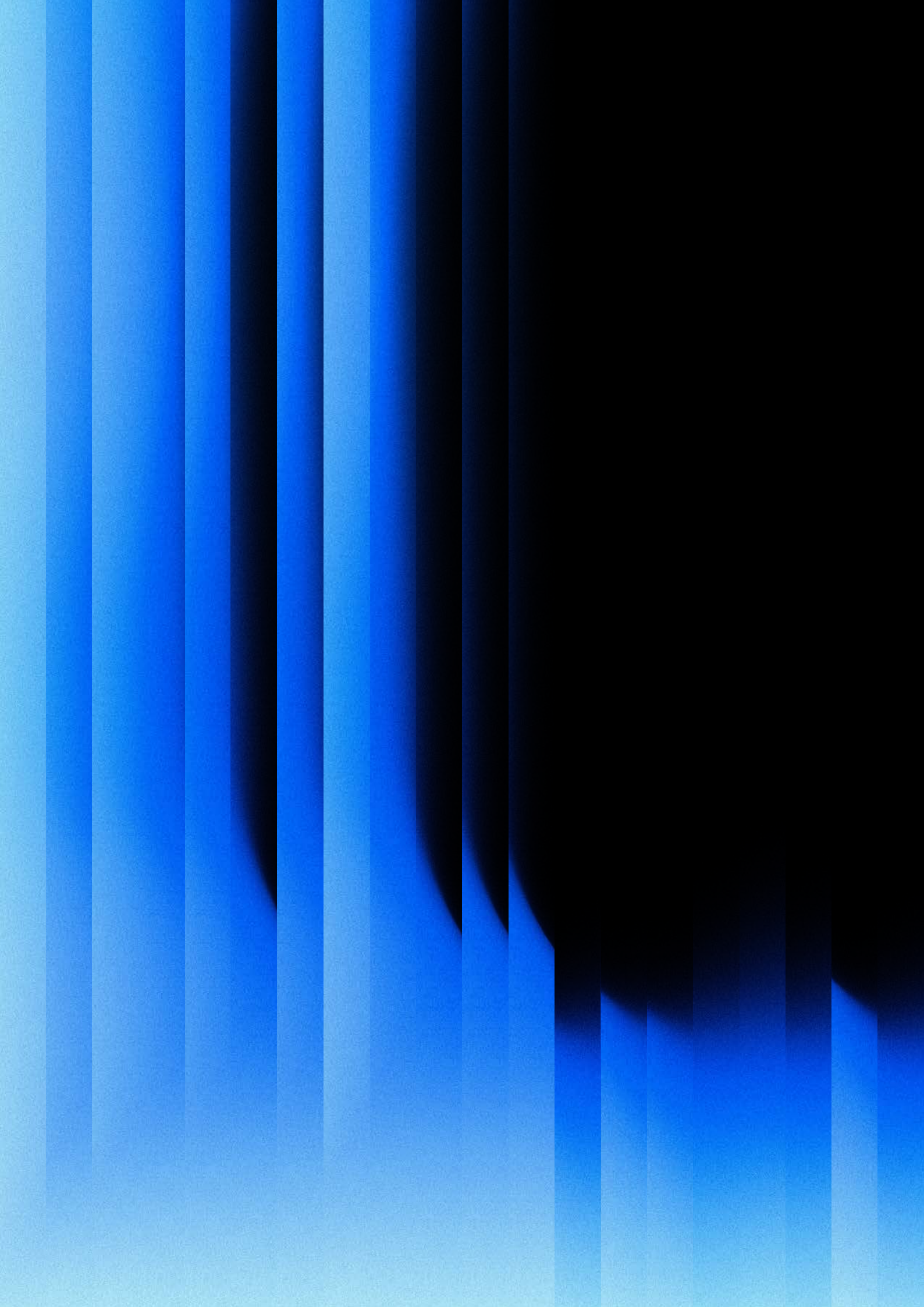


Accelerating digital sovereignty 2030

Luxembourg's Quantum Strategy

THE GOVERNMENT
OF THE GRAND DUCHY OF LUXEMBOURG



Accelerating digital sovereignty 2030

Luxembourg's Quantum Strategy

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Forewords

Luc Frieden

“Innovation is the driving force of human progress and, consequently, of economic and social development. Thanks to the ambitious and coherent vision defined in these strategies, as well as the flagship projects identified, the government will transform Luxembourg into an international centre of reference for the sovereign and secure valorisation of data. We aspire to create an agile centre, founded on trust and transparency, where private and public actors collaborate to put innovation at the service of humanity – European-style innovation, with a Luxembourgish touch!”

Stéphanie Obertin

“National strategies on data, AI, and quantum technologies are the result of excellent collaboration between ministries, public research stakeholders, the private sector, and civil society. The three strategies place humans at the centre of our digital transformation and inspire common ambitions and shared actions to create a dynamic, resilient, and inclusive ecosystem capable of responding to current and future challenges.

The valorisation of data is at the heart of our vision, enabling informed decision-making, the design of judicious policies, and the delivery of effective public services while establishing the foundation for AI and quantum technologies.”

Elisabeth Margue

“Prioritising adoption – this is the principle that guided us in drafting the ambitions and actions regarding AI, whether through the multiplier effect of digital public administration or within Luxembourg’s key sectors such as finance or health. Each company, each person will have a different journey in increasing their AI expertise. Everyone will be able to rely on the great strengths of our country: connectivity, computational resources, and digital skills. Additionally, by adding regulations that accelerate innovation, Luxembourg truly has a strong card to play within the European Union. Let’s be as ambitious as we can be!”

Lex Delles

“Digitalisation is no longer an option: it is an absolute necessity for any business that wishes to gain productivity and remain competitive in an increasingly rapidly evolving environment. This is why Luxembourg is investing in cutting-edge digital infrastructure while facilitating access through the provision of services adapted to the needs of businesses and research. With the future quantum computer MeluXina-Q and the future supercomputer MeluXina-AI placed at the heart of the national AI Factory, we offer businesses of all sizes a favourable framework for innovation to concretely accelerate their digitalisation.

By implementing a digital strategy built around three fundamental pillars - data, AI, and quantum technologies - we are giving ourselves the means to strengthen our digital sovereignty, guarantee our long-term competitiveness, and consolidate the resilience of our economy in an increasingly digitalised world.”

Accelerating digital sovereignty 2030

Luxembourg's ambition in data, artificial intelligence and quantum technologies

As part of the 2023-2028 coalition agreement, the government has committed to promoting innovation with the aim of keeping Luxembourg at the forefront of new technologies and digital advancement. In this context, **data, artificial intelligence (AI), and quantum technologies** constitute the **three areas** that Luxembourg aims to advance in order to continue stimulating its economy, improve the quality of life of its citizens, strengthen its digital and technological sovereignty, and contribute to the digital sovereignty of the European Union.

Since the publication of "**The Data-Driven Strategy for the Development of a Trusted and Sustainable Economy in Luxembourg**" and "**Artificial Intelligence: A Strategic Vision for Luxembourg**" in 2019, as well as the "**Ons Wirtschaft vu Muer**" strategy presented in 2021, technological evolution and its impact on our daily lives has substantially changed. With the rapid popularity of new AI tools in 2023 and the growing importance of data and its valorisation, a review of government strategies became necessary. In parallel, a technological evolution that is certainly less mature but no less fundamental, namely that of quantum technologies, has also rapidly gained momentum. It is therefore opportune, even urgent, to position the country for the next technological era, particularly through the adoption of innovative and high-impact solutions by 2030, thanks to the implementation of dedicated and additional budgets.

Luxembourg focuses on data, AI, and quantum technologies to strengthen its digital sovereignty and remain at the forefront of innovation.

Organisational approach

The government has invited **the Ministry of State (ME), the Ministry for Research and Higher Education (MESR), the Ministry of the Economy (MECO) and the Ministry for Digitalisation (MinDigital)** to identify complementarities and opportunities through national and international initiatives. To benefit from synergies and achieve ambitious objectives by 2030, a **holistic approach** has been adopted by these ministries, while ensuring the participation, from the initial preparations during workshops, thematic meetings and working groups, of representatives from civil society, private and public sectors, as well as experts from Luxembourg's public research. The **monitoring of the strategy implementation** according to its three axes relies on a transversal approach involving the entire government.

For the sake of general coherence, the three priority axes are addressed in **three dedicated documents**. Each document includes an **identical common section** that highlights the shared ambitions and synergy between the three axes, followed by a specific section for each: **data, AI, and quantum technologies.** It is this entire **strategic corpus** that constitutes the national ambition aimed at **accelerating the digital sovereignty of the Grand Duchy by 2030**.

Strategic vision

By 2030, Luxembourg aspires to become a country of digital and technological innovation centred on people, agility, sustainability and international collaboration. To achieve this, the Grand Duchy is determined to stimulate its digital ecosystem to make it increasingly innovative, dynamic, and agile. To ensure coherence, inclusivity, and collaboration within this ecosystem, both public and private sectors - including research and development - will be heavily involved. Built upon international openness, proven economic dynamism, and unparalleled and highly reliable digital infrastructure, the national ambitions regarding data valorisation, AI, and quantum technologies aim to consolidate Luxembourg's character as a European pioneer in digital transition, capable of serving as a model and benefiting from the advantages offered by digital technologies. The vision aims to support digital sovereignty, technological and economic progress, and to promote citizens' well-being.

This common vision for the **strategic corpus** is based on the conviction that digital and technological innovation is essential to ensure the country's competitiveness and future prosperity. Building on its unique advantages such as **cutting-edge sovereign infrastructure** and **the agility of a country of limited size**, Luxembourg will position itself as a leader in the field of high value-added applications in highly regulated sectors and thus offers true complementarity and added value on the European and global stage.

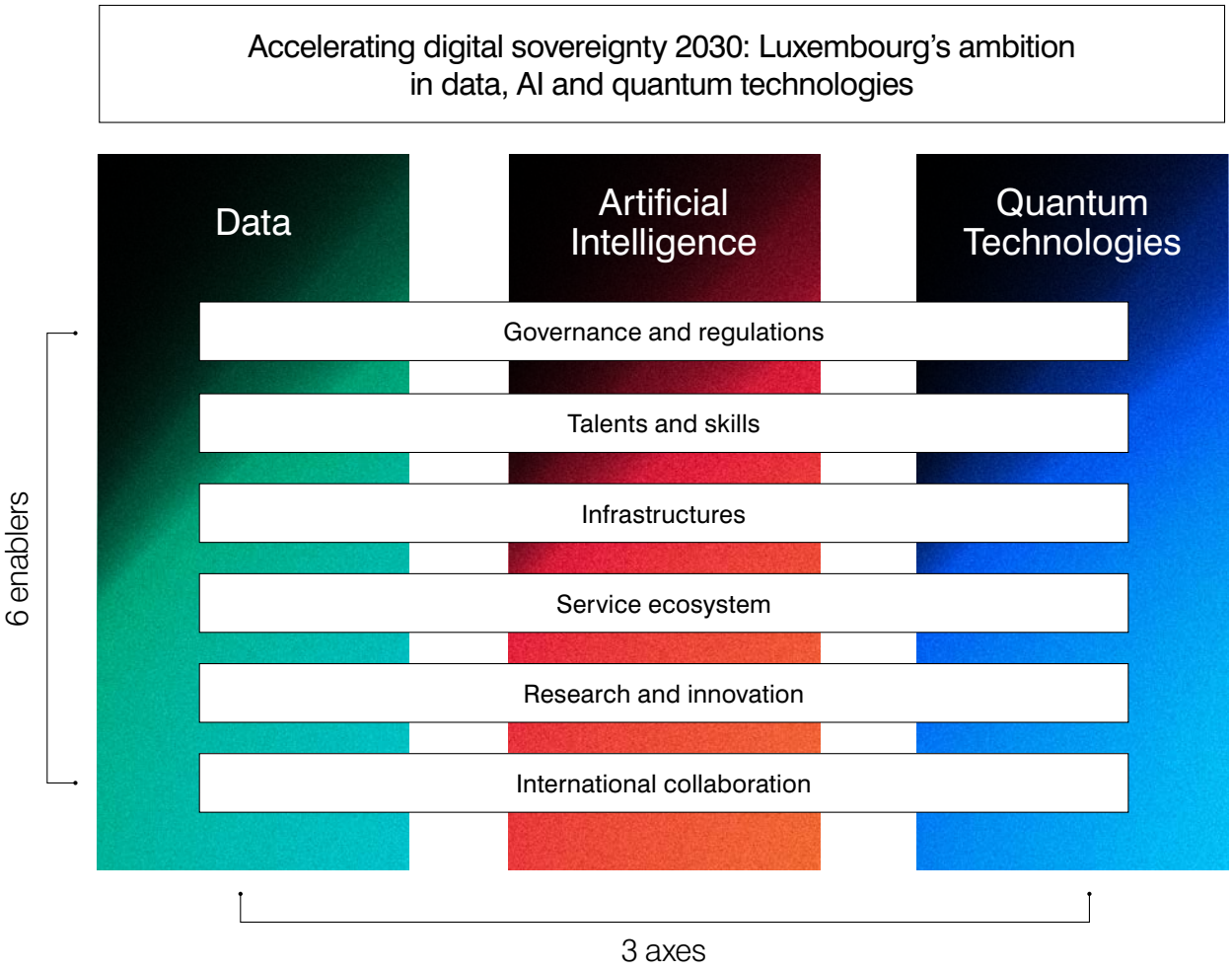
These strategies have been developed to position Luxembourg at the forefront of a future where technology is an essential driver of economic growth and citizens' well-being while ensuring the country's digital sovereignty.

A unified approach: leveraging interactions between data, AI and quantum technologies

Data represents the raw material of digital innovation, artificial intelligence allows value to be extracted from it, and quantum technologies promise to push the current limits of information processing, security, and analysis. To unleash their full potential, these three strategies should not be approached in isolation but rather as complementary components of an interactive technological ecosystem.

