DISCUSSION PAPER

EUROPE'S POLITICAL ECONOMY PROGRAMME

23 MARCH 2023

Quantum technologies and value chains: Why and how Europe must act now

A test case for the EU's technological competitiveness and industrial policies

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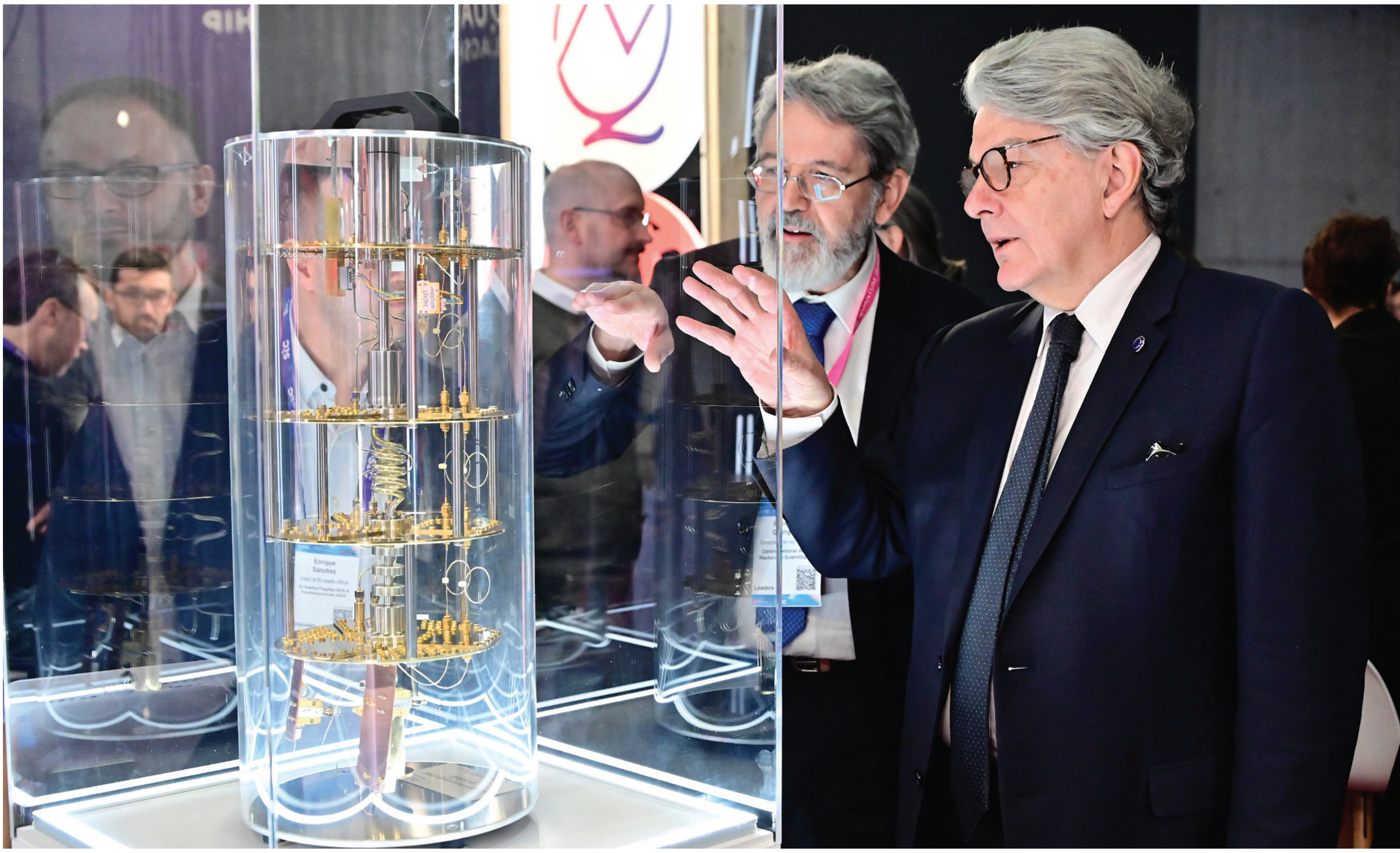

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ACKNOWLEDGEMENTS / DISCLAIMER

This Discussion Paper is the product of a series of workshops, interviews and research conducted in the context of the EPC's 'Europe's Quantum Frontier' project. The project is structured as a task force bringing together actors across Europe's industry and policymaking community to work on EU policy questions and solutions for the development of a European quantum ecosystem. Successive workstreams will focus on issues such as quantum value chains and industrial policy, post-quantum cryptography and cybersecurity, the quantum knowledge economy and quantum ethics. The EPC's work on this project is supported by Quantum Delta NL as a founding partner of the EPC task force.

The author would like to thank Evin Jongen-Fay and Andrea G. Rodríguez for their research support, as well as participants who have provided insights and comments in view of this publication, in particular Neil Abroug, Thierry Botter, Mayra van Houts, Jan-Peter Kleinhans, Ulrich Mans, Frederico Mollet, Julian Rabbie, Jesse Robbers, Enrique Sánchez Bautista, Alice Pannier, Frank Vandermeeren and Teun van der Veen.

Executive summary: Lessons & recommendations

As next-generation foundational technologies, quantum computing, communication and sensing will have significant economic and security implications. Europe's quantum strengths lie in a vibrant ecosystem of research organisations and start-ups, in contrast with the US where Big Tech actors dominate. This growing ecosystem is now at a critical juncture to develop into an internationally competitive European industry. In a year that will see the launch of the EU Sovereignty Fund and the adoption of the European Chips Act, quantum therefore stands as a test case for the EU's technological competitiveness and industrial policy agenda.

This paper is based on research and a series of workshops conducted with European policymakers, stakeholders and industry actors looking into Europe's technological position. Europe's first quantum value chain mappings highlight crisscrossing global supply lines and emerging entrenchments and chokepoints (see Illustration 1).

To address supply chain risks and support the technological position and scale-up of Europe's budding ecosystem of start-ups, Europe must take a proactive industrial stance. Financing is one of the most critical chokepoints for the EU's quantum ambitions, as Europe's leading start-ups need to scale up in the next 6-18 months. Europe's quantum industrial strategy also needs to support synergies and coordination of national efforts to build a single European ecosystem, and define smart international 'cooperate and protect' policies in today's increasingly confrontational geoeconomic environment.

RECOMMENDATIONS FOR THE EU'S QUANTUM INDUSTRIAL POLICY MIX:

KNOW - Embrace tech forecasting at the EU level

Recommendation 1: Map and conduct periodical assessments of Europe's quantum ecosystem's position in international value chains and its access to critical components and materials.

Recommendation 2: Develop analytical tools to monitor the international flows of other key elements of the industrial base, such as investments, skills, related technologies, and final products and uses.

COOPERATE – Combine European efforts in an EU Quantum Industrial Alliance

Recommendation 3: Enhance cooperation between Europe's different national quantum communities and programmes, with a view to ultimately establish a public-private EU Quantum Industrial Alliance (EQuIA).

Recommendation 4: Use the Alliance to drive the development of Europe's industrial ecosystem through roadmaps on factors of industrial growth, operational cooperation such as joint procurement and the federation of infrastructure, and input to EU policy-setting.

INVEST – Mobilise European public-private capital for industrial scale-up

Recommendation 5: Create a smart investment environment focusing on supporting the growth stage and speedy industrial scale-up of European start-ups, actively monitoring, protecting and supporting their technology programmes, financial health, and ownership, including by pairing private/foreign investment with public equity.

