

resource estimations

from quantum algorithms to energetics

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TQCI Benchmark - Paris - CNAM, November 27th, 2026

agenda

1. **quantum computing resource estimates** (Olivier).
2. **quantum computing energetics** (Olivier and Marco).
3. **standardization** (Marco).
4. **sizing the challenge** (Marco and Olivier).
5. **modelling and optimizing energetics** (Marco).
6. **an example of full-stack approach with Quandela** (Ariane).
7. **the quantum computing energetics ecosystem** (Olivier).

quantum computing resource estimations

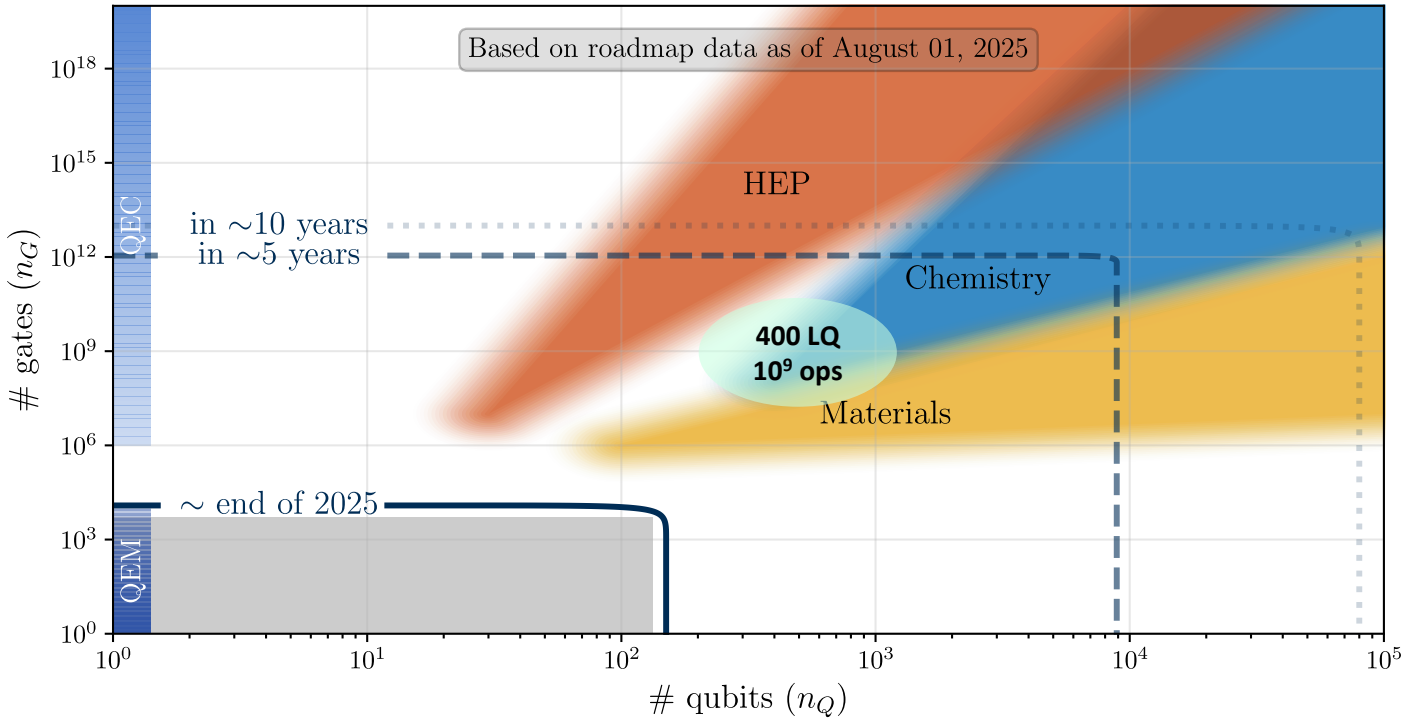
The Grand Challenge of Quantum Applications

Ryan Babbush,* Robbie King,† Sergio Boixo, William Huggins, Tanuj Khattar, Guang Hao Low, Jarrod R. McClean, Thomas O'Brien, and Nicholas C. Rubin
Google Quantum AI, Santa Barbara, CA 93111, United States
(Dated: December 5, 2025)