An integrated approach also allows for **greater sharing of infrastructure** (for example cloud, HPC (high-performance computing) and quantum computing) and **human and financial resources**. These interactions strengthen the country's ability to develop more powerful, safer technological solutions that are better adapted to tomorrow's challenges, particularly in key sectors such as the public sector, finance, cybersecurity, health, culture or space.

The common thread through each of the different documents is provided by **six transversal enablers**. The advantage of this articulation is to avoid a siloed approach and to facilitate synergies. It allows both a thematic reading (by vertical axis) and a pragmatic one (by horizontal action) of Luxembourg's various ambitions in terms of digital technology.



Six action enablers common to the three strategic development axes

The enablers for building a coherent digital ecosystem are as follows:

- Establish and promote governance means and regulations to encourage the use and reuse of data, as well as accelerate the adoption of AI and quantum technologies while guaranteeing data security and protection, infrastructure sovereignty, and reliability of software creation;
- Develop and attract the necessary skills and talents to strengthen national competitiveness, innovate and work in the field of digital technologies, and enhance digital literacy at the societal level;
- Continue to deploy cutting-edge infrastructure adapted to evolving national needs, both public and private, in terms of connectivity and computing;
- Offer a complete range of specialised services to support the dissemination and adoption of data culture and new digital technologies within society and the economy, particularly by offering more efficient and personalised public services, thus reducing the administrative burden for citizens and businesses;
- Stimulate agile research and innovation, at both public and private levels, to solve complex societal challenges;
- Contribute to international initiatives in the field of data, AI, and quantum technologies to promote digital sovereignty and European values.

Implementation of strategies: integrated dynamics and flagship projects

The operationalisation of the strategy will rely on a **set of flagship projects** translating concrete sectoral ambitions into strategic domains such as finance, health, culture, space, education, skills, cybersecurity, energy, mobility, and the optimisation of legislative and administrative processes. This approach will stimulate the digital and innovation ecosystem in Luxembourg through the adoption of innovative and high-impact solutions. To this end, dedicated budgets will also be established to meet the needs expressed by the consulted stakeholders.

This dynamic is supported by integrated governance and dedicated structures such as the **Deep Tech Lab** (see below) and the **collaborative Data, AI, and Quantum Factory platforms** (see below), true catalysts for innovation and coordination.

Flagship projects in key sectors will boost innovation in Luxembourg, supported by dedicated budgets and integrated governance.

Luxembourg's strategic assets for succeeding in its digital transition

Over the past decades, the government has committed to developing cutting-edge infrastructures and has continuously engaged in international initiatives and collaborations. Luxembourg already has a few key elements to assert itself as a digital pioneer on an international scale:

- Luxembourg has the highest density of **"Tier IV" data centres** in Europe. These data centres guarantee the highest level of resilience in terms of electricity, water, and connectivity supply while ensuring a very high level of physical security. Thanks to this security level, these data centres can host highly critical data storage and processing infrastructures.

- Luxembourg is an active and recognised member of AISBL **Gaia-X**, a European initiative aimed at creating an **open, secure, and sovereign data infrastructure** to promote the interoperability of data or cloud services while respecting European standards. Luxembourg plays an important role with a Luxembourgish representative sitting on the board of directors and having leadership of the health ecosystem within this same association.

- Operational since 2023, the **Luxembourg National Data Service (LNDS)** facilitates value creation from secondary use of data for both public and private partners and supports the sharing and reuse of public sector data in a reliable manner. Its approach, unique in Europe, aims to offer a complete range of data-related services (management, access, cataloguing, Ethical, Legal, and Social Issues (ELSI) assessment, pseudonymisation and anonymisation, etc.) in an intersectoral and centralised way to accelerate data exploitation in Luxembourg.

- Luxembourg positions itself as a European leader in digital connectivity, with **high-speed Internet infrastructure** and **5G coverage** that far exceed the EU average.

- Luxembourg is one of the first EU Member States selected to host a supercomputer as part of the EuroHPC network. Operational since 2021, the **HPC MeluXina** was designed in particular to process AI computational tasks. In 2023, MeluXina processed 35% of all EuroHPC AI projects, highlighting its key role in advancing AI in Europe. At the national level, its computing hours are increasingly being used to develop AI applications for a growing number of companies, including startups.

- Luxembourg is among the first seven Member States to have signed in 2019 a declaration on the development and deployment of a European quantum communication infrastructure, the

EuroQCI. From this declaration was born the national initiative **LuxQCI** which aims to create an experimental laboratory for quantum communications, to develop and implement a quantum communications network at the national level in order to interconnect it with the quantum communications networks of other European Union Member States, thus creating the EuroQCI. The development of the national ecosystem in the field of quantum communications is another key objective of the LuxQCI initiative.

Far from being established achievements, these assets must be continuously developed so that Luxembourg can accelerate its digital sovereignty and remain at the forefront of digital technologies and meet national and international needs.

Fostering innovation and creation

Intellectual property has become an economic issue that must be considered to ensure the growth of innovative, creative, and economic actors. It must therefore be integrated in a transversal and strategic manner in the initiatives of the various ministerial departments and in the sectors of the economy and culture, particularly in the context of AI, quantum technologies, and data, so that creative and innovative efforts result in competitive advantages that will ultimately benefit society, the economy, and Luxembourgish culture.

Luxembourg has established a fully developed legal and regulatory framework in the field of intellectual property. This legislative framework helps ensure Luxembourg's position among the leaders in innovation. Luxembourg will continue to engage in discussions and developments in this area at the European and international levels.

It should be emphasised that in the context of the sustainability of the knowledge economy, access to content should not be considered solely in a dematerialised manner. In this regard, and to sustainably guarantee Luxembourg's sovereignty, it is essential to ensure that intellectual resources and access to knowledge are not solely dependent on external operators and their digital resources.

These various elements will help maintain Luxembourg's position at the forefront of knowledge-based and innovative economies, which are guarantees of competitiveness and growth.

Becoming and remaining a key player in the digital ecosystem

The key arguments highlighted below, drawn from the strategies, emphasise specific actions that will contribute to positioning Luxembourg as a key player in the European digital ecosystem:

- Luxembourg will establish centralised data governance to ensure data reuse and exchange in a trusted environment. To facilitate relations with citizens in their administrative procedures, the government is also planning a solid and coherent framework for data exchange by introducing the Once-only principle (a principle whereby a person provides data to administrations only once). To facilitate data access and reuse, while ensuring legal certainty and maintaining citizen trust, the government also aims to establish a precise framework for the reuse of data held by the public sector (G2B) by both public and private actors. It specifically provides for:
  - authorised purposes for which data access and reuse are permitted, e.g., for training, testing, and evaluating algorithms and AI solutions;
  - rigorous control of rules through the intervention of the Government Commissioner for Data Protection with the State (CGPD), acting as the Data Authority in charge of

Luxembourg establishes itself as a European digital hub with a strategy focused on data, AI, and quantum technologies.

authorising data access and reuse based on a specific request by the re-user;

- the fact that data access and reuse take place in a secure processing environment set up by the CGPD and managed by the State Information Technology Centre (CTIE);
- the fact that data is anonymised, pseudonymised, or aggregated (if necessary by a trusted third party) prior to being made available.

- The network of AI Factories will facilitate access to large volumes of data and pool expertise at a European scale. Additionally, Luxembourg will be able to rely on its new MeluXina-AI supercomputer to further accelerate the development of its already dynamic and agile digital ecosystem. The national AI Factory, with its centre in Belval, will constitute a one-stop shop increasing the visibility of available initiatives and offerings, and providing access to essential resources to accelerate AI development in Luxembourg, while promoting collaboration, knowledge exchange, and inter- and intra-sectoral synergies.
- The new MeluXina-AI supercomputer will be integrated with sovereign cloud solutions and Tier IV data centres in a computing continuum. This will offer flexibility, robustness, and security in terms of data protection and IP necessary for applications in highly regulated domains.
- To attract and advance the talents and skills necessary for developing a thriving AI ecosystem, Luxembourg will adopt an agile, sectoral, and inclusive approach, combining pedagogical innovation and close industry-academia collaborations, while capitalising on MeluXina-AI. Luxembourg will equip itself with an advanced AI-based tool to anticipate skills needs in order to align training with labour market developments. To position the country as a model in Europe for equitable access to AI skills, Luxembourg will seek to find a good balance between developing elite talent and the broad inclusion of citizens.
- In order to drive the rapid application of AI in the key economic sector of finance, a major project will be implemented to explore the potential of AI-based use cases. In the same spirit, the health sector is complementing its digital strategy with a major project that uses AI to improve patient medication care, thus driving the application of AI with the aim of making medicine more personalised.
- The Deep Tech Lab (DTL) aims to promote the economic valorisation of Deep Tech research activities in Luxembourg. Its goal is to facilitate interactions between the academic and economic worlds. To achieve this, it encourages the creation of public-private partnerships, the development of spin-offs, and the commercialisation of licenses. Furthermore, the DTL will allow Luxembourg to become a hub that attracts, retains, and develops talent in the field of Deep Tech technologies, to guarantee national sovereignty and realise national ambitions in the areas of data, AI, and quantum technologies. It will usefully complement the existing solutions in Luxembourg to stimulate research, innovation, and entrepreneurship, thereby supporting the activities of this ecosystem as a whole. Additionally, the DTL will constitute a dynamic scientific and technological environment where researchers and engineers can focus on providing innovative and concrete solutions, particularly in the fields of data, AI, and quantum technologies, in line with the ambitions defined in Luxembourg's strategies. Its ultimate goal will be to promote high-level research, both public and private, to address societal and industrial challenges with high added value. Both bottom-up and top-down approaches will be used to identify and address research questions and high-impact innovation areas.
- To prepare for cyber threats in the quantum era, Luxembourg aims to accelerate the transition to post-quantum cryptography and deploy quantum communication networks integrated with the European EuroQCI initiative. This includes support for test beds for secure terrestrial and satellite networks, as well as promoting concrete use cases. The space component, with the development of a QKD satellite, is one of the country's strategic priorities. These efforts will contribute to strengthening national cybersecurity and defence capabilities, in line with its long-term priorities in terms of digital sovereignty, cybersecurity, and space technologies.
- The integration of the MeluXina-Q quantum computer into the existing MeluXina HPC infrastructure and the future coupling with MeluXina-AI allows for intelligent distribution of computational tasks between different architectures, thus optimising the use of available resources. This configuration will create a centre of computing excellence, where the advanced capabilities of classical and AI-specialised supercomputers are enhanced by the unique assets of quantum computers.

All of these strengths and key arguments will allow Luxembourg to present itself as a centre of competence and a true European "hub" at the cutting edge of digital technology.

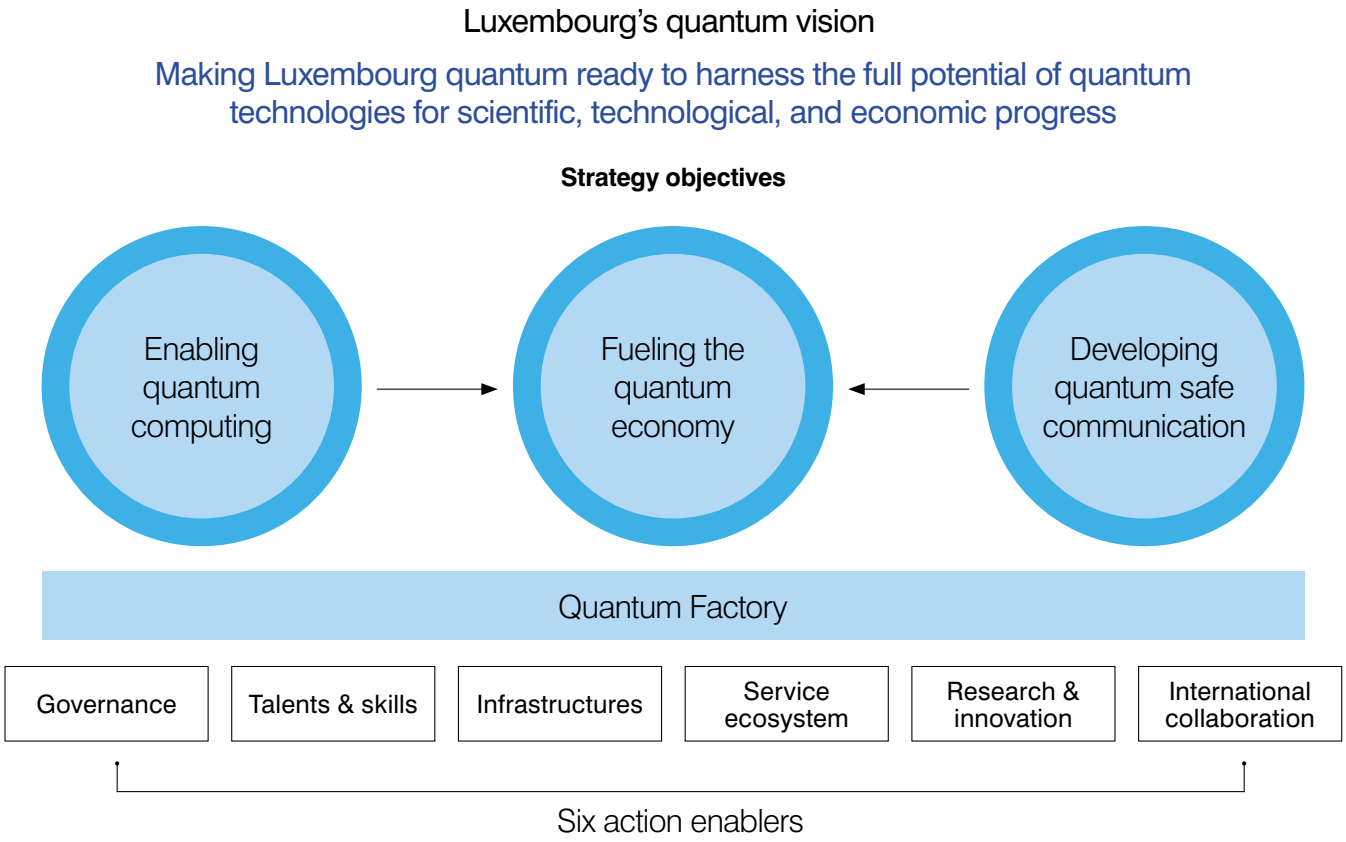
Part 1. Introduction

Strategic vision for quantum

This present national strategy aims to prepare Luxembourg for the quantum era by establishing a high-performing, agile quantum ecosystem, allowing Luxembourg to fully harness the potential of quantum technologies to drive scientific, technological, and economic progress. Beyond enabling new scientific breakthroughs, the strategy focuses on developing, deploying, and commercialising innovative quantum technologies, capabilities, and services across Luxembourg's priority sectors of economic activity.