Recommendation 6: While continuing to provide a broad base of public R&D support across technologies, EU 'fund of funds'-investment tools are needed to leverage private capital into 'series B' and 'series C' financing of maturing start-ups.

In parallel, the announced EU Sovereignty Fund should be used to create dedicated EU Co-investment Facilities that provide equity directly to scale-ups in critical technology areas, such as quantum, with fast turnaround and low bureaucratic overhead.

Recommendation 7: Use the European Chips Act to launch industrial 'first mile'-pilots and establish a financing and project roadmap leading to a future European quantum chips foundry.

PROTECT – Deploy Europe's defensive toolbox, prudently

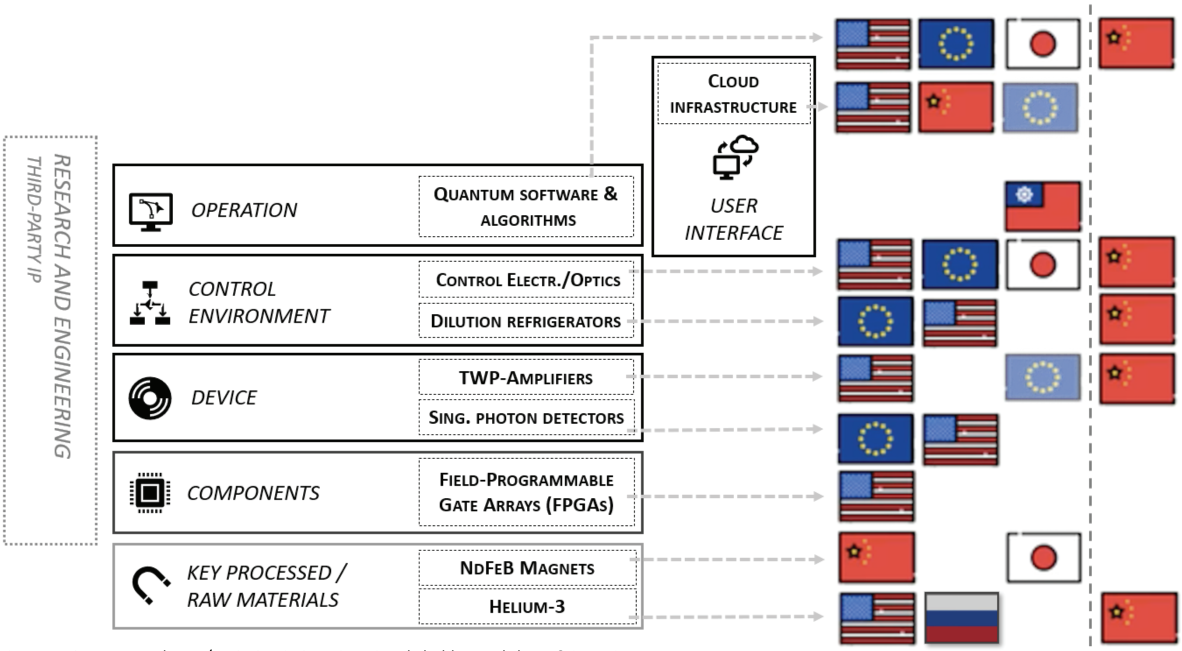
Recommendation 8: Proceed carefully with restrictive export and import policies given the low maturity of quantum technologies and the global needs of Europe's burgeoning start-up ecosystem.

Recommendation 9: Build strategic technological leverage towards the US to guarantee a low-barrier transatlantic space, and develop collaboration schemes with like-minded partners (UK, Switzerland, Canada, Japan, South Korea).

Recommendation 10: In response to both international pressures and technological change, reform Europe's export control framework and promote more active uptake of knowledge security policies.

Illustration 1

The race for technological control and supremacy
- examples from the quantum computer stack



Sources: Quantum Delta NL/TNO, QUIC, QED-C, EPC stakeholder workshops & interviews

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Quantum computing is a next-generation foundational technology with significant economic and security implications. Truly powerful quantum computing might be many years away, but when it arrives it is widely expected to be able to break the digital encryption system that underpins most security and defense communication and business transactions today. The above graph seeks to illustrate emerging chokepoints and entrenchment in the global quantum computing value chain based on the technological position of key actors. The flags provide an assessment and visualisation of what countries/regions hold technological leadership in selected, critical elements of the computer stack, resulting in a high concentration of supply, with low substitutability. China is a prime actor in the development of quantum computing, but its efforts remain largely shielded from international research collaboration and global value chains, as illustrated by the dotted line.

1. Introduction

As scientists and engineers explore the future, quantum systems stand out for their extraordinary complexity and potential. By exploiting quantum mechanical properties, rather than the binary 0 and 1, quantum computers promise to perform calculations exponentially faster than classical systems. Similar improvements are expected in the security of communications and the precision of sensors, placing quantum technologies at the intersection of technological competitiveness and national security concerns.

In an age of deep geopolitical shifts, marked by intensifying US-China strategic rivalry, moves to securitise economic structures are already affecting international open scientific collaboration in this nascent field of technology. A fundamental question looms: as the world is at the cusp of new paradigms in technology, which nation(s) will reap the benefits in economic, technological, and military terms?

For the European Union, quantum is a test case for its (open) strategic autonomy agenda in emerging technologies and willingness to engage in industrial policy. In contrast with the US industrial fabric, where Big Tech actors dominate, Europe's quantum strengths lie in a vibrant ecosystem of research organisations and start-ups. This growing ecosystem is now at a critical juncture: will it be able to develop into an internationally competitive European industry? First mapping exercises reveal critical dependencies in supply chains and the need for European start-ups to scale.

The twin policy challenge of supporting the growth of an industry and accompanying it in a highly competitive and increasingly coercive, international environment requires the right EU policy mix of incentives, support, and protective measures, from increasing public-private industrial cooperation and capital investments to the appropriate use of investment screening and export controls. Rather than a policy of 'closing doors' to international cooperation, the far more important priority appears to be a European 'running faster'-agenda.

In a year that will see the launch of the EU Sovereignty Fund and adoption of the European Chips Act, it's the moment to double down on Europe's quantum ambitions.

2. Background: Why quantum technologies are a test case for the EU now

As the next frontier of computing, sensors, and communication, expectations run high in the world of quantum. Estimates suggest that quantum systems could add up to €850 billion to the economy[1] in the next 15 to 30 years across many industries, including AI, cybersecurity, life sciences, automotive, and finance. Bold claims of quantum computing potential have led to a funding frenzy: in 2021, the global quantum computing market saw investments of more than $3 billion[2]. This scramble has focused on the US, Canada, and the UK[3], and also proved to be fragile when global macroeconomic conditions soured.

With technologies still in their early infancy, some have warned of a quantum 'hype' based on the most spectacular claims of quantum computing potential[4]. Indeed, to this day, creating stable computing conditions has proved elusive. Researchers are still experimenting with different basic architectures, with revolutionary economic applications still out of reach. Yet few doubt that those days will come, and first use cases[5] are being explored using the limited performance of first generation quantum hardware and software.

What also remains real is the race for the future and its strong undercurrents of accelerating geopolitical competition. In 2019, Google announced that its Sycamore processor[6] had solved in minutes a complex problem that would have taken conventional supercomputers thousands of years to crack. Just two years later, the University of Science and Technology of China (USTC) reported solving problems six orders of magnitude harder.

