Key Performance Indicators for Quantum Technologies in Europe

August 2023

Abstract

This document is a recommendation of the Strategic Advisory Board of the European Quantum Flagship and the European Commission to monitor and evaluate the progress of quantum technologies in Europe. It thereby does not merely focus on the Quantum Flagship itself but takes all initiatives and measures into account.

The document is divided into the following topical and technological pillars: **Ecosystem, Quantum Communication, Quantum Computing, Quantum Simulation, Quantum Sensing and Metrology,** and **Education.**

Within those pillars, Key Performance Indicators (KPIs) are formulated to have a perspective towards 2030 and reflect overall research and innovation goals as set forth in the Strategic Research and Industry Agenda[a]. The KPIs include both quantitative and qualitative evaluations of the quoted goals. It is assumed that there is and will be consistent and continued support for fundamental research and basic science which forms the foundation of all further innovations, in order to ensure that we continue to maintain open approaches and excellence in scientific expertise which lead to creating the best conditions for future breakthroughs.

The KPIs were compiled with the best present knowledge of what could be achieved by the quantum community, combining reasonable and attainable results with a healthy dose of ambition. However, the global impact of COVID-19 on innovation of quantum technologies and other potential future impediments to progress necessitate that this paper remains a living document, which must undergo periodic review and adjustment.

The full set of KPIs will be used as a tool to benchmark Europe's overall progress, therefore deviations for single KPIs may occur, naturally.

This document is a result of collaboration between the academic, public, and private sector representatives from the Strategic Advisory Board (SAB), the Quantum Coordination Board (QCB, formerly SEB), the Quantum Community Network (QCN), the European Quantum Industry Consortium (QuIC), and the Flagship coordination office. Multiple rounds of feedback from those bodies were collected to define the KPIs, set appropriate target values for the year 2030, and estimate the annual progress required to reach those targets.

The KPI values for 2022 were measured in the beginning of the following year by surveying the members of the SAB, the QCB, the QuIC and the Flagship coordination office. The plausibility of the collected results was verified by the SAB. References and explanations are given at the end of this document. In some cases the current definitions were not deemed precise or clear enough, so that n/a is quoted. This means in practice that work is ongoing to improve the corresponding KPI, to be used to evaluate the 2023 achievements.

[a] 2022 Strategic Research and Industry Agenda: https://qt.eu/media/pdf/Quantum-Flagship_SRIA_2022.pdf

KPI Scorecard

KEY

- Ahead of schedule
- On schedule
- Needs progress
- Behind schedule

KPI Ecosystem	2021 value	2022 value	2030 target
Investment (M€)	344 M€	408 M€	1000 M€
Lab-to-market	79	95	250
Lab-to-fab infrastructure and value chain	1	9	n/a
Job Creation	n/a	n/a	n/a
Patent Creation/IP Retention (rank)	n/a	n/a	Top 2 globally
Supply Chain & Strategic autonomy	0	35	n/a

KPI Quantum Communication	2021 value	2022 value	2030 target
Performance	2	5	20
European Technical Leadership (km)[b]	1.3 km	1.3 km	500 km
Deployment (areas; nodes)	1 (8)	15 (10)	n/a
Adoption	5	9	30

KPI Quantum Computing	2021 value	2022 value	2030 target
Performance	0	0	3
European Technical Leadership (q volume)	32	128	n/a
European Impact Leadership	70	70	500
Accessibility	0	4	n/a
Accessibility (HPC/QCS network)	0	0	5

KPI Quantum Simulation	2021 value	2022 value	2030 target
Performance	0	0	8
Market Readiness	0	0	12
European Technical Leadership[c]	-	100	n/a

KPI Quantum Sensing and Metrology	2021 value	2022 value	2030 target
Market Readiness	3	5	20
Next-generation Technologies	0	2	7

KPI Education	2021 value	2022 value	2030 target
Outreach	7	33	100
Education	0 (0)	20 (12)	180 (90)
Adopting	1	17	225
Diversity and Equity	0	10	90

[b] Entanglement distance between quantum processing nodes.
[c] Number of qubits in Europe's most advanced quantum simulator.

KPIs Ecosystem

1. Investment

Total amount of EC investment in the form of venture capital (EU quantum start-ups), corporate seed-funding (EU incubators & accelerators), and EU public investment (EU public-private ventures).

2021 value	344 M€
2022 value	408 M€
progression/year	+90 M€
2030 target	1000 M€

2. Lab-to-market

Number of quantum start-ups, spinoffs, incubators, accelerators, as well as public private joint ventures in Europe (given for all pillars, including established EU companies that enter the field).