Building on Luxembourg's role as a trusted and secure hub for data-driven innovation, the strategy places particular emphasis on quantum communication and cybersecurity. One important aim is to prepare the country's public and private actors and their data infrastructure to protect critical systems from quantum-based threats, thus strengthening the digital sovereignty.

In parallel, Luxembourg seeks to expand on its existing strengths in high-performance computing (HPC) and artificial intelligence (AI), leveraging the disruptive potential of quantum computing to accelerate industrial transformation and maintain technological competitiveness.



National quantum strategy in a nutshell

To realise its vision for the quantum era, Luxembourg's national quantum strategy defines three core strategic objectives:

- Develop expertise and services in quantum computing,
- Establish a resilient data infrastructure capable of withstanding quantum-era threats by developing a terrestrial and satellite-based quantum communication network and transitioning to post-quantum cryptography (PQC),
- Generate economic value from quantum technologies.

To achieve these objectives, the strategy outlines targeted actions across six strategic enablers, aligned with those set out in the national data strategy and the AI strategy:

- Providing effective governance,
- Developing targeted talent and skills,
- Establishing cutting-edge quantum infrastructure,
- Advancing services and capabilities in quantum technologies,

- Promoting world-class scientific research,
- Fostering dynamic international partnerships between academia, industries and governments.

These strategic objectives and measures were developed through a collaborative effort involving multiple government ministries, supported by input from research institutes, public institutions, and private-sector stakeholders.

The first section of the strategy introduces quantum technologies, presents the overarching objectives and implementation approach, describes the current state of quantum research and innovation in Luxembourg, and situates the strategy within both national and European policy frameworks. The second section, structured around the six strategic enablers, elaborates on the ambitions and key actions to be undertaken.

The strategy concludes with a dedicated roadmap, outlining the key milestones and measures required to position Luxembourg as a leading player in the rapidly evolving field of quantum technologies.

General approach

Introduction to quantum technologies

Quantum technologies, grounded in the fundamental principles of quantum mechanics, harness quantum effects in material and atomic systems to enable revolutionary advancements in computing, communication, sensing, and materials science, far surpassing classical capabilities.

While quantum physics has been explored since the early 20th century, with pioneers like Planck, Einstein, and Bohr laying its foundations, early technological applications, such as transistors, lasers and atomic clocks, relied on collective quantum effects rather than directly manipulating individual quantum systems. Today, advancements in isolating and controlling individual quantum states of elementary particles like photons and electrons have ushered in the “Quantum 2.0” era, enabling the development of groundbreaking technologies in key innovation fields like quantum computing, communication and sensing. These technologies fundamentally differ from classical systems, offering entirely new capabilities rather than incremental improvements.

Over the past two decades, quantum technologies have shifted from pure research to early commercial applications, with leading global companies investing heavily. Quantum computing promises to solve complex mathematical problems beyond classical limits, quantum sensing enables ultra-precise measurements for healthcare and aerospace, and quantum communication is becoming crucial for ultra-secure data transmission and storage, protecting against rising cyber threats.

For Luxembourg, quantum technologies present a strategic opportunity in key areas like materials science, cybersecurity, defence, and finance, while further solidifying its leadership in digital innovation. According to a 2024 McKinsey study[1], the global quantum market is projected to reach $90 billion by 2030 and $173 billion by 2040, with quantum computing driving the largest economic impact. As of 2023, national government investments in quantum R&D have reached approximately $42 billion, with Europe, the United States, and China leading the charge.

Quantum technologies are revolutionising computing, communication, and sensing, offering capabilities far beyond classical systems. Luxembourg aims to harness this potential through a national strategy to strengthen its position in the global quantum landscape.

[1] McKinsey Digital (2024), “Quantum Technology Monitor”

This global investment race mirrors the transformative rise of AI a decade ago, with quantum technologies poised to revolutionise industries ranging from space and healthcare to finance, cybersecurity, and logistics.

Luxembourg must act decisively to secure its position in this evolving technological and economic landscape. Developing a comprehensive national quantum strategy, with clear, actionable steps, reflects the government's ambition to harness these advancements and position the country as a key player in the field of quantum technologies.

Building a quantum future: Luxembourg's key strategic objectives

Despite significant advancements in the field, quantum technologies still face major challenges, including hardware limitations, scientific uncertainties, difficulties in controlling and manipulating quantum states, and industry adoption barriers such as low awareness, limited sector readiness, and a global talent shortage. Luxembourg's national quantum strategy aims to address these challenges by fostering a robust, interconnected quantum ecosystem, leveraging its public R&D strengths, ICT expertise, and public-private partnerships through a multidisciplinary agile and sectorial transversal approach.

Key actions include the establishment of collaboration frameworks, targeted funding mechanisms, education and training programmes, talent attraction initiatives, and strategic partnerships. These are complemented by sustained investments in quantum infrastructure, particularly through European initiatives such as EuroHPC and EuroQCI, to accelerate scientific progress and the development of quantum solutions, ensuring that Luxembourg remains a competitive player in the global quantum landscape.

The first key objective of this strategy is the successful implementation and adoption of MeluXina-Q, Luxembourg's first quantum computer, which will be integrated into the national HPC facility in Bissen as part of the EuroHPC network. This system will serve as an enabler for early quantum algorithms and software development, supporting national and European research efforts. Further, the national quantum strategy seeks to establish a framework that unites existing efforts in quantum algorithm research, builds new capabilities through the integration of the quantum computing platform into the HPC architecture, and drives the development of innovative hardware and software solutions with economic impact.

The second key strategic objective is the development of a quantum secure communication infrastructure. Luxembourg, as an active participant in the EuroQCI initiative, aims to establish testbeds for secure terrestrial and satellite-based communication networks, while

Luxembourg is building a robust quantum ecosystem to turn today's challenges into tomorrow's breakthroughs.

also fostering the development of the technological components needed for next-generation quantum communication networks. In parallel, Luxembourg is committed to strengthening its role in European research initiatives including, for example, the *Quantum Internet Alliance* under the *European Quantum Flagship* programme, and to promoting the development and deployment of quantum-resistant cryptographic algorithms. The latter builds on Luxembourg's strong national cybersecurity expertise to safeguard its digital infrastructure against future threats, in a field known as *Post-Quantum Cryptography* (PQC).

The third strategic objective is to drive economic growth through quantum technologies, creating new business opportunities for Luxembourg. Key focus areas include wide bandgap (WBG) semiconductors for quantum chips, as well as leveraging advances in quantum communication and computing. By strengthening its quantum foundation, Luxembourg aims to secure technological leadership and long-term economic resilience in the emerging quantum economy.

To advance quantum technologies, Luxembourg will promote interdisciplinary collaboration and cross-sectoral synergies, aligning with the EU's approach and reaffirming its commitment through the endorsement of the EU Quantum Declaration. Subject matter experts emphasise that accelerating quantum development and addressing strategic challenges requires the creation of innovation clusters focused on quantum technologies. These clusters should foster strong collaboration among academia, industry, and government to drive both national and international progress.

In response, the present strategy proposes to establish key thematic clusters within Luxembourg's quantum ecosystem. Inspired by the AI Factory model, these will form a "Quantum Factory", a collaborative network that pools resources and expertise to meet scientific, technological, and ecosystem needs. Each cluster will have tailored objectives, from advancing research and infrastructure to supporting industry adoption. Regular workshops, training initiatives, and knowledge-sharing platforms will further strengthen collaboration, drive innovation, and support the effective deployment of quantum technologies. In doing so, the Quantum Factory will serve as an integrative mechanism to support the achievement of the strategy's overarching goal.

Basics of quantum technologies

Quantum technologies are rapidly advancing and encompass three main areas, namely quantum computing and simulation, quantum communication, and quantum sensing. Each holds significant potential to transform Luxembourg's economy and society.

Quantum computing and simulation

Quantum computing leverages the principles of quantum mechanics to solve problems beyond the reach of classical computers. Unlike classical bits, quantum bits (qubits) can exist in a superposition of states, enabling the simultaneous processing of many possibilities and exponential speedups for specific algorithms. This makes quantum computing especially valuable for high-complexity tasks as encountered for instance in the fields of materials science, climate modelling, financial optimisation, and logistics.

A key application is quantum simulation, which makes use of controllable quantum systems to model complex quantum phenomena. This capability has significant implications across various fields, including materials science, chemistry, drug discovery, and fundamental physics, where it can accelerate breakthroughs by providing deeper insights into the behaviour of matter at the quantum level.

Currently, quantum computers are in the so-called *Noisy Intermediate-Scale Quantum* (NISQ) era, where systems have limited qubits and relatively high error rates. While NISQ devices show promise for niche applications, achieving large-scale, *Fault-Tolerant Quantum Computing* (FTQC) remains a long-term objective. FTQC requires quantum error correction (QEC) to mitigate decoherence and computational errors, which in turn demands systems with millions of high-fidelity qubits, which constitutes a major technological challenge.

Several hardware approaches are being explored, including superconducting qubits, trapped ions, semiconductor-based spin qubits, and photonic qubits. Private companies are driving progress in this area, though a practical quantum advantage, where quantum systems outperform classical counterparts in real-world tasks, has yet to be realised.

Quantum communication

The urgency of quantum communication arises from the increasing vulnerability of today's digital security systems. Despite continuous cybersecurity and defensive measures, cyberattacks are becoming more sophisticated, and European agencies warn that current measures are ill-equipped for the quantum era[2]. Quantum communication leverages the principles of quantum mechanics such as superposition and entanglement to enhance the security of data transmission and storage, enabling advanced communication technologies. The most mature technology in this space, *Quantum Key Distribution* (QKD), enables secure cryptographic key exchange by detecting eavesdropping attempts.

Although QKD is undergoing experimental deployment in sectors like finance, defence, and telecommunications, where secure communication is critical, its broader adoption faces infrastructure challenges, especially in scaling beyond direct, point-to-point fibre links.

The long-term vision is a global quantum internet, where entangled qubits enable ultra-secure, long-distance communication and distributed quantum computing. Progress toward this vision involves three generations of quantum communication technologies:

1. **QKD:** Enables secure point-to-point communication, resistant to unlimited computational power; already partially in commercial use.
2. **Entanglement-Based QKD:** Supports multi-user quantum networks for dynamic, secure communication, such as city-wide infrastructures connecting multiple government institutions.
3. **Quantum Repeater Networks:** Facilitate long-distance terrestrial quantum communication without trusted nodes, paving the way for scalable, quantum-safe networks.

In parallel, Post-Quantum Cryptography (PQC) is being developed to protect classical digital systems against future quantum threats. PQC designs asymmetric cryptographic systems that, based on current knowledge, are resistant to quantum attacks while remaining compatible with classical hardware. These algorithms rely on mathematical problems considered hard for both classical and quantum computers to solve. In August 2024, the U.S. National Institute of Standards and Technology (NIST) released three post-quantum encryption standards, namely CRYSTALS-Kyber for general encryption, and CRYSTALS-Dilithium and SPHINCS+ for digital signatures.

Given the 'store-now-decrypt-later' threat, hybrid cryptographic solutions that combine PQC with classical encryption are being prioritised globally, supported by a crypto-agility approach that allows systems to adapt to evolving threats.

[2] Bundesamt für Sicherheit in der Informationstechnik (2023), "Position Paper on Quantum Key Distribution"

Quantum sensing

Quantum sensing leverages quantum mechanical principles such as superposition, entanglement, and coherence to measure variables like time, magnetic fields, gravity, and temperature with exceptional precision. Key applications include:

- **Quantum gravimetry** for geological mapping and resource exploration.
- **Ultra-sensitive magnetometers** for medical imaging and brain activity monitoring.
- **Atomic clocks** for highly accurate timekeeping and synchronisation.
- **Quantum gyroscopes** for navigation without relying on GPS.

Other emerging technologies such as quantum LiDAR and quantum Radar promise enhanced sensing capabilities for autonomous vehicles and aerospace applications, though significant technical challenges remain. While classical sensors often remain more practical and cost-effective, quantum sensors are already demonstrating clear advantages in niche areas such as biomedical research, geophysical surveys, and semiconductor failure analysis.

Wider adoption of quantum sensors will depend on the development of scalable, cost-efficient production methods that can integrate with existing technologies.

Quantum computing isn't just a leap in processing power—it is a paradigm shift that redefines our very approach to solving the unsolvable.

Quantum ecosystem in Luxembourg

Quantum research community

Luxembourg hosts a well-established and high-level quantum research community that excels in various areas, including quantum computing and simulation, and quantum communication. This community contributes significantly to both academic and applied research, as well as the industrial sector.

The University of Luxembourg has prioritised quantum technologies in its strategic framework and current Four-Year Plan[3]. Two of its major contributors in this field are the *Faculty of Science, Technology and Medicine* (FSTM) and the *Interdisciplinary Centre for Security, Reliability and Trust* (SnT).

The FSTM conducts both theoretical and applied research in quantum science, with expertise spanning quantum information theory, computing, cryptography, metrology, and sensing. Researchers develop quantum algorithms for computational mechanics and data science, explore diverse quantum computing platforms, and advance quantum metrology for precision measurements. In cybersecurity, FSTM focuses on quantum and post-quantum cryptography, secure communications, and quantum-resistant encryption. It also leads computational quantum physics research and hosts a cutting-edge quantum optics platform for investigating ultrafast quantum interactions.