With the unprecedented gains in speed and power, quantum technologies bring opportunities and risks that go to the core of today's strategic competition. Most significantly perhaps, in time, quantum computing is expected to break the encryption methods[7] that today underpin secure communications in security and defence, as well as most business transactions. Ultimately, quantum technologies will, like all emerging technologies, have significant dual-use applications.

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THE WEST'S DRAMATIC REASSESSMENT OF ECONOMIC SECURITY

Europe's ambitions in quantum technologies are therefore inseparable from today's broader context of eroding international trust, hardening geopolitics, and a fast-changing geoeconomy. Russia's aggression on Ukraine, as well as China's international rise and illiberal value base, have shaken the West's fundamental assumptions. It has led to a re-examination of economic strength, interdependence, and vulnerability, with as an upshot, a new race to maintain technological leadership, through both a *running faster* agenda and *defensive* economic measures,[8] such as restrictions on foreign direct investment and export controls.

The US administration recently set out its aim for 'maintaining as large a lead as possible' over China.

US policies towards China are a case in point. In an important change of doctrine[9], the US administration recently set out its aim not only for a "sliding scale advantage", but for "maintaining as large a lead as possible"[10] over China in technologies seen as foundational for economic growth and military advantage. US export controls[11], banning the transfer of sensitive technologies from AI and semiconductor manufacturing equipment to quantum, have been ratcheted up in response, with further controls expected soon. Quantum technologies are singled out in the US Critical and Emerging Technologies List[12] and the US Innovation and Competition Act[13], which aim to boost investment in cutting-edge technology and protect critical supply chains to maintain US leadership.

Recent global shocks have also engendered a radical change in the European outlook. In the past few years, the EU has been confronted by the need to catch up in much of the digital space, as it belatedly realised it had been surpassed by the world's tech leaders[14] and was left dependent in critical areas. For a long time, Europe's tech policy focused most visibly on regulating use cases and ensuring that technological development responded to societal needs. Industrial policy, capacity building, and supply chain security came a distant second.

This can no longer be. On the one hand, China is increasingly apprehended as a strategic rival and dangerous partner should dependencies remain overimportant. On the other, Europeans are realising that US leadership and coercive measures draw up new geoeconomic borders also for European companies, in law or *de facto*, through the American administration's extra-territorial reach[15] and increasingly protectionist stance, putting pressure on open international science collaboration, supply chains, and European business models. For example, in January 2023, after significant pressures the Dutch government agreed to align its national policies with US export restrictions vis-a-vis ASML's chip fabrication machines[16]. It is likely that US policies will have significant consequences for the EU's deep tech sectors.

EUROPE'S TRIALS (AND FAILURES) IN EMERGING TECH AND INDUSTRIAL POLICY

To stay in the race between the US and China, Europe is dramatically revaluing its approach to economic security and domestic industrial and technological ambitions. Ongoing EU efforts to map critical dependencies[17], the rise of public-private 'industrial alliances', and greater public funding for sectors from batteries to semiconductors, participate in a broad set of economic policy responses, often badged under the theme of building the EU's (open) strategic autonomy.

The European Chips Act[18] is perhaps the foremost example, with direct implications for quantum. In a bid to address critical dependencies and build the security of supply, the European Chips Act aims to give Europe leverage over key segments of the semiconductor value chain. It consists of three pillars aiming to one, bolster innovation 'from lab to fab'; two, attract investment and enhance domestic production capacities; and three, set up a monitoring and response mechanism in case of supply disruptions. For quantum, the Act encourages the creation of pilot lines for the testing and experimentation of quantum chips and a design library.

While there might be a change of mindset in Europe, the strategic turn will not come easy.

While there might be a change of mindset in Europe, the strategic turn will not come easy. The Chips Act stands as a test case for Europe's new industrial policies, global value chain posture, and geoeconomic thinking. A central objective announced by the Chips Act has been to operate the most advanced semiconductor fabrication plants (fabs) capable of 2nm (nanometer) chips within the EU by the end of this decade. Yet, as argued by Kleinhans (2021)[19], such a policy of domestic reshoring could be ill-advised. Looking at the global semiconductor map and relative strengths, the tens of billions in public and private investment in Europe required for chasing the 2nm fab could be better spent elsewhere. Keeping up in the technological race is many times more resource-intensive today than 50, 30, or even 10 years ago, meaning no single region can go for full autonomy across a broad spectrum of technologies. International specialisation and degrees of dependency are inevitable.

Contemporary industrial policy, therefore, requires tough choices informed by clarity on the objectives pursued and a deep understanding of the industry and its global value chains. As Europe has experienced in other foundational areas, there are many parameters determining success or failure. In cloud technologies, a European industrial alliance[20] only got off the ground at the end of 2021, after earlier ambitions for a sovereign European cloud, such as Andromède[21] and Gaia-X,[22] started small and late compared to the US hyperscalers and were enfeebled by external pressures and a lack of European coordination. For EU quantum ambitions to succeed, Europeans must better navigate through the geoeconomic and industrial policy challenges than has been the case in cloud and semiconductors until now. Quantum is still nascent enough to allow for shaping Europe's ecosystem into a full-fledged industrial sector.

Contemporary industrial policy requires tough choices informed by a deep understanding of the industry and its global value chains.

EUROPE'S FAST-GROWING QUANTUM ECOSYSTEM

In October 2018, the European Commission launched the Quantum Technologies Flagship[23], a large-scale scientific leadership initiative pooling resources from research institutions, industry, and public funders with a budget of €1 billion over ten years. University clusters play a significant role in the advancement of Europe as a quantum actor, not only by attracting and developing talent but also as centres of experimentation and nodes of connection within the Quantum Flagship programme. As part of the Flagship's work, a strategic research agenda[24] on quantum technologies was adopted in 2020.

Since 2021, at least 14 member states have launched national quantum initiatives (NQIs), either through consortiums, direct R&D investment schemes, or combined with ambitious national quantum strategies. These national initiatives aim to develop Europe's research excellence into fully-fledged quantum ecosystems and often announce significant funding, as is the case in France (€1.8 billion, 2021[25]), Germany (€2 billion, 2021[26]), and the Netherlands (€615 million, 2021[27]). In 2021, the European Quantum Industry Consortium (QuIC) was founded with the mission of boosting the European quantum industry's competitiveness and development. Overall, Europe's efforts correspond to a total investment of more than €5.7 billion over a five-year period, dedicated to advancing different quantum technologies, enabling science, training, and innovation.

In contrast to the US, where several Big Tech actors (IBM, Google, Intel, Amazon) dominate the quantum field, Europe's quantum industry is largely start-up based. Though the United States and Canada top the overall list of start-ups, Europe was the region that registered the most launches in 2021[28]. Companies such as IQM and Bluefors (Finland), Pasqal and Alice&Bob (France), Plancq (Germany), Delft Circuits and QBlox (the Netherlands), and Multiverse (Spain) are leading the way in Europe.

However, as it needs to grow, this ecosystem faces important tests in the months ahead. Several of Europe's 'quantum champions' are currently reaching maturities requiring so-called 'series B' and 'series C' financing[29], in the range of 25 to 150 million euros, to enable industrial development and scale-up. This financing is not readily available in Europe.