2021 value	79
2022 value	95
progression/year	+20
2030 target	250

3. "Lab-to-fab" infrastructure and value chains

Number of EU research institutions offering open application labs, testbeds, production cleanrooms, with testing, prototyping and calibration service facilities accessible to European SMEs, covering TRL 2-6.

2021 value	1
2022 value	9
progression/year	-
2030 target	n/a

4. Job creation

Number of jobs in quantum technologies.

2021 value	n/a
2022 value	n/a
progression/year	-
2030 target	n/a

Remark: Comprehensive study under consideration.

5. Patent creation and IP retention

Quantum-related European patents granted versus distribution of granted patents globally.

2021 value	n/a
2022 value	n/a
progression/year	-
2030 target	Top 2 globally

Remark: Comprehensive study under consideration.

6. Supply chain and strategic autonomy

Number of components (supply chain) of quantum technologies which were formerly imported to EU and are now produced in EU that are of strategic importance and needed for self-sufficiency.

2021 value	0
2022 value	35
progression/year	-
2030 target	n/a

KPIs
Quantum Communication

1. Performance

Number of complementary subsystems, advancing the state of the art, necessary for Quantum Communications networks or to build a quantum internet.

2021 value	2
2022 value	5
progression/year	x1.2
2030 target	20

2. European technical leadership

Entanglement distance in a quantum network based on entanglement distribution and quantum processing, linking processing nodes in two metropolitan networks (average of 20 km) via a quantum repeater backbone (>500 km).

2021 value	1.3 km
2022 value	1.3* km
progression/year	-
2030 target	500 km

***Remark**: 33km on a fibre spool between buildings 400m apart.

3. Deployment

Number of connected European metropolitan areas (and QKD nodes) integrated with a commercial telecom infrastructure, including both terrestrial and satellite QKD links with a secure key rate of at least 100 bit/s.

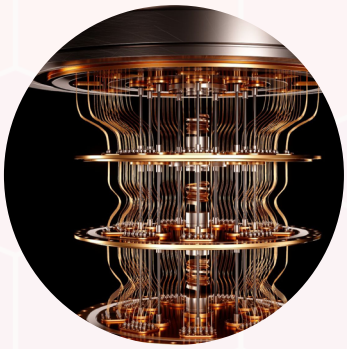
2021 value	1 metropolitan area; 8 nodes
2022 value	15 metropolitan areas; 10 nodes
progression/year	-
2030 target	n/a

4. Adoption

Number of Quantum Communication services that enable commercial adoption for the public as well as private sector.

2021 value	5
2022 value	9
progression/year	+2.7
2030 target	30

KPIs
Quantum Computing



1. Performance

The number of unique European quantum computing hardware stack systems/services demonstrating quantum advantage (i.e., outperforming a non-quantum hardware system/service in the solution of the same problem) by an ad-hoc benchmark created for proof.

2021 value	0
2022 value	0
progression/year	-
2030 target	3

2. European technical leadership

Largest quantum computing capacity based on a European (or alternatively a widely adopted global) quantum volume benchmark.

2021 value	32
2022 value	128
progression/year	-
2030 target	n/a

3. European impact leadership

Quantum algorithms and use cases created with clear impact orientation in basic science, applied science, industries, and the public sector (aligned with the UN and EU 2030 goals).

2021 value	70
2022 value	70
progression/year	x1.3
2030 target	500

Remark: Data from QuIC use cases database, no 2022 update.

4. Accessibility

Number of entities providing public or private access from fully European quantum computing facilities (also based on fully European computing stack) to institutions, academia, research centers and companies.

	4a	4b
2021 value	0	0
2022 value	4	0
progression/year	-	-
2030 target	n/a	5

4b: **Number of access through the HPC/QCS network, according to the Digital Decade KPI:** "Quantum computing measured as the number of operational quantum computers or quantum simulators, inc. as accelerators of HPC supercomputers, deployed and accessible to the user communities."

KPIs
Quantum Simulation

1. Performance

Number of unique EU quantum simulators (services) outperforming the best-known algorithm running on the best classical computer on at least one relevant real-life computational problem.

2021 value	0
2022 value	0
progression/year	+1
2030 target	8

2. Market readiness

New unique industrial or societal real-life applications (products & services) introduced by EU companies, based on any quantum simulation.

2021 value	0
2022 value	0
progression/year	1 by 2023; +2/year thereafter
2030 target	12

3. European technical leadership

The number of qubits or simulated particles of Europe's most advanced non-gate-based quantum simulator.

2021 value	-
2022 value	100
progression/year	x1.4
2030 target	n/a

KPIs Quantum Sensing and Metrology

1. Market readiness

Number of different (publicly known) product classes or service classes (or use cases) based on quantum sensors developed, implemented and sold by European companies or deployed in the EU.