The SnT conducts advanced research in quantum computing and communication across multiple domains. Its work encompasses secure quantum networks, addressing key aspects such as software, cryptography, networking, signal processing, and optics. SnT is also deeply involved in quantum and post-quantum cryptography, focusing on algorithm design, analysis, and the development of encryption standards to protect against future quantum threats.

Furthermore, the *Luxembourg Institute of Science and Technology* (LIST) plays a vital role in the national quantum ecosystem, focusing on semiconductor-based quantum hardware. With an emphasis on scalable quantum chips, LIST conducts research in quantum communication, distributed computing, and sensing. Key areas include photonic integrated circuits, quantum colour centres, and spin-based quantum processors and memories, contributing to the development of next-generation quantum technologies.

[3] https://www.uni.lu/en/about/profile/mission-strategy-values/

Quantum innovation and industry

Quantum computing

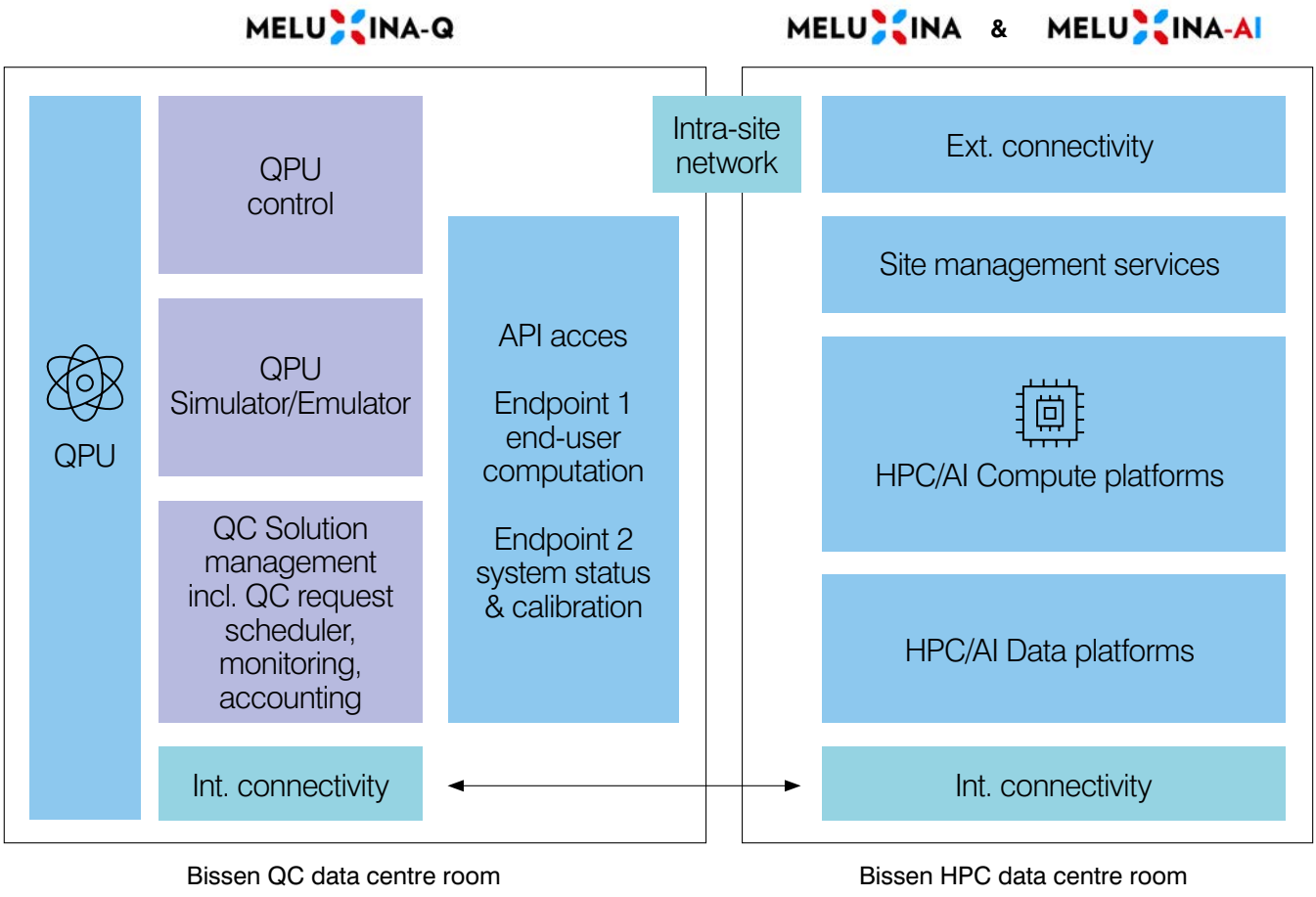
Luxembourg has recently demonstrated its ambition in quantum computing through its successful participation in the EuroHPC call for hosting quantum computers. Under the lead of the Ministry of the Economy and the Ministry of Research and Higher Education, the country has been selected for this initiative and will begin the acquisition phase of its quantum computer system in 2025. The system will be hosted by LuxProvide within the national HPC competence centre in Bissen, with operations set to begin in 2026.

MeluXina-Q will be seamlessly integrated into the existing MeluXina HPC infrastructure and later connected to the upcoming MeluXina-AI supercomputer, creating a high-performance hybrid computing ecosystem, that will be hosted in a secure Tier IV-certified data centre in Bissen. The integration of quantum computing within a traditional HPC infrastructure remains a pioneering endeavour, as very few quantum computers are currently installed outside of development labs or research environments.

MeluXina-Q will be designed and built with considerations for sustainability and reliability. The computing platform will be based on a silicon spin qubit foundational technology, which offers promising scalability opportunities for the future and can be produced with proven silicon industrial processes where the provisioning chain is secured in Europe. The technology pathway follows the diversification strategy implemented at European level.

Quantum communication

Under the leadership of the *Department of Media, Connectivity and Digital Policy* (SMC) within the Ministry of State, Luxembourg has been a key driver in quantum communication, joining the EuroQCI programme, led by the European Commission and the *European Space Agency* (ESA) in 2019 and aligning with the EU's vision for a secure quantum communication network. As part of its efforts, the country has established an experimental QKD testbed at the University of Luxembourg. A significant milestone was recently achieved with the successful implementation of a first terrestrial cross-border QKD connection with Belgium. Further national and cross-border QKD projects with several EU member states (e.g. BENELUX-QCI,



Simplified MeluXina-Q architecture blueprint

TransEuroOGS), involving private actors and public research institutes are currently underway, aimed at implementing first integrated quantum communication networks, combining fibre-optic and satellite links for secure data transmission. Luxembourg is also involved in international QKD projects through the collaboration with non-European countries or entities, some of these projects being ESA funded (e.g. INT-UQKD).

Since 2017, several Luxembourg-based industry players, with support from the *Luxembourg Space Agency* (LSA) and the *European Space Agency* (ESA), have been actively involved in developing space-based QKD as a foundational component of the EuroQCI initiative. EuroQCI is set to be integrated into the EU's upcoming secure satellite constellation, IRIS², creating a unified network that combines cutting-edge quantum security with established satellite communication infrastructure.

Luxembourg plays a key role in the IRIS² project. The country will contribute to the design and deployment of the satellite constellation and will also host one of the programme's main control centres for operation.

A key component of EuroQCI is EAGLE-1, a QKD satellite mission developed under ESA's ARTES programme. Luxembourg leads the EAGLE-1 project, with satellite operator SES at the front. The mission is scheduled for launch in 2026 and will enable the testing and validation of space-based QKD technology from *Low Earth Orbit* (LEO). Later, EAGLE-1 will integrate satellite and terrestrial quantum networks to enable cross-border QKD, paving the way for scalable, quantum-secured services within the future IRIS² infrastructure.

Policy context in Luxembourg

Luxembourg is actively fostering digital transformation and creating an environment that supports technological innovation. National quantum research and development efforts are guided by the country's overarching digital, research, and innovation strategies, which provide a foundation for technological advancements, including quantum technologies. The development of a national quantum strategy provides a clear, agile and transversal framework for Luxembourg's ambitions and priorities, fostering the growth of a quantum economy within a broader technological landscape.

Active participation in European initiatives such as EuroHPC and EuroQCI ensures that Luxembourg's quantum computing and communication efforts align with pan-European programmes and policy frameworks, contributing to the development of a cohesive European quantum infrastructure.

Technical standardisation in quantum technologies

Luxembourg, through its national standardisation body ILNAS[4], actively engages in European and international quantum standardisation efforts. Via the ILNAS/NSC03 commission, it facilitates national participation in various quantum standards development initiatives, monitors global developments, and ensures the transfer of relevant information to the national market. This effort is particularly important as quantum computing and quantum communication are rapidly evolving from experimental research to practical applications.

Luxembourg's national research and innovation strategy and its relevance to quantum technologies

In 2020, Luxembourg introduced its National Research and Innovation Strategy[5], aimed at building a sustainable, diverse, and knowledge-driven digital economy over the next decade. The strategy is structured around four key research and innovation priorities, among which the pillar "Industrial and Service Transformation" is particularly relevant to quantum technologies.

This specific pillar focuses on advancing autonomous systems, robotics, next-generation IT and communication systems, space telecommunications, and materials science. These fields align closely with key quantum areas such as quantum computing, quantum cryptography, quantum-enhanced telecommunications, and quantum materials research. The National Research and Innovation Strategy will be updated to reflect key strategic areas, including the quantum-specific research priorities defined in the present strategy.

Quantum technologies for defence

The *Directorate of Defence of Luxembourg* (Lux DoD) coordinates and implements national defence policy, ensuring the Luxembourg Armed Forces are properly staffed and equipped to protect national security interests and fulfil both national and international missions. Lux DoD is responsible for planning investments, developing military capabilities, and supporting the diversification of the country's defence efforts. Today, Luxembourg Defence and its Armed Forces maintain a broad range of skills across land reconnaissance, air, space, and cyber defence.

Quantum technologies, recognised as emerging and dual-use disruptive technologies, are expected to significantly impact military and defence capabilities. Their growing importance is underscored by NATO's first Quantum Strategy, published in late 2023.

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[4] Institut luxembourgeois de la normalisation, de l'accréditation, de la sécurité et qualité des produits et services (ILNAS)

[5] Luxembourg Government (2020), "National Research and Innovation Strategy"

The EU is advancing its leadership in quantum technologies through the Quantum Pact and key initiatives in quantum computing, communication and sensing. Luxembourg contributes to this strategic push for digital sovereignty and technological innovation.

From a cyber defence perspective, the *Competence Hub in Research in Cybersecurity and Cyber Defence* (Cyber Research Hub), launched by the Lux DoD in partnership with the University of Luxembourg, promotes and funds various research projects, including those related to quantum technologies.

In response to rising cybersecurity threats, Luxembourg Defence is exploring the use of quantum technologies for secure transmission and storage of confidential information. Future capabilities in quantum computing and sensing may be developed in collaboration with national and international partners, as technology, policy, and market readiness advance.

European policy and framework

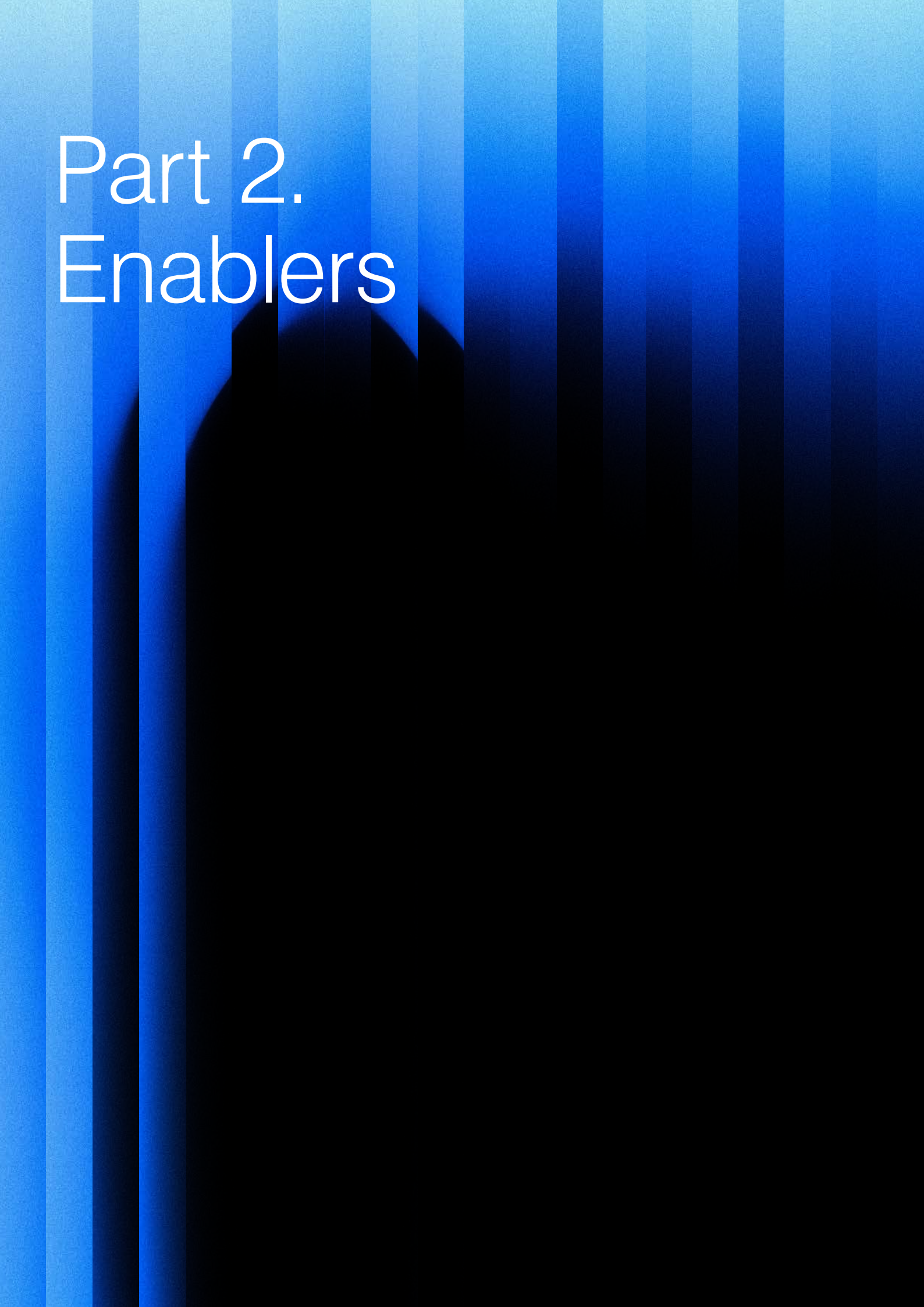
The EU is positioning itself as a global leader in quantum technologies, recognising their strategic importance for scientific and industrial innovation. The Quantum Pact launched in December 2023 underscores the EU's commitment to building a world-class quantum ecosystem, aligning with the Digital Decade strategy and broader digital sovereignty goals.