3. Zooming in on value chains and capital: Europe's quantum ecosystem at a critical juncture

In contrast to other areas of emerging technology, Europe's starting point in quantum is promising. At the political level, quantum technologies have been defined as strategic, given their foundational role in future digital ecosystems and far-reaching economic and societal impact[30], including through security, defence, and space applications.[31] The combined research strengths and funding efforts of the EU and its member states have made Europe a competitive actor in the current state of technological development. With nearly 7 billion euros combined, Europe ranks only behind China in public investment in quantum.[32]

But there are also clear warning signs. A recent Boston Consulting Group report[33] highlights the lack of joined-up efforts across member states and an inability, so far, to scale up the ecosystem of small, emerging actors. In a highly challenging macroeconomic environment where technological and industrial development is a matter of strategic competition, building Europe's quantum ecosystem is becoming an even greater challenge. It will require a strong focus on future value chain risks and on the concrete means to scale up Europe's budding fabric of start-ups.

In contrast to other areas of emerging technology, Europe's starting point in quantum is promising.

It is still early days to speak about a quantum value chain in the classical sense. The low degree of technological maturity has meant, until now, that quantum development is essentially a matter of competition for ideas. In quantum computing, European and global developers are experimenting with at least six rather different, technological platforms: *photonics; quantum dots in silicon; nitrogen-vacancy centres in diamonds; superconducting transmons; trapped ions; and Rydberg atoms*. There are no clearly established technologies, hardware and software implementations, or related production and distribution schemes. Yet US and European R&D has reached the stage where it expands beyond basic science and research and requires significant private-sector involvement to push into industrialisation and early commercialisation. The EU therefore faces the twin policy challenge of supporting the growth of an industry while also accompanying it in a highly competitive and increasingly coercive international environment.

As Europe's quantum ecosystem stands on the cusp of scale-up, the more we know about its technological position and possible dependencies, the better investment strategies can be developed to support its long-term strengths and international position. As for other critical areas of the economy, technology and value-chain mapping should now be considered an essential part of the industrial policy toolbox for Europe's quantum ambitions.

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EUROPE'S FIRST SUPPLY CHAIN MAPS: BRINGING OUT WHAT'S CRITICAL

The European quantum community recently conducted its first technology and value chain mappings, which have already yielded critical results. Although there is little data on what is being shipped around the world, R&D labs rely on equipment from a large number of high-end suppliers. First analyses highlight not only crisscrossing global supply lines but also emerging entrenchments and chokepoints.

In the surveys conducted, Europe's industry anticipates serious supply chain disruptions in the next few years, with potential chokepoints dispersed across the technological stack and factors of production. This is consistent with similar studies in the US: in a recent survey[34] by the US Quantum Economic Development Consortium (QED-C), 60% of respondents suggested that some form of supply chain disruption is likely in the next three years relating to materials, components, or manufacturing and assembly equipment.

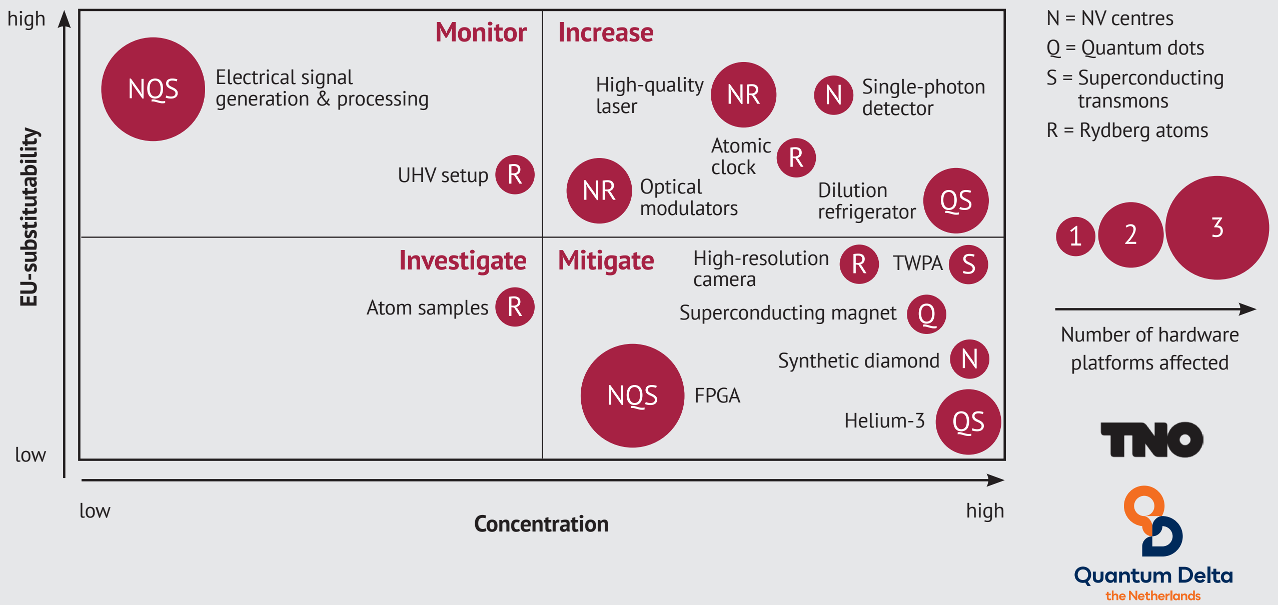
Monitoring these chokepoints at the firm and industry levels and through national quantum programmes is important to anticipate potential future dependencies. Monitoring tools are currently being developed, such as the Commission's Supply Chain Alert Notification (SCAN) monitoring system[35] but it requires further attention from the EU's policymaking community. If Europe stands by its ambitions in quantum, access to critical resources and technologies at home and abroad must be secured.

QUANTUM CRITICAL TECHNOLOGIES: MAPPING CONCENTRATION AND SUBSTITUTABILITY

In September 2022, Quantum Delta NL, in partnership with the Dutch national research organisation TNO, released a white paper with the first attempted mapping in Europe of supply chains for critical materials and components required for quantum computing.[36] It was followed by a second mapping for quantum communications released in March 2023. These efforts use an assessment methodology that builds on the framework for analysing strategic dependency developed by the European Commission[37]. The below mapping identifies the concentration and substitutability of critical components and materials of four technological platforms in quantum computing.

Most at-risk components and materials are those with high levels of production concentration and low levels of EU-substitutability, designated under the heading '*Mitigate*' in the bottom right quadrant. This said, active supply chain strategies might also be required for the components found in the three other quadrants.

Applying this methodology, Europe's 167-member strong quantum industry consortium, QuIC[38], conducted a similar but broader mapping exercise based on a survey across the European industry. While the results are business sensitive and remain confidential, they point to clear chokepoints and the need for mitigating strategies. **17 technologies, components or materials are deemed critical across Europe's different quantum computing platforms**, with clear limits on EU supplies. Of those, six are particularly critical, with both low commercial availability and substitutability. Across the European industry inadequately long and unreliable lead times and pessimism about future accessibility are being reported.



This will require more mapping efforts and active industrial and international strategies aimed at resilient value chains. Crucially, it is not just a matter of reacting defensively; the emerging nature of the quantum value chains must also be seized upon to develop areas of European comparative advantage and leadership.