2021 value	3
2022 value	5
progression/year	+2
2030 target	20

2. Next-generation technologies

Number of demonstrated sensing technologies exploiting advanced quantum effects (entanglement, collective coherence etc.)

2021 value	0
2022 value	2
progression/year	+0.7
2030 target	7

KPIs
Education

1. Outreach

Establish a successful communication and outreach program to raise awareness of quantum technologies: Number of outreach and training events promoted on the Quantum Flagship website (following the continually updated criteria laid out by the running Flagship Coordination and Support Action (CSA)).

2021 value	7
2022 value	33
progression/year	+10
2030 target	100

2. Education

Developing an open-source ecosystem of validated and scalable QT education and training modules: Number of open source, curated (didactically validated) QT education modules accessible via the Quantum Flagship repository.

2021 value	0 (0 validated)
2022 value	20 (12 validated)
progression/year	+20 (+10 validated)
2030 target	180 (90 validated)

3. Adoption

Pan-European institutional adoption of the competence framework for planning, conducting and evaluating QT educational and training efforts: Number of entities (companies, universities and training institutions such as corporate training and vocational) actively using the competence framework in their workforce development and curriculum development efforts.

2021 value	1
2022 value	17
progression/year	+25
2030 target	225

4. Diversity and equity

Fostering structural integration of equity and diversity initiatives into QT education and training: Number of entities (companies and educational institutions) contributing to the coordinated Quantum Flagship efforts following the guidelines developed in the CSAs, reported into the European Quantum Education Center (EQEC), now superseded by the European Quantum Readiness Center (EQRC).

2021 value	0
2022 value	10
progression/year	+10
2030 target	90

References

As outlined above, the 2022 values were obtained via survey of the SAB, QCB, and QuIC members. Below we give explanations and references behind the respective results:

Ecosystem

1. Source: European Commission.
2. Defined as number of SMEs with QuIC membership.
3. 1) Quantum Information Technology Testing Facility (QITT), TNO, NL; 2) Istituto Nazionale di Ricerca Metrologica (INRIM); 3) Quantum Technology Competence Center (QTZ); 4) Kavli Nanolab, TU Delft; 5) Nanofabrication lab, MC2, Chalmers University of Technology; 6) CSIC open facility for quantum circuit testing; 7) Commissariat à l'énergie atomique et aux énergies alternatives - Information and Electronics technologies Lab (CEA-Leti, FR); 8) Imec (BE); 9) VTT, Finland.
4. n/a
5. n/a
6. For year 2021, the value is zero by definition. The 2022 value represents the progress with respect to year 2021.

Communication

1. Consensus of survey for the 2022 value.
2. In QIA at TU Delft. 33km on a fibre spool between buildings 400m apart at Ludwig-Maximilians-University of Munich.
3. Consensus of survey for the 2022 value. Connected metropolitan areas: Bristol, Vienna, Graz, Geneva, Cambridge, Cambridge-London, Delft, Poznan-Warsaw, Poznan, Berlin, Madrid, Barcelona, Ostrava, Paris, Padua.
4. IDQuantique, Toshiba & BT, Airbus, Thales, Q-Bird, QO Jena, ThinkQuantum, LuxQuanta (all these entities were partners in the OpenQKD H2020 project).

Computing

1. Consensus of survey.
2. AQTION: 10.1103/PRXQuantum.2.020343
3. QuIC database for Computing and Simulation use-cases.
4. Consensus of survey. EU entities offering access to full-stack systems: PASQAL, Quantum Inspire, LUMI supercomputing centre and AQT.

Simulation

1. Current examples only work 'in principle', with no real-life problems solved yet.
2. Consensus of survey.
3. The 2021 value is under review. PASQAL / MPQ-LMU Munich for the 2022 value.