Key initiatives on EU level include:

- Quantum Computing: The EuroHPC Joint Undertaking aims to deploy Europe's first quantum-accelerated supercomputer by 2025 and achieve global leadership by 2030. Luxembourg joined in 2024, planning to operate a quantum computer as of 2026.
- Quantum Communication: The EuroQCI initiative, launched in 2019 and supported by all EU member states, is developing a secure quantum communication network integrated with the IRIS² satellite system. Efforts also focus on standardising quantum-safe encryption.
- Quantum Hardware: The European Chips Act supports quantum chip development and manufacturing, complementing broader quantum initiatives.

Moreover, the Quantum Flagship, a €1 billion programme launched in 2018, along with Horizon Europe, the Digital Europe Programme (DEP), and the European Innovation Council (EIC), drives research and innovation, to transform breakthroughs into market-ready innovations.

Part 2. Enablers



Six enablers of action

Building on the creation of a dynamic and interconnected quantum ecosystem, the three strategic objectives of the present strategy as set out in section "General Approach", will be achieved by the same six enablers of action defined in the national data strategy and the AI strategy. Each enabler involves specific actions and targets that will work together to achieve these objectives.

1. Governance and regulations
2. Talents and skills
3. Infrastructures
4. Service ecosystem
5. Research and innovation
6. International collaboration

1. Governance and regulations

Ambition: Building a robust governance framework for Luxembourg's national quantum strategy

To ensure the effective implementation of the present strategy, a comprehensive governance framework will be established, focusing on coordination, expert guidance, and measurable outcomes. Growing the quantum sector is a long-term effort requiring sustained collaboration among public research institutions, industry, public organisations, and governmental entities.

› **Action 1:** Creation of a national quantum coordination office

A central component will be the establishment of a *National Quantum Coordination Office* (NQCO), serving as the main body to align resources and initiatives in implementing the national quantum strategy. This office will coordinate R&D programmes, skills development, international engagement, and regulatory efforts, ensuring a cohesive ecosystem. A key mission will be to provide strategic guidance on scientific and technological priorities while monitoring global quantum technology trends, keeping Luxembourg aligned with international developments and maintaining a competitive edge.

To foster continuous dialogue and cooperation, the NQCO will organise biannual meetings that convene governmental representatives and key national public and private stakeholders from the research and innovation sectors to review ongoing activities, assess technological progress, address emerging challenges, and strengthen cross-sector collaboration. These meetings will drive research and innovation initiatives tailored to the needs of a future national quantum economy, ensuring alignment between public, private, and academic actors.

Progress will be measured through clear milestones and key performance indicators (e.g., number of projects, patents, trained professionals, and real-world applications), ensuring transparency and informed decision-making to build a resilient quantum ecosystem.

› **Action 2:** Establishment of advisory committees for strategic quantum initiatives

Under the NQCO, the government may establish special advisory committees composed of representatives from relevant government institutions, supported by external technical experts as appropriate, to oversee key initiatives aligned with the national quantum strategy. These committees will focus on high-priority areas, particularly on achieving the goals associated with quantum computing and quantum communication.

The advisory committees will coordinate and monitor these initiatives, aligning them with national priorities, European policies, and broader economic objectives. Their role is also to foster ecosystem development and generate synergies between research entities, public and private users, and infrastructure and service providers by:

- **Enhancing knowledge exchange:** Facilitating interactions between public and private stakeholders, connecting end users with research institutes to share best practices and insights.

- **Developing and testing use cases:** Identifying future applications and collaborating with relevant actors for practical testing and validation.
- **Ensuring regulatory alignment:** Acting as a liaison between ministries and stakeholders on upcoming European regulations and standardisation efforts.

These advisory committees will play a pivotal role in driving coordinated action and ensuring that Luxembourg's strategic quantum initiatives are effectively integrated into both national and European contexts.

2. Talents and skills

Ambition: Fostering and attracting talent and expertise to build a robust quantum ecosystem

The promotion and attraction of talent and expertise are fundamental to establishing a thriving quantum ecosystem. Quantum technologies are highly complex, requiring an interdisciplinary blend of expertise in physics, computer science, engineering, and cybersecurity.

Luxembourg has already taken significant steps to cultivate quantum talent through initiatives within its academic and research institutions. The University of Luxembourg, for example, offers a range of quantum-focused courses within its *Department of Physics and Materials Science* (DPHYMS) and *Department of Computer Science* (DCS). These programmes cover quantum information theory, computational methods in physics, quantum mechanics, quantum networks, and PQC, providing both foundational and advanced knowledge in quantum science and engineering.

Building a strong talent pipeline ensures that Luxembourg is equipped with the researchers, engineers, innovators, and technical experts needed to harness the full potential of quantum technologies. In addition to specialised quantum education programmes, fostering a diverse and skilled workforce through workshops and upskilling initiatives is crucial to meeting industry demands.

› **Action 3:** Strengthening education, training, and workforce development

To achieve the strategic objectives outlined in this strategy, the government aims to strengthen competencies in quantum technologies, with a particular emphasis on quantum computing, quantum communication, and cybersecurity. This requires expanding existing initiatives and developing new programmes to address current gaps and anticipate future needs. The following measures are proposed to advance this effort:

Develop specialised quantum education programmes

- Launch dedicated Master's and PhD programmes in quantum information science, focusing on quantum computing, algorithms, and applications in industry and research.
- Expand interdisciplinary education by integrating quantum studies with fields like data science, cybersecurity, AI, and HPC.
- Introduce basic quantum technology modules into secondary school physics curricula to prepare future generations for careers in quantum technologies.

Enhance student skills through interdisciplinary and collaborative approaches

- Enhance collaboration across university departments (Physics, Computer Science, Engineering) through joint research initiatives and co-taught courses.
- Align educational programmes with national infrastructure projects like the upcoming quantum computer platform MeluXina-Q.
- Explore joint professorships between national institutions to strengthen research ties and knowledge exchange.

Expand training, outreach, and workforce development

- Provide a variety of training opportunities, including workshops, certification programmes, and executive courses, to develop a quantum-ready workforce.
- Implement upskilling initiatives targeting industry needs.
- Provide specialised training for professionals from related fields, such as computer science, engineering, and physics, to facilitate their transition into the quantum sector (e.g. Digital Learning Hub).

- Promote outreach through public lectures and partnerships (e.g. Scienteens Lab and Luxembourg Science Centre).

Attract and retain talents

- Partner with leading universities abroad to support research and student exchanges.
- Develop joint quantum technology courses with international institutions to enhance access to top-level expertise in Luxembourg.
- Attract global quantum physics talents by offering a competitive research environment leveraging state of the art services, infrastructure and research programmes (AI Factory, MeluXina-Q, LuxQCI, Cyber Research Hub).

These measures must be implemented through a collaborative effort involving all relevant stakeholders, with academia and governmental institutions playing a leading role. These efforts will also be reinforced by joint initiatives developed in conjunction with the national data and AI strategies to ensure an interdisciplinary approach, bridging the gap between quantum technologies, AI, and data science. This will support the comprehensive development of a strong talent pipeline and pool, enabling the workforce to tackle cross-sector challenges effectively.

3. Infrastructures

A core focus of Luxembourg's national quantum strategy is strengthening the national quantum computing and quantum communication infrastructure, aligning with EuroHPC and EuroQCI to enhance its role in the European quantum ecosystem. The two key strategic infrastructure objectives are:

1. **Developing quantum computing expertise and services, with the MeluXina-Q quantum computing platform acting as a key enabling capability.**
2. **Establishing a dynamic national quantum communication network, alongside measures to transition to post-quantum cryptography, to ensure the long-term resilience, security, and sovereignty of Luxembourg's data infrastructure and cybersecurity posture.**

In the following, these two strategic objectives will be elaborated in greater detail.

Ambition: Developing quantum computing expertise and services, with the MeluXina-Q quantum computing platform acting as a key enabling capability

As an early adopter of high-performance computing within the EuroHPC JU network, Luxembourg recognises the transformative potential of quantum computing to solve complex problems that exceed the capabilities of conventional supercomputers. To capitalise on this, Luxembourg, through LuxProvide, and under the leadership of the Ministry of the Economy and the Ministry of Research and Higher Education, successfully secured a EuroHPC JU-hosted quantum computer in 2024 through a competitive European call. The procurement phase of the quantum computer system MeluXina-Q is scheduled for 2025, with implementation and operations set to begin in 2026.

The successful implementation of the MeluXina-Q quantum computer is a key national ambition. Its commissioning is expected to serve as a catalyst for early-stage quantum algorithm and software development, supporting both national and European research efforts. This strategy aims to unite existing initiatives in quantum algorithm research, foster new capabilities through the integration of the quantum computing platform into the HPC architecture, and drive the development of innovative hardware and software solutions with tangible economic impact.

› **Action 4:** Successful implementation and adoption of MeluXina-Q as strategic national digital infrastructure

To fully leverage the potential of the MeluXina-Q quantum computing platform, successful implementation and broad user adoption are essential. As a cornerstone of Luxembourg's high-performance computing (HPC) landscape, MeluXina-Q will play a pivotal role in advancing research and driving industrial innovation by integrating quantum capabilities into national and European digital infrastructures.

As part of the implementation phase of MeluXina-Q, the following measures will be taken to unlock the value of quantum computing for Luxembourg's research and industrial ecosystem and to facilitate its adoption:

Scalable Quantum Platform: Launch with an initial quantum processing capability, followed by a mid-term upgrade to a more powerful Quantum Processing Unit (QPU) within its four-year lifespan to expand quantum processing capabilities.

Comprehensive Quantum Solution: Provide an advanced and comprehensive software environment and integrated gateway for hybrid computing with MeluXina and MeluXina-AI, supporting quantum simulation and algorithm development.

Seamless user experience: Operate MeluXina-Q as a dedicated computing partition with a user-friendly interface that lowers the adoption barrier for researchers and industry, including cost-effective access for national R&D stakeholders.

Integrated Development Environment: Embed quantum tools within the MeluXina software stack, offering access to extensive libraries and quantum simulators.

Pan-European Accessibility: Connect MeluXina-Q to the EuroHPC Federation Platform[6] to provide secure, flexible access to quantum, HPC, and AI resources for users across Europe, enhancing cross-border collaboration and innovation.

› Action 5: Building expertise and partnerships to harness the full potential of quantum computing

With the implementation of MeluXina-Q, Luxembourg seeks to establish a strong quantum computing ecosystem that unlocks its full potential. Developing competencies is crucial for the successful introduction and application of quantum computing technologies, especially since quantum infrastructure, software ecosystems, and market expertise are still in their early stages compared to classical computing.

The present strategy emphasises several key measures that allows to create a flourishing quantum computing ecosystem.

Knowledge centre and training: The government supports the creation of a knowledge hub for quantum computing, thereby also promoting staff development through conferences, workshops, and experience exchanges. Training focuses on using world-class quantum simulators integrated with the MeluXina(-AI) supercomputers, covering relevant applications for the Luxembourg ecosystem.

Luxembourg aims to become a major player in quantum computing by developing cutting-edge expertise and services. A key element of this effort is the MeluXina-Q platform, a EuroHPC-hosted quantum computer, set to drive innovation, research, and economic impact from 2026 onward.

Local and international collaboration: Since 2024, LuxProvide has hosted quantum computing training for participants from Luxembourg, Ireland, and Japan. In collaboration with the Digital Learning Hub, a tailored training portfolio is being developed. Additionally, partnerships with the University of Luxembourg and LIST are instrumental in onboarding users and supporting the deployment of MeluXina-Q.

Research and industry integration: Collaboration with the newly established HPC and Quantum Computing research group at the University of Luxembourg will focus on developing and validating initial practical use cases for quantum computing, encouraging early adoption by industry, start-ups, and academia. LuxProvide, the University of Luxembourg, and Luxinnovation, as founders of the Luxembourg National Competence Centre in HPC, will assess national needs and promote wider access to HPC. As part of this effort, a quantum readiness framework should be developed to support SMEs and start-ups in exploring and investing in quantum technologies, supported by ongoing dialogue with stakeholders to ensure alignment with ecosystem needs throughout the implementation and operation phases.

European and international partnerships: Luxembourg engages with the other seven EuroHPC Quantum hosting entities to share best practices and develop hybrid supercomputing-quantum software environments. Existing collaboration with Ireland's ICHEC supports joint projects like HPCQS and NEASQC, aimed at practical quantum applications, especially in finance.

[6] EuroHPC JU (2024), "Paving the Way for the EuroHPC Federation Platform"

› Action 6: Building a quantum software ecosystem

For now, the use of quantum computing is limited due to the need for specialised hardware, skilled researchers, and complex algorithm development. Broad adoption will require a user-friendly ecosystem, similar to machine learning's democratisation, with standardised tools, automated frameworks, and extensive training. Challenges include integrating quantum algorithms with classical systems, early-stage hybrid frameworks, hardware-dependent specialised languages, and unique quantum-specific faults that hinder debugging.