AFFIRMING EUROPE'S TECHNOLOGICAL POSITION IN CONTESTED GLOBAL VALUE CHAINS

The question of Europe's quantum value chain posture is coming to a head not only in light of these first industry mappings but also in reaction to sharpening geopolitical rivalries. In years to come, US and Chinese national security strategies are poised to make a strong mark on global value chains. The US administration's resolve to keep quantum-science advancing technologies away from China will likely translate into a steadily more restrictive sanctions regime, inevitably drawing up policy and industrial choices also for Europe. Whether US restrictions are enforced extraterritorially or cooperatively with Europeans, the scope for research and market integration with China is likely to be significantly curtailed.

If Europe stands by its ambitions in quantum, access to critical resources and technologies at home and abroad must be secured.

UNPACKING EUROPE'S (OPEN) STRATEGIC AUTONOMY OBJECTIVE

The notion of 'strategic autonomy' conceals what should often be distinguished as three rather distinct policy goals: *national security*, *technological competitiveness*, and *supply chain resilience*. Whereas developing post-quantum cryptography[39], to avoid future breaches into our most confidential and secure data, is a matter of national security, striving for the most advanced 2nm semiconductor[40] fabs serves more evidently a purpose of economic leadership as these chips are expected to yield 45% higher performance and 75% lower energy use than today's most advanced 7nm node chips. Yet another issue is the security of supply for the economy, which, in the case of semiconductors, should lead to focusing on the more 'primitive' chips, between 60 and 28nm, used in refrigerators, cars, and planes.

Ultimately, differentiating between these three policy objectives points back to the most convincing definition of Europe's (open) strategic autonomy doctrine: "*do with others what we can and alone what we must*" (or *"as open as possible, as autonomous as necessary"*).[41] Differentiation of objectives is an essential prism for analysing interdependency and vulnerability. Intuitively, security of supply concerns will be much more compatible with an international division of labour than national security and technological competitiveness motivations. This is an analysis that must be done specifically, technology by technology.

At the current stage of technological development, Europe's investment in quantum is, for obvious reasons, not driven by concerns about the security of supply for the wider economy. Quantum technologies are neither incorporated into broader technological ecosystems nor widely commercially available. The race for quantum leadership therefore comes down to technological competitiveness and national security motives, which, in turn, suggests a strong focus on domestic actors.

The US administration's resolve to keep quantum-science advancing technologies away from China will likely translate into a steadily more restrictive sanctions regime.

These patterns of strong future limitations in the exchange of scientific ideas, expertise, and technology are an important argument for a strategic approach to Europe's technological position. At the same time, uncertainty as to what technological platforms will ultimately prove viable for industrial exploitation pushes, *prima facie*, in the direction of a relatively open value chain policy. The QED-C study[42] concluded that "the establishment of a well-defined, complete, and stable supply chain for the sector will remain in flux for [the next few years], if not longer." Nascent quantum technologies should therefore not be treated as more mature industries, such as chips, in the definition of protective policies.

An overreacting 'protect and control' agenda would be particularly detrimental to Europe's quantum ecosystem, given its dependence on global supply chains. Any domestic or foreign initiative, hindering their access to global value chains, such as import/export tariffs or controls, is liable to hold back European start-ups. However, an *open* value chain posture is not antithetical to, nor does it dispense from, an *active* policy in line with Europe's objective of (open) strategic autonomy. Moreover, early-stage technological development means there is an opportunity for Europe to shape the market and a risk that others do so ahead of Europeans.

As in many other areas of technology, current US policies are a wake-up call. The underlying geopolitical and security motivations for cutting off China might be valid. Even so, Europe is confronted with the awkward situation where the US *de facto* makes Europe's policy and industrial choices. In a world of economic confrontation where coercive measures are easily resorted, the EU must build its own 'negotiation chips'.

The recently proposed EU anti-coercion instrument[43] has been pointed to as providing possible leverage, but it is neither likely nor desirable that such instruments are put to use across the transatlantic space. What is more important is reciprocity and mutual dependence across the value chain. Europe's aim with the US should be a low-barrier transatlantic space guaranteeing supply chain security and industrial and trade opportunities for both, but that requires having equal negotiation cards on both sides. Only through a strong domestic technological and industrial base and by holding key assets and enablers in the global quantum value chain, as recognisable in the French national quantum strategy[44], will Europe be able to ensure this.

Europe's aim with the US should be a low-barrier transatlantic space guaranteeing supply chain security and industrial and trade opportunities for both.

EUROPE'S CRUX: FINANCING FOR NEXT STAGE GROWTH

What is shaping up as the most critical limitation on Europe's industrial ambitions is access to investment funding. A significant lesson from the field of semiconductors is Europe's difficulties in translating research distinction into start-ups and then scale-ups and global industry leaders. Despite Europe having doubled its share of global research contributions[45] over the past 25 years (1995: 13%, 2020: 25%), European companies hold a market share of below 10% in global chip sales[46] revealing significant inefficiencies in the European ecosystem's capacity to get value from R&D.

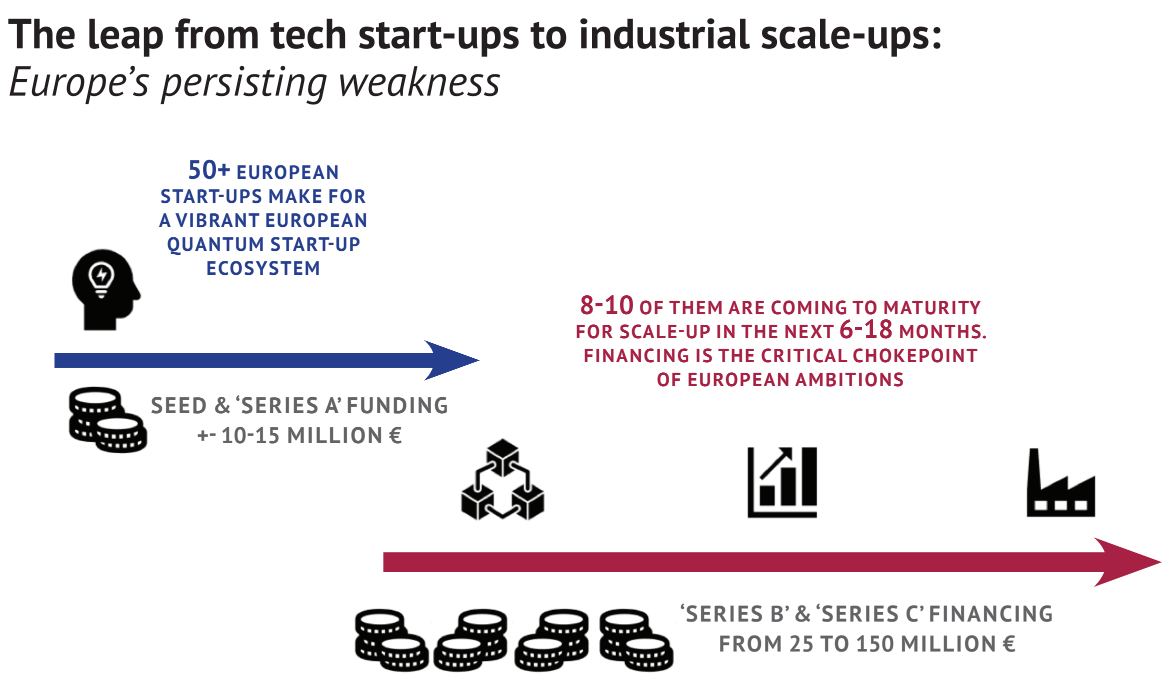
Once a technology is proven and tested, capital investment is the sinews of successful industrial development. This is a point of particular European weakness.