Sensing & Metrology

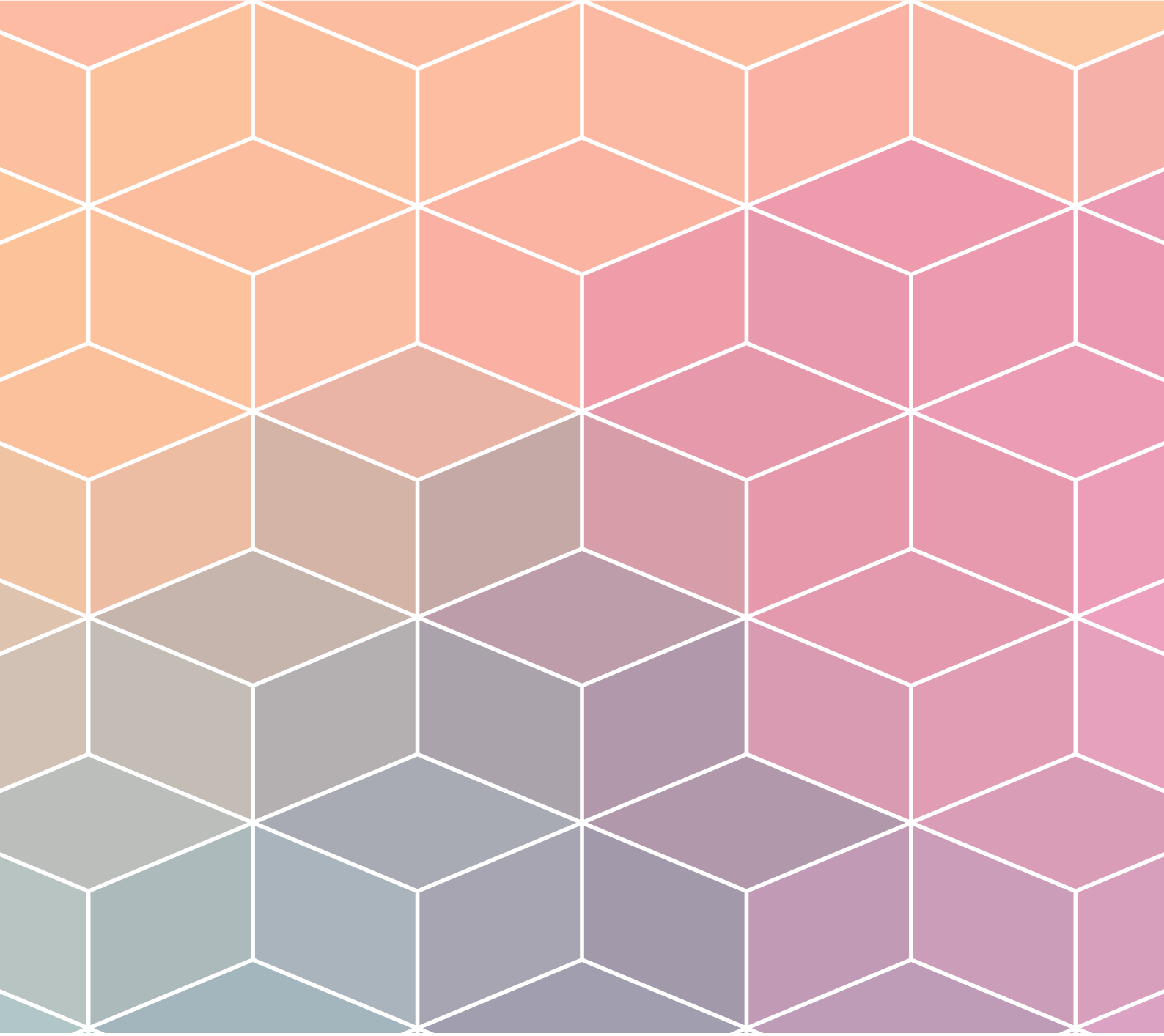
1. Optical atomic clocks; cold-atom gravitometers; NV-centre magnetometers; superconducting single photon detectors; NV-centre in diamond for signal frequency measurements.
2. Consensus of survey: Subshot-noise imaging, NV Centres.

Education

1. QTEdu (https://qt.eu/events/?q=&tags%5B%5D=education-outreach).
2. QTEdu (https://qt.eu/events/?q=&tags%5B%5D=education-outreach) and QURECA (https://platform.qureca.com/courses/).
3. TU Delft; U Helsinki; TU Braunschweig; PTB; Qureca; Airbus Space and Defense; Auantum Investor Mentorship Programme; Aarhus University; ICFO; CTU Prague; Science Melting Pot; University of Pisa; Quarks Interactive; University of Barcelona; Instituto Superior Técnico; RWTH Aachen; University of Strasbourg.
4. ICFO; CNR; Switzerland; QURECA; University of Paderborn; CSIC; University of York; Forschungszentrum Jülich; PQI – Portuguese Quantum Institute; Spanish Foundation for Science and Technology.

Notes

- The 2030 target for the KPIs Quantum Ecosystem 3, Quantum Ecosystem 6, Quantum Communication 3, Quantum Computing 4a, and Quantum Simulation 3, is currently under review.
- The definition of the KPIs Quantum Computing 1 and Quantum Computing 2 is currently under review.



QUANTUM FLAGSHIP

European Commission

Compiled by the Strategic Advisory Board of the European Quantum Flagship

Feedback on this document or suggestions for its future editions can be send to: observatory@pqi.pt

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