Luxembourg will foster a robust quantum software ecosystem that supports the development of both proprietary and open-source solutions across the quantum computing software stack. Particular emphasis is placed on automated tools for programme analysis, testing, debugging, and repair, to ensure the reliability of quantum software and enable its deployment in practical, real-world applications.

Given that quantum programmes must integrate seamlessly with existing software infrastructures, the aim is to develop intelligent systems for data analysis, storage, and secure hardware access. Medium-term goals include close collaboration between researchers and key quantum players to develop specialised tools for quantum requirements analysis and software design, leveraging AI-driven natural language processing methods for instance, to help developers identify quantum integration opportunities.

Investing in talent is key, with a focus on experts in functional analysis, software engineering, and AI-based software generation. Combined with access to advanced infrastructure, including quantum simulators, quantum computers, and generative AI platforms, this will be crucial for advancing quantum software development.

Ambition: Establishing a dynamic national quantum communication network, alongside measures to transition to post-quantum cryptography to ensure the resilience of national data communication

Luxembourg has pursued a long-term strategy to expand its digital infrastructure as a cornerstone of its transition toward a digital and innovative economy. The *Department of Media, Connectivity and Digital Policy* (SMC) within the Ministry of State is leading the quantum communication initiatives in Luxembourg and has developed QKD initiatives for the national quantum communication infrastructure, aligning with the EU's objectives for a secure, quantum-safe communication network within the framework of the EuroQCI programme.

In addition to continuous investments in high-performance computing and big data infrastructures, Luxembourg boasts one of the most advanced digital broadband networks in the EU, ensuring optimal national and international connectivity. Building on this robust digital foundation, Luxembourg is committed to enhancing its cybersecurity and cyber defence capabilities, as laid out in its Fourth National Cybersecurity Strategy[7].

The rise of quantum computing presents growing risks to existing encryption methods, increasing the urgency of developing quantum-secure communication systems. Two key technological solutions are:

- *Post-Quantum Cryptography* (PQC): Uses quantum-resistant algorithms, allowing immediate integration into existing systems, though it requires larger keys and increased computational overhead.
- *Quantum Key Distribution* (QKD): Provides provably unbreakable security based on the principles of quantum mechanics but is limited by infrastructure and range constraints.

While PQC provides a viable short-term solution for quantum resilience, QKD is advancing as a long-term option for high-security use cases. Existing QKD systems enable secure point-to-point communication over several hundred kilometres using optical fibre and trusted nodes. Ongoing research is focused on expanding these capabilities through free-space transmission, multi-user networks, and entanglement-

[7] Luxembourg Government (2021), "National Cybersecurity Strategy IV"

based protocols, especially suited for urban environments. The development of quantum repeaters will be critical for enabling longer-distance terrestrial communication and reducing reliance on trusted intermediaries.

To address quantum threats, Luxembourg prioritises the accelerated adoption of PQC, while continuing to develop QKD infrastructure and expand network capabilities to ensure long-term cybersecurity resilience. The government is also committed to driving innovation in this field, generating economic value for local stakeholders and reinforcing Luxembourg's role as a trusted and competitive actor in the quantum technology field.

› **Action 7:** Creation of impactful applications for the first generation of quantum communication

As part of its EuroQCI efforts and building on ongoing activities, the government supports the development of practical QKD use cases for non-academic users, focusing on first-generation quantum networks (point-to-point), spanning terrestrial, space-based, and hybrid systems. With a leading position in space-based quantum communication, Luxembourg aims to strengthen and expand its strategic advantage in this domain.

Given the high costs and early stage of technological maturity in quantum communication equipment, the government must take on the role of frontrunner and early adopter. To this end, it supports the establishment of initial experimental quantum network applications connecting public stakeholders, while inviting private partners to gain hands-on experience through pilot projects in real-world scenarios. These efforts will prioritise high-risk sectors vulnerable to cybersecurity threats, such as defence, energy, healthcare, data centres, and government institutions. Over time, the initiative will extend to private organisations handling sensitive data, fostering broader adoption of quantum communication technologies.

Key strategic priorities include:

- **Secure quantum communication for data spaces:** Enhancing data security for data space communication by integrating QKD into data connectors, enabling quantum-safe transmission of sensitive health and research data (e.g. in initiatives such as *Clinnova,* the upcoming *Genome* EDIC, or the *European Health Data Space* (EHDS)).
- **Demonstration of space-based QKD:** Supporting the testing and validation of space-based QKD capabilities to bridge experimental technologies with operational services, and promoting early adoption in sectors such as government, finance, telecommunications, cloud, and healthcare.

Luxembourg aims to build a secure quantum communication network and adopt post-quantum cryptography to increase its digital resilience and reinforce its leading role in secure terrestrial and satellite-based communications.

- **Towards commercial QKD services by 2030:** Supporting initiatives aimed at developing commercial long-distance satellite-based QKD services, positioning Luxembourg as a frontrunner in quantum-secure space communication.

The strategy also focuses on developing national expertise in the deployment, operation, and key management of QKD systems. Real-world data will be used to improve bit rate, range, and network performance. Raising awareness among private stakeholders and collaborating with the telecom industry will be essential to foster demand-driven development.

› **Action 8:** Advancing a next-generation quantum communication network in Luxembourg

Luxembourg aims to become a national testbed for multi-user quantum communication networks, enabling the validation of second- and third-generation technologies. The country's expertise across the quantum network stack, both in software and hardware, provides a strong foundation.

A key strategic measure is the development of a dynamically configurable, multi-user quantum network using entanglement-based QKD, enabling secure, on-demand connections without trusted nodes, through collaboration with relevant key actors and stakeholders.

Initial efforts will focus on inter-city connections between public and institutional users. Leveraging the country's high-quality optical fibre infrastructure, rural and non-urban sites could be integrated in a second phase. Starting with government institutions and public administrations, the network could gradually expand to include entities classified as critical infrastructure, such as healthcare, finance, data centres, and other key sectors, enabling the development of impactful use cases with significant economic and societal relevance.

Given the early stage of entanglement-based QKD, public-private partnerships and collaboration with start-ups will be key to accelerating innovation. Luxembourg also supports collaboration in EU-level programmes, thereby strengthening Luxembourg's role with the European quantum ecosystem and actively contribute to the development of third-generation quantum networks. These networks, incorporating quantum repeaters and quantum memory-based relays for secure long-distance communication, aim to lay the groundwork for a future quantum-secure internet.

› Action 9: Foster the development of foundational technologies for quantum communication networks and beyond

Expanding on its goal to become a testbed for next-generation quantum communication networks, Luxembourg is committed to advancing elementary quantum technologies to foster innovation in quantum communication. The government actively supports R&D efforts in software and hardware development, that focuses on creating national quantum network technologies tailored for dedicated use cases in cryptography, sensing, and computing.

By integrating developed software at the network layer and hardware at the physical layer with quantum repeaters, Luxembourg aims to enhance quantum network capabilities. The adoption of a *Software-Defined Networking* (SDN) approach presents a promising strategy, enabling centralised management and programmability, both essential for seamless quantum network integration.

In this context, SDN could enable the creation of a unique testbed for quantum repeater networks locally in Luxembourg, developed through collaboration between local actors. This testbed may serve as a platform for advancing the integration of key hardware components, including quantum memories, in-chip entanglement sources, and detectors, alongside in-chip Quantum Random Number Generators (QRNG) and modulators. This ensures that the network can evolve in complexity while maintaining high performance and reliability, thereby supporting transformative applications in secure communication, delegated computing, and beyond.

Additionally, the government will support R&D in photonic quantum chip development, a critical enabler for scalable quantum networks. Photonic quantum chips are essential components for quantum repeaters with integrated memory, enabling greater network range and reliability.

- **Focus on wide-bandgap (WBG) semiconductors**: Materials such as silicon carbide (SiC) and gallium nitride (GaN) offer stable quantum defects that can be exploited for quantum chip development across communication, computing, and sensing applications. However, challenges remain in preserving quantum coherence, which is critical for their functionality.
- **Quantum sensing potential:** WBG-based quantum chips hold significant promise for quantum sensing, enabling high-precision sensors in sectors such as defence, healthcare, and infrastructure monitoring. As quantum sensors are expected to be among the first commercially viable quantum technologies, developing dedicated research in this area is a strategic priority and addresses a current gap in Luxembourg's quantum R&D ecosystem.
- **Long-term approach and economic goals:** The present strategy emphasises medium- to long-term research to advance scientific knowledge and stimulate economic growth by investing in promising technologies like quantum chips. These efforts aim to attract global quantum companies, support the creation of startups, and generate skilled employment, generating returns via patents, commercial applications, and international partnerships. In alignment with the EU Chips Act, Luxembourg is also exploring participation in Quantum Pilot Lines to contribute to and benefit from EU chip fabrication capabilities.

› Action 10: Preparing for and addressing the transition to post-quantum cryptography

With quantum computing posing a growing threat to classical encryption, Luxembourg is prioritising a secure and proactive transition to PQC, alongside the deployment of QKD, to safeguard its critical infrastructure and sensitive data. Under the leadership of the *Haut-Commissariat à la Protection Nationale* (HCPN), Luxembourg co-signed a joint declaration with 18 EU member states highlighting the urgency of integrating quantum threat preparedness into cybersecurity strategies.

As a digital and financial hub with strong PQC expertise, the country aims to support public administrations, critical sectors, and businesses in navigating the complex migration to quantum-safe encryption. Given the evolving nature of PQC algorithms and practical implementation challenges, such as larger key sizes, increased computational demands, and system integration, Luxembourg promotes a phased, hybrid approach combining traditional and quantum-safe cryptography to ensure enhanced resilience and redundancy.

Acknowledging the complexities of migrating to PQC, the government aims to develop a national-level roadmap to guide this transition in alignment with the European Commission's recommendation for a

coordinated approach to PQC[8]. R&D efforts will play a central role in this transition. Luxembourg aims to intensify research in PQC, building on the strong expertise already present in the country. These efforts will focus on developing efficient algorithms and addressing the practical challenges of implementation. Leveraging the upcoming national hybrid HPC-quantum computing platform, researchers will be able to assess quantum attack timelines to inform realistic migration schedules and use the platform as a sandbox to test PQC protocols across various computing hardware.

In collaboration with key actors such as the HCPN, the *Luxembourg House of Cybersecurity* (LHC), Incert G.I.E., and other relevant stakeholders, the present strategy prioritises the following actions to ensure a smooth and dynamic transition to PQC:

- **Quantum threat analyses:** Identify vulnerable assets and applications through comprehensive cryptographic inventories, enabling risk-based mitigation and cost-effective solutions.
- **Comprehensive migration frameworks:** Develop guidelines ensuring seamless PQC adoption with backward compatibility and minimal system disruption adopting a crypto-agility approach.
- **Collaborative support mechanisms:** Explore establishing a dedicated PQC hub to assist companies with technical expertise and strategic guidance during the transition.
- **Awareness initiatives:** Organise workshops, conferences, and policy discussions to highlight the importance of quantum-safe communication among stakeholders.
- **Research and standardisation:** Enhance PQC research to develop advanced cryptographic protocols, supporting security standards and interoperability across sectors.
- **Talent and skills development:** Launch educational initiatives to equip students and professionals with advanced mathematical and cryptographic skills needed for PQC implementation.
- **International collaboration:** Align with global efforts through cooperation with organisations like the *European Network and Information Security Agency* (ENISA), ensuring a coordinated approach to PQC and cybersecurity challenges.

Luxembourg's PQC efforts aim to strengthen national cybersecurity, protect critical sectors, and support businesses in adopting quantum-safe solutions. The strategy emphasises a coordinated, cross-sectoral approach, recognising that effective implementation requires collaboration among government bodies, industry players, IT service providers, and public institutions.

› **Action 11:** Exploring the defence potential of quantum technologies

In today's complex geopolitical landscape, Luxembourg Defence is exploring quantum technologies for the secure transmission and storage of confidential data. The Cyber Research Hub, established with the University of Luxembourg, supports dedicated cyber-R&D, including quantum communication.

Beyond cybersecurity, quantum technologies offer long-term potential for developing innovative defence capabilities. Luxembourg's approach aims not only to strengthen national security but also to generate economic value through the development and commercialisation of quantum-based solutions.

To support this vision, the government will promote quantum defence applications through targeted measures, including public-private partnerships and international collaboration.

Luxembourg's quantum strategy strengthens national digital sovereignty and security, while positioning the country as a key player in Europe's emerging quantum economy through advanced infrastructure, talent development, and technological innovation.

[8] European Commission (2024), "Commission Recommentation of 11.4.2024 on a Coordinated Implementation Roadmap for the Transition to Post-Quantum Cryptography"

4. Service ecosystem

Ambition: Driving innovation and economic impact through strengthened collaboration within Luxembourg's quantum ecosystem

Luxembourg's national quantum strategy places strong emphasis on advancing quantum science and technology while generating economic impact by uniting expertise from industry, academia, and research. Central to this approach is the creation of specialised quantum clusters that act as hubs for knowledge exchange, workforce development, and technological innovation. Built on strong collaborative networks between researchers, industry partners, and public institutions, these clusters are designed to accelerate the development of quantum technologies, address key challenges, and bridge the gap between fundamental research and market-ready applications.

› **Action 12:** Creation of a Quantum Factory

To support this ambition, Luxembourg aims to develop the concept of a Quantum Factory, a collaborative and integrative network inspired by the AI Factory. It will bring together quantum clusters under a shared architecture to pool resources, infrastructure, tackle scientific and technological challenges, and accelerate innovation in strategic sectors. With international outreach, the Quantum Factory will drive cross-sector collaboration, support talent development and attraction, and stimulate ecosystem-wide innovation.