Once a technology is proven and tested, capital investment is the sinews of successful industrial development. This is a point of particular European weakness. Europe generates 36% of all funded start-ups but only 14% of the world's unicorns, according to McKinsey[47]. This predicament repeats from sector to sector because of a fragmented single market and shallow talent pools but most predominantly a lack of ease of financing and an undersupply of late-stage capital.

In this regard, the challenge in quantum technologies is no different. The EU's Quantum Technologies Flagship[48] and national quantum innovation programmes have directed significant public funding towards fostering research and innovation excellence. Europe's quantum ecosystem now faces the test of converting research and innovation and growing entrepreneurship into industrial scale. This is a formidable challenge: quantum development is more capital-intensive than other areas of emerging tech such as AI algorithms. Furthermore, Europeans face Big Tech competitors with colossal war chests. Of the top ten major tech companies investing in quantum[49], five are in the US, four are in China, and none are in the EU. In its June 2022 Quantum Tech Monitor,[50] McKinsey showed that the US and Europe both account for roughly 25% of all quantum start-ups but differ markedly in access to private funding, with US firms receiving 50% of all funding and European ones only 5%.

The EU has developed several instruments to push start-ups towards technological maturity[51] and early industrialisation. The European Innovation Council (EIC) Accelerator[52] offers equity investments of up to 15 million euros or more for strategic technologies such as quantum. In addition, the European Investment Fund has launched a €300 million pilot, Escalar[53], to direct venture capital towards Europe's scale-up challenge. These initiatives are bearing fruit: from an initial €2.5 million grant and €15 million of equity investment, Finnish quantum hardware start-up IQM[54] could successfully crowd in a further €128 million[55] in venture capital. The Franco-Dutch start-up Pasqal[56] similarly secured €100 million in a recent 'series B' financing round involving the EIC, national innovation funds and private investors.

Illustration 2



Yet, with rising interest rates and tightening financing conditions, Europe's quantum industry reports that the momentum to bring in EU investors is waning. European private investment and capital pools are insufficiently deep to carry coming needs in today's macroeconomic environment. On average, European venture capital funds are half the size of their US counterparts, and in total, they raise a third of the money. Singapore's Temasek fund[57] led the recent capital expansion of quantum start-up Pasqal.

The Dutch and French quantum programmes now anticipate dozens of companies needing to move on from the 'seed capital' and 'series A' financing stage to 'series B' and 'series C' funding.[58] This entails a step up in financing from the 10-15 million euro range per company to a 25-150 million bracket requiring important private capital pools willing to invest in high-risk deep tech. If Europe is serious about industrial policy and quantum development, more scale-up money is needed and that requires giving a boost to today's public-private financing infrastructure. The European Tech Champions Initiative (ETCI)[59] is significant in this regard. Hosted by the European Investment Bank (EIB) Group, this 'fund of funds' has secured commitments of €3.75 billion from Belgium, France, Germany, Italy and Spain to back high-tech companies in their late-stage growth phase. For Europe's burgeoning quantum industries, the test lies in whether and how soon this money will reach them, and that will likely require also more targeted instruments.

4. Prospects: Deploying Europe's defensive and offensive toolbox

As international economic pressures and competition in quantum development ratchet up, an active 'Europe first' stance involving industry and government is required to defend own interests. This participates in a new paradigm of trade and industrial policy where forms of state intervention play a steadily more significant role. However, the need to ensure that technology develops responsibly should not mean that it becomes a game of making quantum a state-controlled technology. On the contrary, the EU's long-term vision must help define the right policy mix between a 'protect' response and a 'promote' agenda capable of growing Europe's industry.

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All considered, rather than strict control measures that would contradict the overall competitive position of Europe's start-up ecosystem, Europe's best bet is to develop an ambitious 'running faster' agenda based on current strengths. In this context, Europe's quantum industrial ambitions must develop four important levers: technological mapping and forecasting (KNOW); synergies between national quantum ecosystems with the creation of a European Quantum Industrial Alliance (COOPERATE); redoubled public-private investment into scale-up (INVEST); and proper use of Europe's defensive toolbox (PROTECT).

A. KNOW – *EMBRACING TECH FORECASTING AT THE EUROPEAN LEVEL*

The bedrock of effective industrial policies is a thorough understanding of the industry's global environment, including supply chains and technological positions. Just as it is important to have a monitoring system in place as markets change and to signal dependencies early on, the deployment of strategic policy tools, such as targeting export restrictions or investment in innovation or specific companies, must be informed by an assessment of medium to long-term needs and opportunities. Europe should therefore invest in resources and state-of-the-art tools for technological forecasting.

RECOMMENDATION 1 **Map and conduct periodic reassessments of Europe's quantum ecosystem's position in international value chains and its access to critical components and materials.**

So far, the EU's mapping of strategic dependencies on third countries[60] has focused on supply chains of low to medium complexity, such as raw materials, industrial goods and well-established technologies. Mapping emerging technologies subject to rapid change, such as quantum, is a much taller order and requires deep analytical capacities[61]. The setting-up of the Observatory of Critical Technologies[62] is a first step in this direction. In the US, similar discussions are underway, mandated by the US CHIPS and Science Act[63] and supported by the Quantum Economic Development Consortium (QED-C).

European quantum technologies mapping exercises could be completed iteratively, every two years, in close and trusted collaboration between government and industry, given the sensitivity of security-related and proprietary information.

RECOMMENDATION 2 Develop analytical tools to monitor the international flows of other key elements of the industrial base, such as investments, skills, related technologies and final products and uses.

Until now, the supply chain mapping exercises conducted by Europe's industry have focused on possible dependencies linked to the most promising hardware stacks in quantum computing. But Europe must also map and act on other crucial parameters of its quantum industry ambitions. In the US, the QED-C study[64] reported a lack of technical expertise in hardware and software design as the next most important future chokepoints after access to raw materials and manufacturing equipment.

In addition to monitoring international flows of critical components and materials, Europe should similarly aim to map key elements of the industrial base, such as research investments, skilled workers, and final quantum technology products. An optimal quantum strategy would also look at other factors of exposure, capacity and dependence such as the overall digital and technological ecosystem (e.g. cloud infrastructure) and access to distribution channels.

B. COOPERATE – *COMBINING EFFORTS IN AN EU QUANTUM INDUSTRIAL ALLIANCE*

Another major challenge to Europe's quantum ambitions, as highlighted by a recent Boston Consulting Group report, is fragmentation. Europe lacks the level of public-private coordination seen in the US and China, and efforts don't yet combine to form an interconnected ecosystem. All member states' national quantum initiatives started as domestic strategies and policies, in effect creating national silos across Europe. As in other tech areas, this could quickly become Europe's predicament. Coordination failure will hold back industrial development and efforts to scale. It will also limit Europe's capacity to develop common policies and speak with one voice in international fora such as the EU-US Trade and Technology Council and export control discussions.

RECOMMENDATION 3 Enhance cooperation between Europe's national quantum communities and programmes, beyond current efforts by the EU Quantum Technologies Flagship, with the aim ultimately to establish a public-private EU Quantum Industrial Alliance.