As a first step, an assessment will be carried out to identify priority areas for the creation of thematic quantum hubs within the Quantum Factory. These hubs should focus on research and development and may include, for example, a Centre of Excellence in Quantum Information Science to foster interdisciplinary research, a mission-oriented quantum R&D lab or a dedicated hub for advancing PQC research.

Each hub will have tailored objectives according to its technological focus and maturity level. Workshops, training programmes, and joint projects will address interdisciplinary challenges, while knowledge-sharing platforms will help align national research priorities and promote best practices.

A central priority will also be the integration of quantum technologies with AI and data science, enabling the formation of multidisciplinary teams comprising domain experts, AI researchers, data scientists, and software engineers. These teams will have access to HPC platforms and related services, working in close synergy with universities, startups, and industry actors to fast-track innovation and application.

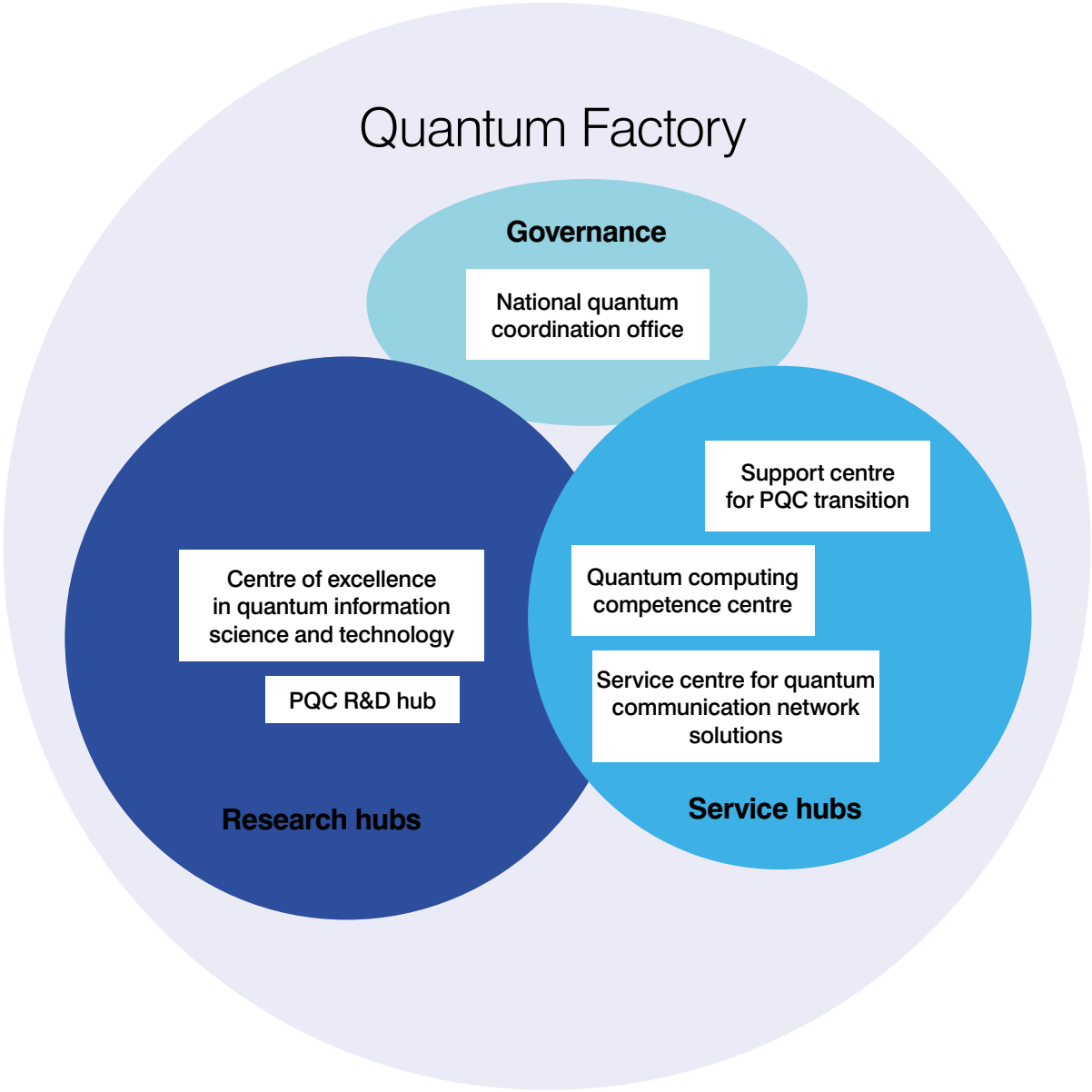
› **Action 13:** Adoption of quantum technologies through the creation of a service ecosystem

As quantum technologies evolve, the present strategy aims to foster their adoption by developing a robust service ecosystem that supports research, industry, and public institutions. While many quantum technologies remain in development, areas like quantum computing, PQC, and quantum communication have matured enough for first real-world integration.

Luxembourg aims to foster the uptake of quantum technologies by supporting the creation of specialised service hubs and initiatives alongside the previously mentioned research hubs to benefit local stakeholders. For example:

- A support centre for PQC that assists businesses in navigating the complex transition to quantum-safe cryptography, offering technical expertise and raising awareness of quantum-related threats.
- A national awareness campaign on quantum communication that informs both public and private stakeholders, as well as society at large, about the threats posed by quantum computers and the need for a quantum-secure infrastructure.
- Support for the development of quantum communication network services, encouraging local actors to enter the market, and building a competitive and sustainable service landscape.
- A dedicated service centre that supports the implementation of quantum algorithms and promotes adoption of quantum computing among local industry and research institutions.

The Quantum Factory represents a collaborative and integrative network, combining thematic research clusters, service hubs, and cross-sectoral partnerships to accelerate the development and deployment of quantum technologies in strategic areas. It will support the country in building a robust and agile quantum ecosystem capable of fully leveraging the potential of quantum technologies.



Concept of a Quantum Factory that functions as a collaborative and integrative network of dedicated clusters

5. Research and innovation

Ambition: Strengthening Luxembourg's quantum research and innovation ecosystem

The present strategy positions research and innovation as the foundation of Luxembourg's quantum ambitions, with the goal of developing a globally competitive research ecosystem that drives scientific excellence and technological progress. Key objectives include strengthening both fundamental and applied quantum research, setting mission-driven R&D priorities supported by a structured investment framework, and ensuring sustained support for foundational quantum science to attract and develop top talent and enable future breakthroughs.

› **Action 14:** Establishing focused quantum research priorities

The strategy aims to elevate quantum research within Luxembourg's broader innovation agenda by reinforcing strengths in fundamental science, applied technologies, and industry adoption. Key research priorities will be incorporated into an update of the National Research and Innovation Strategy, ensuring alignment with national goals and ecosystem development.

A structured funding framework based on these priorities will support both top-down initiatives in core areas aligned with the priorities defined in the present strategy, i.e. quantum computing, quantum communication, and quantum cybersecurity, as well as bottom-up programmes to stimulate excellence in basic and applied research.

By uniting research, industry, and resources within a collaborative approach, Luxembourg aims to transform its quantum ambitions into innovation and economic impact.

The key research priorities that have been identified are:

Quantum computing and algorithms

- Development of quantum algorithms for optimisation, AI, and computational mechanics
- Investigation of different quantum computing platforms (e.g., superconducting qubits, trapped ions, silicon spin qubits)
- Quantum control of noisy devices to enhance fault tolerance and improve quantum error correction strategies
- Quantum software verification and validation

Quantum communication network

- Research on secure quantum communication architectures, including terrestrial and space-based QKD, quantum repeaters, and entanglement-based networks
- Hybrid quantum-classical models integrating PQC and QKD for secure communication
- Scalable quantum network protocols, advancing towards the future Quantum Internet

Quantum cryptography and post-quantum cryptography

- Development of quantum-resistant cryptographic algorithms
- Research on secure quantum key establishment, hybrid security models, and real-world implementations
- Standardisation and industry implementation of PQC

To cultivate a thriving quantum research ecosystem, research activities in connected areas as outlined below, may also be supported in view of advancing both fundamental and applied quantum research and to ensure Luxembourg remains engaged with key developments in these emerging fields, fostering future innovation and talent development.

Quantum information theory

- Research on quantum information processing for quantum computing, cryptography, and metrology
- Quantum entanglement, coherence, and error correction for scalability and fault tolerance in quantum technologies

Quantum metrology and sensing

- Quantum-enhanced sensing technologies for high-precision measurements in healthcare, defence, and critical infrastructure monitoring
- Quantum parameter estimation to improve sensitivity and accuracy in metrology applications

Computational quantum physics and quantum chemistry

- Density Functional Theory (DFT) and quantum chemistry calculations for materials and surface science, chemistry, and biology applications
- Development of quantum approximations for materials modelling and simulation
- Quantum simulations of molecular and condensed matter systems for material design

Condensed matter physics and quantum materials

- Strongly correlated quantum systems, topological materials, quantum phase transition, and multiple functional effects
- Exploration of quantum defects in solid-state systems, such as silicon carbide (SiC) and gallium nitride (GaN), for quantum computing, sensing, and communication
- Hybrid architectures for optimised operation of quantum systems (phase tuning, wavelength tuning and conversion, charge control, temperature)

› Action 15: Strengthening Luxembourg's quantum research ecosystem through strategic funding

Sustaining the quantum ecosystem requires well-adapted funding mechanisms that balance continuity and innovation. This includes support for new research groups, expanding existing teams, and investing in cutting-edge infrastructure. A balanced approach between competitive funding and top-down strategic investments is essential to achieve the strategic goals and to drive broader quantum research and innovation. The Luxembourg National Research Fund (FNR) plays a key role in supporting the quantum research ecosystem through national funding calls, international collaboration, and industry-led innovation programmes, while also fostering a strong talent pipeline by supporting PhD candidates, postdocs, and early-career researchers.

To further strengthen the ecosystem, the strategy promotes in addition to the classical bottom-up funding schemes:

- Mission-driven innovation programmes aligned with national objectives, including high-risk, high-reward research (e.g. National Centres of Excellence in Research (NCER) programme)
- Industry-led R&D programmes to increase private sector involvement
- Greater participation in EU programmes and consortia
- Strategic capacity-building through new research groups in emerging quantum domains
- Targeted investments in infrastructure and equipment to support long-term scientific goals

› Action 16: Centre of excellence in quantum information science and technology (QIST)

In line with the vision of the Quantum Factory to establish interconnected clusters to foster interdisciplinary collaboration and resource consolidation, the present strategy proposes evaluating the establishment of a Centre of Excellence in Quantum Information Science and Technology (QIST).

This centre would:

- **Unite global experts in one location** to focus on high-impact quantum information technologies such as quantum cryptography, quantum AI, optimisation, and quantum simulation.
- **Advance practical applications** in key industries like finance, defence, energy, materials science, and logistics by raising technology readiness levels.
- **Serve as a hub for international collaboration**, enhancing Luxembourg's global quantum presence and strengthening EU research network ties.
- **Host visiting researcher programmes**, **conferences**, and **forums** to promote research excellence and global engagement.

This centre would become a cornerstone of Luxembourg's global quantum presence, driving groundbreaking discoveries and long-term scientific leadership while being a pole of attraction for talents in the quantum field.

› Action 17: Valorisation of quantum R&D – Luxembourg's deep tech lab

Alongside the broader and more foundational concept of a Centre of Excellence in QIST, the present strategy, aligned with the data strategy and the AI strategy, supports the creation of a mission-oriented technology lab designed to serve as a dynamic hub where researchers and engineers can fast-track the development of innovative, practical solutions geared toward commercialisation in fields aligned with national strategic priorities.

In the domain of quantum technologies, the lab will drive the valorisation of scientific and technological progress in quantum computing, quantum communication, and quantum cryptography, while working closely with Luxembourg's private sector to ensure real-world applications and economic impact. Furthermore, the lab will play a critical role in attracting world-class talent, as well as retaining and developing local talent, by providing a highly attractive and dynamic work environment.

6. International collaboration

Ambition: Fostering european and global collaboration in quantum technologies

The Luxembourg government recognises that achieving its quantum ambitions requires strong collaboration across academia, industry, government, and international partners. Given the complexity and transformative potential of quantum technologies, an interdisciplinary and collaborative approach is essential, particularly one that emphasises European and global synergies.

At the European level, the EU aims to build a world-leading quantum ecosystem, promoting both scientific excellence and industrial applications, while laying the groundwork for breakthrough innovations. Luxembourg aligns its efforts with this vision, actively participating in joint initiatives focused on quantum infrastructure and collaborative research. This commitment is reflected in Luxembourg's endorsement of the European Quantum Technology Declaration, also known as the Quantum Pact.

The Quantum Pact provides a framework for pan-European cooperation, uniting signatory countries around the shared goal of establishing the EU as a global leader in quantum innovation. To achieve this, it outlines several key objectives: coordinating research and development initiatives and deploying European quantum infrastructure; accelerating the adoption of quantum technologies by strengthening the connection between research and industry; supporting the growth of startups, scale-ups, and EU-based technology leaders; and enhancing investment, skills development, and Europe's strategic autonomy through the establishment of dedicated quantum fabrication capabilities.

› **Action 18:** Strengthening Luxembourg's role in the european and global quantum ecosystem

The present quantum strategy emphasises active engagement in European initiatives like EuroHPC, EuroQCI, Quantera, and future quantum related actions to enhance its visibility, impact, and contribution to the European quantum ecosystem. These programmes offer frameworks for scientific cooperation, infrastructure development, and industrial innovation, allowing Luxembourg to leverage European expertise and resources.

To strengthen its position, Luxembourg will pursue bilateral and multilateral agreements for knowledge exchange, joint R&D, and technological advancements, with a focus on quantum computing, quantum communication and cybersecurity. Collaboration with neighbouring countries is essential for interoperability within European quantum communication networks, ensuring seamless integration with international pathways (both space-based and terrestrial). Beyond Europe, Luxembourg remains open to partnerships with nations that share the same values and standards.