The EU Quantum Flagship has provided a strong impetus to European R&D ambitions, but these efforts have been mostly focused on the lower range of technology readiness. It is neither an industrial programme nor a policy platform. Coordination efforts are however going in the right direction with recent initiatives, such as a trilateral Dutch-French-German initiative[65], and discussions currently underway to create a network of national quantum initiatives. The industry platform QuIC[66] is another significant effort at creating a more joined-up ecosystem, bringing together researchers, small and large corporations and investors, in the development of common strategic goals, roadmaps and their implementation. The European High-Performance Computing Joint Undertaking (EuroHPC)'s recent selection of six sites to host and operate the first EuroHPC quantum computers[67] also pushes towards more joint action.

The logic is not to put 27 member states on an equal footing but rather to develop an open-to-all-partners approach building on EU assets no matter their status.

These different formats of coordination are useful and must be supported. Still, as international competition increases, further synergies and intensification of cooperation will be required to sustain a robust European quantum industry. The natural next step is the creation of an EU Quantum Industrial Alliance (EQuIA) on the model of what has been developed in other strategic areas such as cloud, clean hydrogen and batteries. Industrial alliances[68] are the EU's chosen model of public-private cooperation and stand as an interesting inflexion of EU industrial policy. The logic is not to put 27 member states on an equal footing but rather to develop an open-to-all-partners approach building on EU assets no matter their status (countries, regions, industry, investors, research institutes, civil society). An EU Quantum Industrial Alliance would provide critical recognition of quantum as a strategic ecosystem for Europe as it reviews its industrial and technological posture.

RECOMMENDATION 4 Use the Alliance to push the development of Europe's industrial ecosystem through roadmaps on key factors of industrial growth and operational cooperation such as joint procurement, as well as to input on key matters of EU policy-setting.

The European Commission's recent New European Innovation Agenda[69] proposed to position the EU more markedly as a coordinator and enabler for Europe's deep tech ecosystems. In operational terms, the EU Quantum Industrial Alliance would serve as a coordination platform to advance roadmaps, best practices and cooperation on ecosystem-critical topics such as start-up/scale-up financing, investment screening, skills and talents. It could also involve the development of specific vehicles in support of operational needs such as the federation of infrastructure, joint procurement to lower costs and waiting times for key raw materials and components, or if need be, the establishment of an Important Project of Common European Interest (IPCEI).

Finally, the Alliance would serve the purpose of facilitating concertation between the industrial community and policymakers so that quantum becomes a more prominent item on the policy economic agenda. The past six months have shown that in conversations with the US, Europe doesn't always have a well-concerted voice. The last EU-US TTC conclusions on transatlantic quantum cooperation were driven from the top political level at the European Commission, not as an outcome of European actors developing an international strategy together first as Europeans.

C. INVEST – *MOBILISING EUROPEAN PUBLIC-PRIVATE CAPITAL FOR INDUSTRIAL SCALE-UP*

If Europe is serious about industrial policy and quantum development, there needs to be money on the table and that requires taking another look at today's public-private financing infrastructure. Europe must avoid becoming the quantum technology nursery for major foreign financial or corporate actors taking Europe's most promising industrial prospects elsewhere. In an ideal world, Europe's start-ups would remain based on European equity, to maximise the chances of keeping long-term value-added at home. Yet domestic tech capital pools are not deep and risk-willing enough to meet the growing financing needs. Europe, therefore, today has no choice but to fall back on a significant extent of foreign capital but also public financing both to lead the way for private risk-taking and to ensure a degree of European ownership and control.

If Europe is serious about industrial policy and quantum development, there needs to be money on the table. Europe must avoid becoming the quantum technology nursery for major foreign financial or corporate actors taking Europe's most promising industrial prospects elsewhere.

In parallel, as the European Chips Act is being finalised, Europe must think through the steps and financial requirements for the build-up of tomorrow's critical industrial infrastructure such as a European quantum chips design and production facilities, leading in time to having a foundry on European soil. The EU should recognise what has been called the "SpaceX business model"[70], namely that for complex new technologies the first purchaser will often be the state. As quantum technologies reach maturity, it will therefore be important that EU agencies and member states purchase quantum computers and communications technology from EU-based quantum computer companies.

RECOMMENDATION 5 Create a smart investment environment focusing on industrial scale-up, with active monitoring and protection of the financial health, ownership and technology programmes of European start-ups, and the use of public equity to attract and balance European and foreign private investment.

The EU's framework for screening of foreign direct investment[71] (FDI), agreed upon in 2019, aims to safeguard key European assets through enhanced national screening capacities and improved European coordination. Yet, the application of FDI screening to a start-up ecosystem such as quantum is far from unproblematic and implementation efforts vary from country to country, raising level playing field concerns. An excess of administration, zeal in enforcing screening, or the banning of foreign investments *tout court*, will do more harm than good to young and resource-constrained start-ups.

Rather than rough-and-ready administrative decisions by national FDI authorities, what is needed is smart investment screening, where national quantum programmes participate in monitoring the technology, financial health, and ownership of European start-ups and play a role in seeking out like-minded long-term investors, willing to participate in the building of Europe's industrial base. This must be matched with public readiness to finance and take equity stakes in key companies, both to lead the way for private risk-taking and to ensure a degree of European ownership and control.

RECOMMENDATION 6 While continuing to provide a broad base of public R&D support across technologies, enhanced EU 'fund of funds'-investment tools, such as the European Tech Champions Initiative and the EIF Escalar fund, are needed to leverage private capital into 'series B' and 'series C' financing of maturing start-ups. In parallel, the EU Sovereignty Fund should be used to create dedicated EU Co-investment Facilities providing equity directly to scale-ups in critical technology areas, such as quantum, with fast turnaround and low bureaucratic overhead.

The European Innovation Council (EIC) and the European Investment Bank (EIB) already propose several investment vehicles for Europe's start-ups, such as the EIC Accelerator and EIB venture debt[72]. Still, they tend to be one-off, small ticket instruments that are broad in their technological focus. More emphasis is needed on big-ticket second-stage financing options to bridge the 'valley of death'-gap between seed and 'series A' financing and initial public offerings (IPO). An important game-changer for this investment segment is the European Investment Fund (EIF)'s Escalar pilot initiative,[73] which tops-up private venture capital scale-up funds, including on non-*pari passu* terms. In today's adverse macroeconomic environment, this pilot must now be sized-up by several multiples if Europe is to address the 'second equity gap' for Europe's green and technological start-ups. The European Tech Champions Initiative (ETCI), with its €3.75 billion firepower, is a welcome further step in this regard.

More emphasis is needed on big-ticket second-stage financing options to bridge the 'valley of death'-gap between seed and 'series A' financing and initial public offerings.

In parallel, more targeted instruments are needed capable of providing equity directly to European quantum scale-ups, with enough money, fast turnaround, and low bureaucratic overhead. Taking inspiration from the €150 million EIF joint equity instrument for AI scale-ups launched in 2020[74], the EU should establish a Quantum Co-Investment Facility taking equity stakes, on market terms, alongside EIF-backed fund managers and private investors, in quantum companies moving into their growth phase. If 20 to 30 European quantum start-ups are expected to mature in the next five years, each requiring, on average, €100 million and a public lead investment of 20%, the overall effort amounts to €400-600 million. The case for directing President von der Leyen's still undefined EU Sovereignty Fund[75] into specific technology areas, including quantum, in this way, is compelling.

The EU's recently proposed Listing Act[76], to ease the later access to public markets, is another welcome development. Yet, in many respects, it's time to think bigger. For example, if the EU is serious about not missing the next big thing in technology, a question is also why Europe still does not have a European Nasdaq Capital Market[77] proposing a continent-wide equity market for small caps.