At the academic and industrial levels, the government is committed to expanding public-private partnerships to accelerate quantum innovation through joint workshops, dedicated aid schemes, and mechanisms that translate academic breakthroughs into commercial applications. To encourage quantum technology adoption, the government will promote public procurement of quantum solutions through EuroHPC and EuroQCI projects and explore tax incentives and similar mechanisms to stimulate private sector investment and industrial scale-up, while also positioning Luxembourg as a hub for international quantum startups.

Part 3.
Flagship projects

Cybersecurity: Democratising cybersecurity

Cybersecurity threat intelligence data is seldomly shared and mostly stays in proprietary feeds. Such data is thus not available for innovation, thus strengthening the position of oligopolistic cybersecurity vendors. As a result, unaffordable prices leave SMEs (representing > 95% of the EU economy) vulnerable, posing significant risks to supply chains and economic stability. To strengthen economic resilience, SMEs therefore require access to affordable security solutions defending them against the ever-evolving threat landscape.

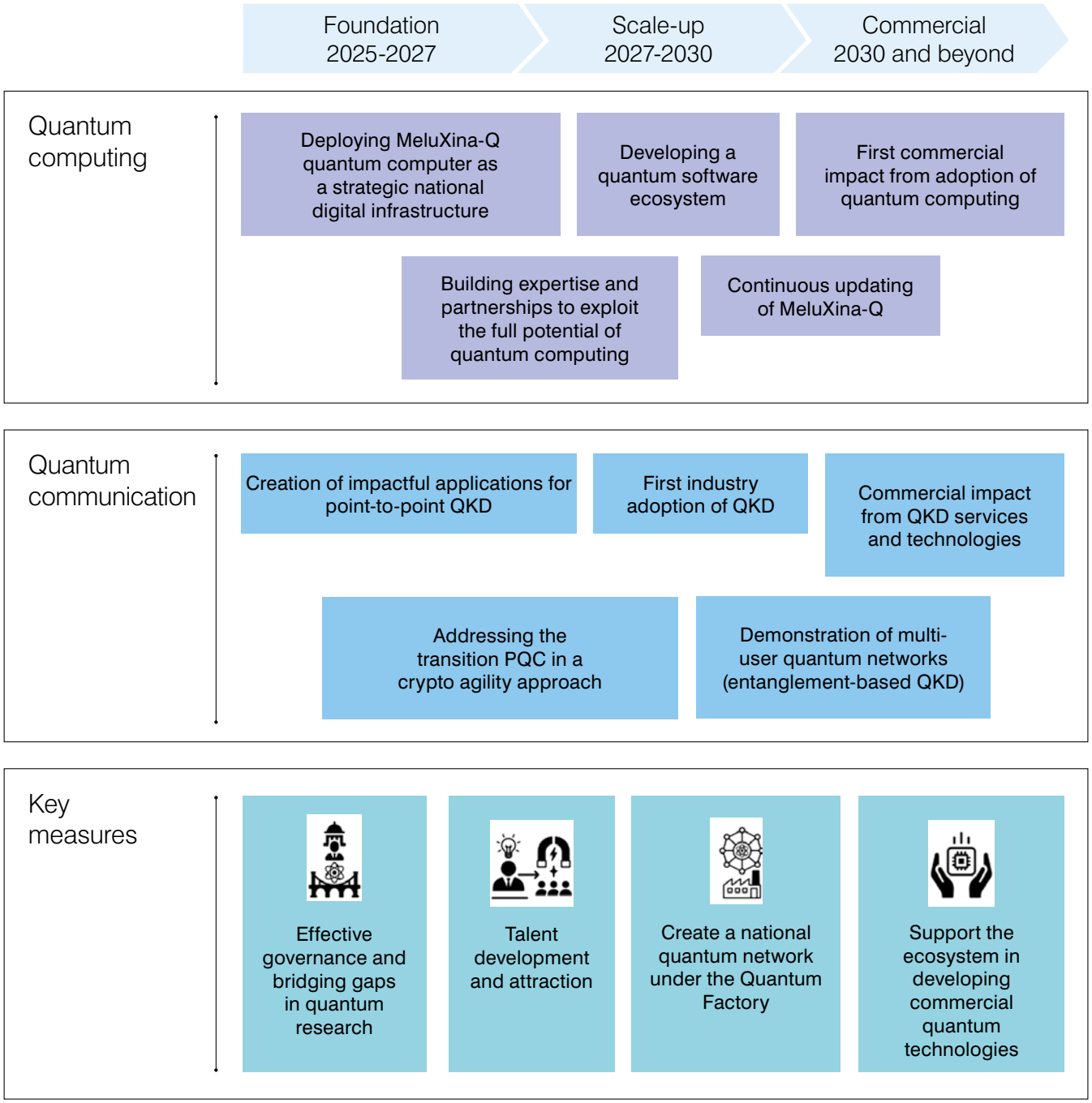
An effective way to address this market failure is to open the cybersecurity data economy. Today's data economy relies extensively on cloud infrastructures. Therefore, Luxembourg participates in the IPCEI Next Generation Cloud Infrastructure and Services (IPCEI-CIS) and its contribution will materialise through the macro project CLoud & dAta SecUrity reSource cENter (CLAUSEN), creating the first Open Cybersecurity Data Space (OCDS) in Europe. Such a data space fosters synergies by facilitating the collection and exchange of cybersecurity-related data like threat intelligence, vulnerabilities, and efficiency of protective measures. Furthermore, it nurtures AI Factories with cybersecurity data, which is indispensable for the creation of new autonomous cybersecurity tools that SME can afford.

As faster and more sophisticated cyber threats need quicker and more effective responses, the ambition of the present flagship project is to further support the cybersecurity ecosystem with AI, applied on vast amounts of raw and contextualised cybersecurity data. The aim is to enhance the readiness of all stakeholders by equipping them with the necessary knowledge and tools to handle cyber threats.

- **As a primary focus**, the project aims to gain a deeper understanding of adversaries by utilising existing threat intelligence gathering tools, and by shaping the collected raw data with the help of AI into threat intelligence. The integration of this data will enable quicker analysis of malicious behaviours and the processing of larger volumes of such activities. The resulting intelligence will be made available to the cybersecurity community, to law enforcement agencies, and to judicial authorities to support their efforts in identifying and combating cyber threats and securing companies and citizens. Finally, the gathered threat intelligence will be aggregated with the help of AI into cyber weather reports, which, among other benefits, increases the accuracy of risk management and improves the resilience of the Luxembourg economy.
- **A secondary focus** of the project aims at strengthening governance, risk, and compliance for SMEs. New risk information, including metrics, risk scenarios & mitigation techniques related to the adoption of new AI technologies, will be provided to the private sector. Furthermore, the use of new and continuously updated models will democratise governance and risk management by providing easy-to-use AI-powered human interfaces. This will enable proactive and safe integration of AI into governance platforms to improve the accuracy of risk treatment decisions and investments. SMEs will be supported in their compliance journey by offering a platform that helps them design and implement tailored information security policies, procedures, and guidelines.
- **A third focus** lies on managing risks that accompany the emerging technologies. Those cover inherent vulnerabilities of AI systems, and the quantum threat for cryptography. To address these challenges, the Luxembourg ecosystem needs guidance, testing infrastructure and tools to adopt post-quantum cryptography (PQC), and mechanisms to evaluate AI implementations, models and machine learning processes.

Part 4. Conclusion

Luxembourg's quantum strategy roadmap



Phase 1: Establishing the foundation (2025-2027)

Implementing a national governance framework to coordinate quantum initiatives and foster collaboration between academia, research institutions, industry, and government. Expanding quantum education at the Bachelor and Master levels, addressing gaps in the research ecosystem, and investing in advanced research equipment and infrastructure to support long-term strategic goals. Integration of research priorities in the National Research and Innovation Strategy update and implementation of targeted funding schemes for mission-driven R&D while reinforcing fundamental research as a foundation for innovation and knowledge creation.

Deploying MeluXina-Q as Luxembourg's national quantum computing infrastructure to enable the acceleration of research on quantum algorithms and forging strategic partnerships to encourage industry adoption. Focus on developing practical use cases of first-generation quantum communication and optimising network performance through real data, as well as addressing the transition to PQC through a crypto-agile approach. Establishing specialised quantum R&D hubs, to foster interdisciplinary collaboration and strengthening international integration through active participation in European quantum initiatives.

Phase 2: Scaling the ecosystem (2027-2030)

Expanding quantum training programmes to support industry workforce development and public outreach. Establishing a national collaborative network under the Quantum Factory initiative, integrating quantum research hubs and specialised service centres to accelerate industry adoption. Evaluating the creation of a Centre of Excellence in QIST to consolidate resources, enhance research excellence, and elevate Luxembourg's global visibility in quantum research.

Continually developing MeluXina-Q into a cutting-edge quantum computing platform that provides lasting support for public research and early industrial adoption. Creating a quantum software ecosystem to foster new applications and tools, enhancing the usability and accessibility of quantum computing. Advancing the demonstration of first multi-user quantum networks with societal and economic impact, and supporting the development and commercialisation of quantum technologies (e.g. quantum chips).

Phase 3: Achieving commercial impact (2030 and beyond)

Realising the first commercial breakthroughs in quantum computing and quantum communication networks, integrating quantum solutions into industry to drive computing advancements, secure communications, and cryptography innovation. Position Luxembourg as a key player in quantum innovation, attracting investment, talent, and high-tech industries. Sustaining long-term competitiveness in the global quantum economy, ensuring Luxembourg remains at the forefront of quantum science and technology, while maximising its societal and economic benefits.

Conclusion

In conclusion, the national quantum strategy reflects the government's commitment to laying the foundation for positioning Luxembourg as a key player in the quantum era. This is built on ambitious objectives in the key areas of quantum computing and quantum communication, clear, targeted actions across the six strategic enablers, and an integrated approach through the development of a Quantum Factory concept.

By fostering a high-performing ecosystem focused on economic value creation, skills enhancement, and the development of cutting-edge digital infrastructure, Luxembourg is equipping itself to harness quantum technologies while reinforcing its digital sovereignty.

Through strong partnerships between the public sector, academia, and industry, the country aims to transform scientific advancements into practical, competitive solutions, contributing to technological progress, digital security, and sustainable economic growth.

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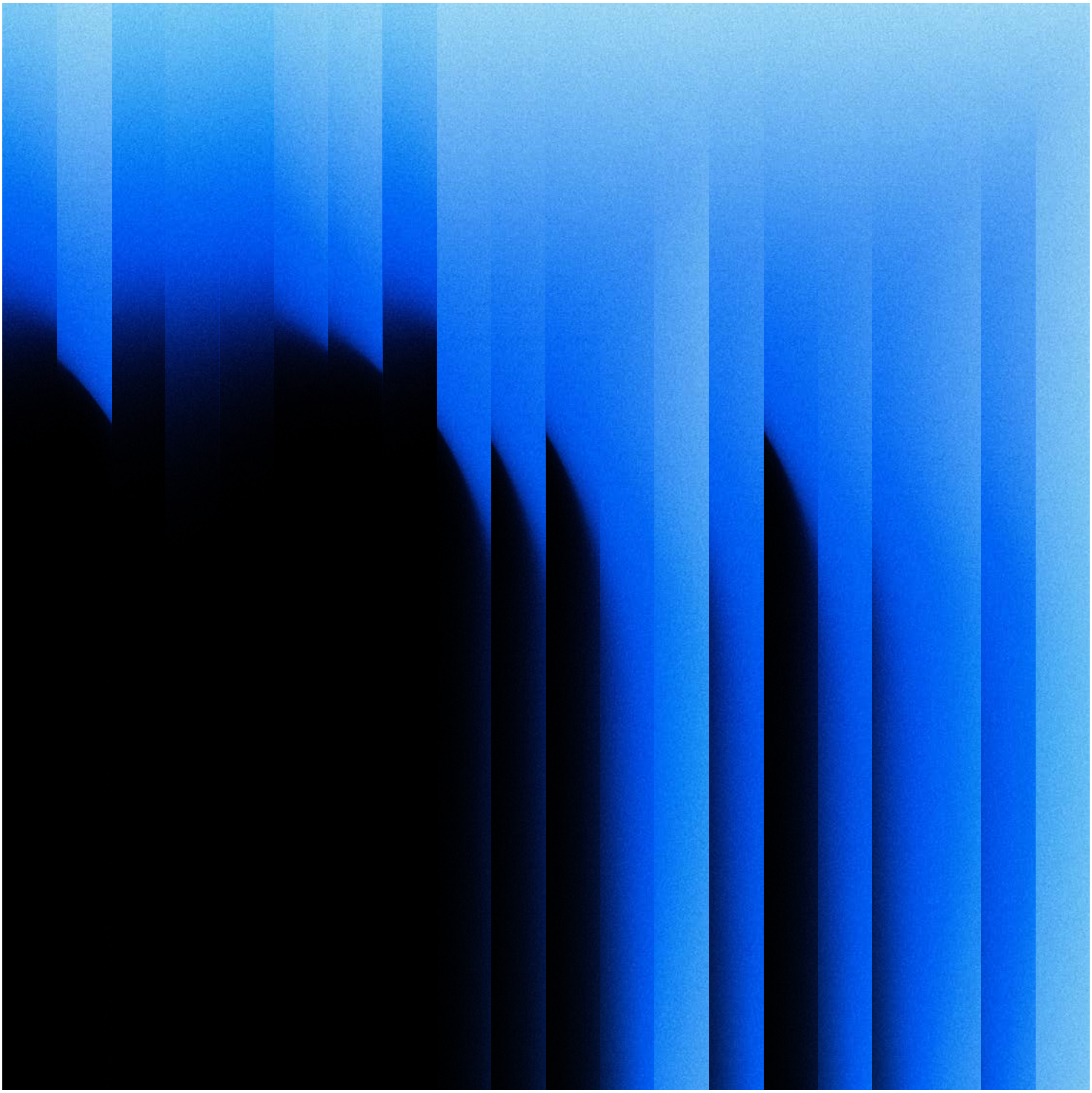

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