RECOMMENDATION 7 Use the European Chips Act to launch industrial 'first mile'-pilots and establish a financing and project roadmap for a future European quantum chips foundry.

The European Chips Act aims to put Europe back on the world's semiconductor map by building European capacities throughout the value chain. This catch-up attempt is worthy, but there is also a risk that by focusing on the current state of semiconductor technology Europe misses out on the next big thing. In the US, semiconductor funding within the CHIPS and Science Act of 2022 will generate significant funding also for quantum chip development, with first pilot financing announcements expected soon from the US National Science Foundation and Department of Energy.

HIGH STAKES: WILL EUROPE ONE DAY HAVE A QUANTUM COMPUTING "ASML"?

With a market value of around 240 billion euros and the only firm in the world[78] capable of making the highly-complex machines needed to manufacture the most advanced chips, Dutch-headquartered ASML is Europe's tech juggernaut. Its history is illustrative of opportunities but also the demands on nascent industries. ASML started small, in a shed next to Philips in Eindhoven some 35 years ago, as a start-up experimenting with lithography systems for the then-emerging but already fiercely competitive semiconductor market. Towards the end of the 1980s, ASML had few customers devouring financing needs to scale up. But it also had a strong belief in its ongoing R&D. It managed to convince Philips of one final cash injection that eventually carried it to a mature industrial and financial position with a subsequent public listing on the Amsterdam and New York stock exchanges.

The European Chips Act must similarly lay the ground for building critical quantum manufacturing capacities in Europe. As long as technology platforms remain uncertain, and given the limited Chips Act financing available, this would for now consist of a round of calls for the first-mile pilots involving EU and national co-financing. At the same time, it is important to establish in the Chips Act the project and financing mechanics that will develop a fully-fledged foundry project once the technology and financing are available. This will require a capacity to make robust industrial choices: the logic of industrial policy cannot be that of member states' 'rates of return' and a sprinkling of efforts across 27 countries. It requires focusing on the five to six countries where there are meaningful quantum ecosystems, and ultimately, settling on one foundry project at the most appropriate location.

D. PROTECT – *DEPLOYING EUROPE'S DEFENSIVE TOOLBOX, PRUDENTLY*

Finally, the first instinct in response to a geoeconomy with increasingly hard edges is to develop Europe's own 'protect' agenda. There can be good reasons for ringfencing Europe's assets, and the EU has an increasingly sophisticated toolbox of instruments to do so. Yet the policy options to diminish future dependencies and develop own industries should not be reduced to an all-purpose protect agenda. The use of defensive tools such as export controls, foreign direct investment screening and knowledge security policies requires a nuanced debate.

RECOMMENDATION 8 **Proceed carefully with restrictive export and import policies, given the low maturity of quantum technologies and the global needs of Europe's fragile start-up ecosystem.**

The US administration's declared bid to keep quantum-science advancing technologies away from China will likely soon result in further US export restrictions.[79] It will also have consequences for European industry and value chains, either directly, if applied extraterritorially, or indirectly. European countries with an important technological base in quantum, such as Finland, France, Germany, and the Netherlands, are currently under significant pressure to come to an understanding with the US on parallel restrictive measures.

Leaving overarching political and value considerations aside, the technological and industrial justifications for these measures can seem questionable. The 'dual use'[80] risks of technologies that have yet to prove any cases at all are not evident. Restrictions might also not be the best claim to future technological leadership. A 2022 RAND Corporation report[81] assessing US and Chinese national scientific research bases, government activities, private enterprise activities, and technological achievements similarly recommended close monitoring but keeping supply chains open as the best path to maintain US quantum industrial base advantage. This conclusion is even more true for Europe's budding start-up ecosystem, given its dependence on the exchange of ideas and access to technologies globally.

RECOMMENDATION 9 **Build strategic technological leverage vis-à-vis the US to guarantee a low-barrier transatlantic space and develop collaboration schemes with like-minded partners (UK, Switzerland, Canada, Japan, and South Korea).**

As China breaks off from global value chains, Europe must aim for a low-barrier transatlantic space with the US to guarantee its supply chain security as well as industrial and trade opportunities. Only through a strong domestic technological and industrial base and holding key assets and enablers in the global quantum value chain will Europe have the negotiating cards to achieve this. The emerging nature of the quantum value chains must be seized upon to develop areas of European comparative advantage and technological leadership building on current strengths, technological forecasting and a collective, Europe-wide push.

European coordination is also needed on export controls. As competences are shared with member states, the EU is not the direct interlocutor of the US nor a party to the multilateral Wassenaar arrangement[82] discussions. Still, the EU has a useful role to play through the EU-US Trade and Technology Council[83] (TTC) in facilitating transparency, exchange of information, and cooperation on quantum value chain policies. In other words: strengthening collaboration on quantum-related policies with the US should be considered a priority. The EU should also support the creation of smart collaboration schemes, as a matter of priority, with other like-minded partners such as the United Kingdom, Switzerland, Canada, Japan and South Korea.

Only through a strong domestic technological and industrial base and holding key assets and enablers will Europe have the negotiating cards to ensure its position in the global quantum value chain.

RECOMMENDATION 10 **In response to international pressures and technological change, reform Europe's export control framework and promote a more active uptake of knowledge security policies.**

Reform of the EU's dual-use export control regime is necessary, be it only in response to the impasse within today's multilateral Wassenaar group where Russia is still a party. An increased role for the EU in multilateral fora while avoiding creating a coordination nightmare among its 27 member states should be considered. Equally important, reform should be the occasion of a broader debate on the role of export controls in emerging digital technologies, such as quantum, where traditional notions of 'exports' are challenged by the switch from high-performance computing being commercialised as a manufactured good to its provision as a service through the cloud.

Finally, in a frontier domain of innovation such as quantum technologies, Europeans must not be naïve about the ways and means of international competition. The threat of foreign state or corporate interference targeting research findings, intellectual assets and critical vulnerabilities requires an active protective stance. The recent EU Toolkit on foreign interference in research and innovation[84] provides an inventory of best practices to prepare and respond at the firm and state levels, including developing national knowledge security contact points. Supporting national initiatives to implement knowledge security guidelines for specific technology fields across Europe should be a priority.

5. Conclusion

It might be early days still for Europe's emerging quantum industry, but the international environment is changing fast. In a range of technological fields, supply chain security and dependence have become the critical parameters of geoeconomic rivalry and confrontation. Quantum technologies are no exception. As an important field for Europe's strategic autonomy and long-term economic prosperity and security, the moment has come for the EU to take a much more active industrial stance.

In a year that will see the launch of the EU Sovereignty Fund and the adoption of the European Chips Act, it's the moment to double down also on Europe's quantum ambitions.

Europe's best bet appears to be to develop an ambitious 'running faster' agenda based on current strengths rather than a markedly defensive position that would contradict the overall competitive position of Europe's start-up ecosystem. Yet, this now requires a more determined will to support Europe's nascent quantum industry through knowledge, capital and cooperation. In a year that will see the launch of the EU Sovereignty Fund and the adoption of the European Chips Act, it's the moment to double down also on Europe's quantum ambitions.

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The EPC's Quantum Frontier Project and its task force have been established with the Dutch national quantum organisation, Quantum Delta NL, as a founding partner and supporter.

With the strategic support of King Baudouin Foundation
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