arxiv.org/abs/2511.09124

Horizon	Problem	Stage III applications	Problem size	Stage IV(b)		Stage IV(c)	
				Logical q.	Toffolis	Phys. q.	Time
Medium	Trapdoor claw-free functions [104]	Classically verifiable quantum advantage	1024 bits	1600 [141]	$8 \cdot 10^6$	–	–
	DQI for OPI [58]		4095 variables 70 constraints	1900	$6 \cdot 10^6$	$8 \cdot 10^5$ [142]	1 hour
	Topological data analysis of random graphs [62]	Unknown	256 vertices 16-cliques	500 [143]	$7 \cdot 10^9$	–	–
	Factoring [34]	Breaking RSA	2048 bits	1400	$7 \cdot 10^9$	$1 \cdot 10^6$ [44]	1 week
	Binary discrete log [34]	Breaking outdated cryptosystems	233 bits	3000	$4 \cdot 10^6$	$4 \cdot 10^6$ [36]	8 min
Furthest	Elliptic curve cryptography [34]	Breaking elliptic curve cryptography	256 bits	3000	$5 \cdot 10^7$	$9 \cdot 10^6$ [35]	4 hours
	Tensor PCA [30]	Unknown	100 variables	900 [144]	$1 \cdot 10^{15}$	–	–
	XOR-SAT refutation [82]	Unknown					
	QAOA for max 8-SAT [102]	Unknown	179 variables	28000	$5 \cdot 10^{11}$	$7 \cdot 10^7$ [145]	15 hours

physics simulation resource estimates

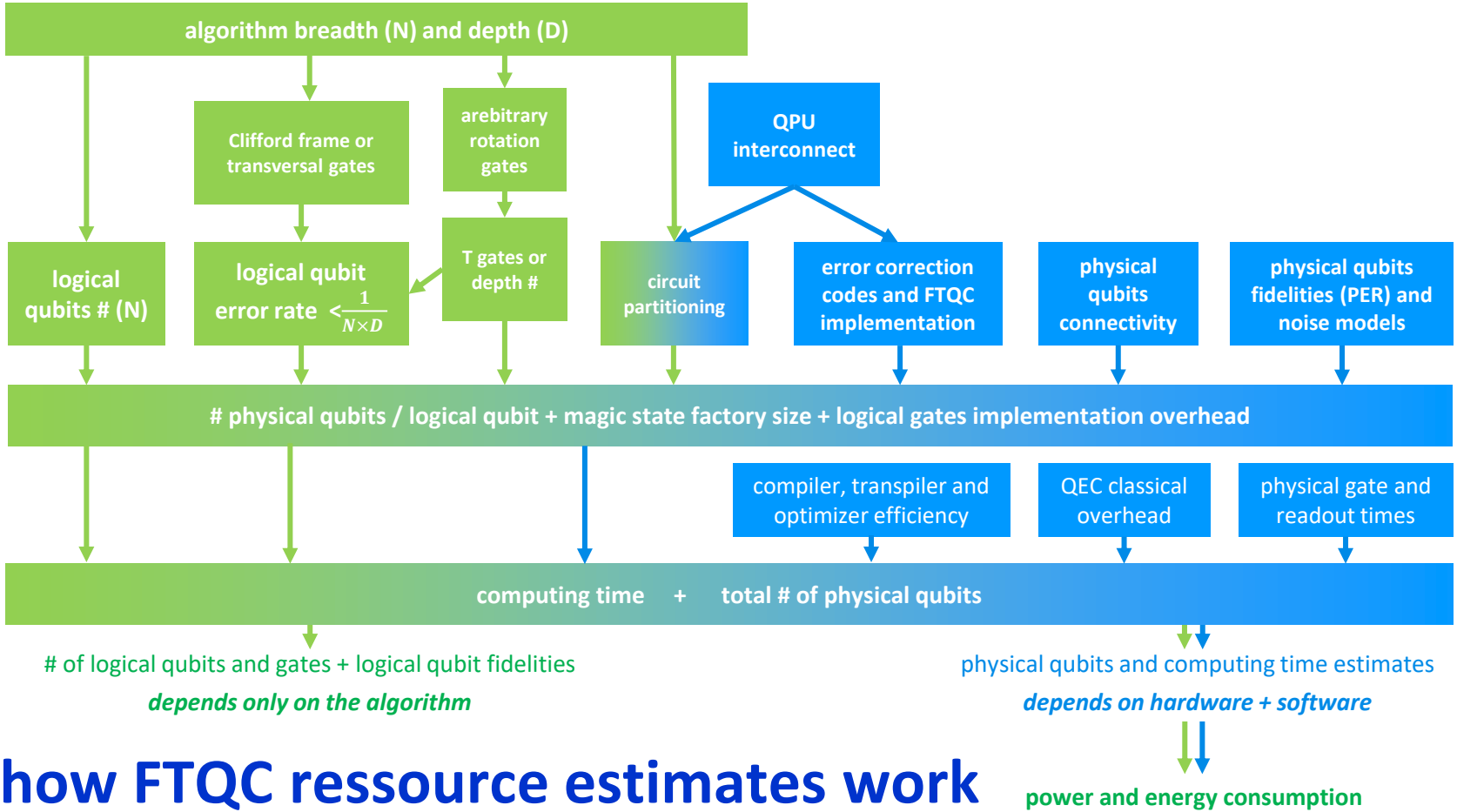


Quantum Computing Technology Roadmaps and Capability Assessment for Scientific Computing -- An analysis of use cases from the NERSC workload by Daan Camps, et al, arXiv, September 2025 (69 pages).

quantum chemistry

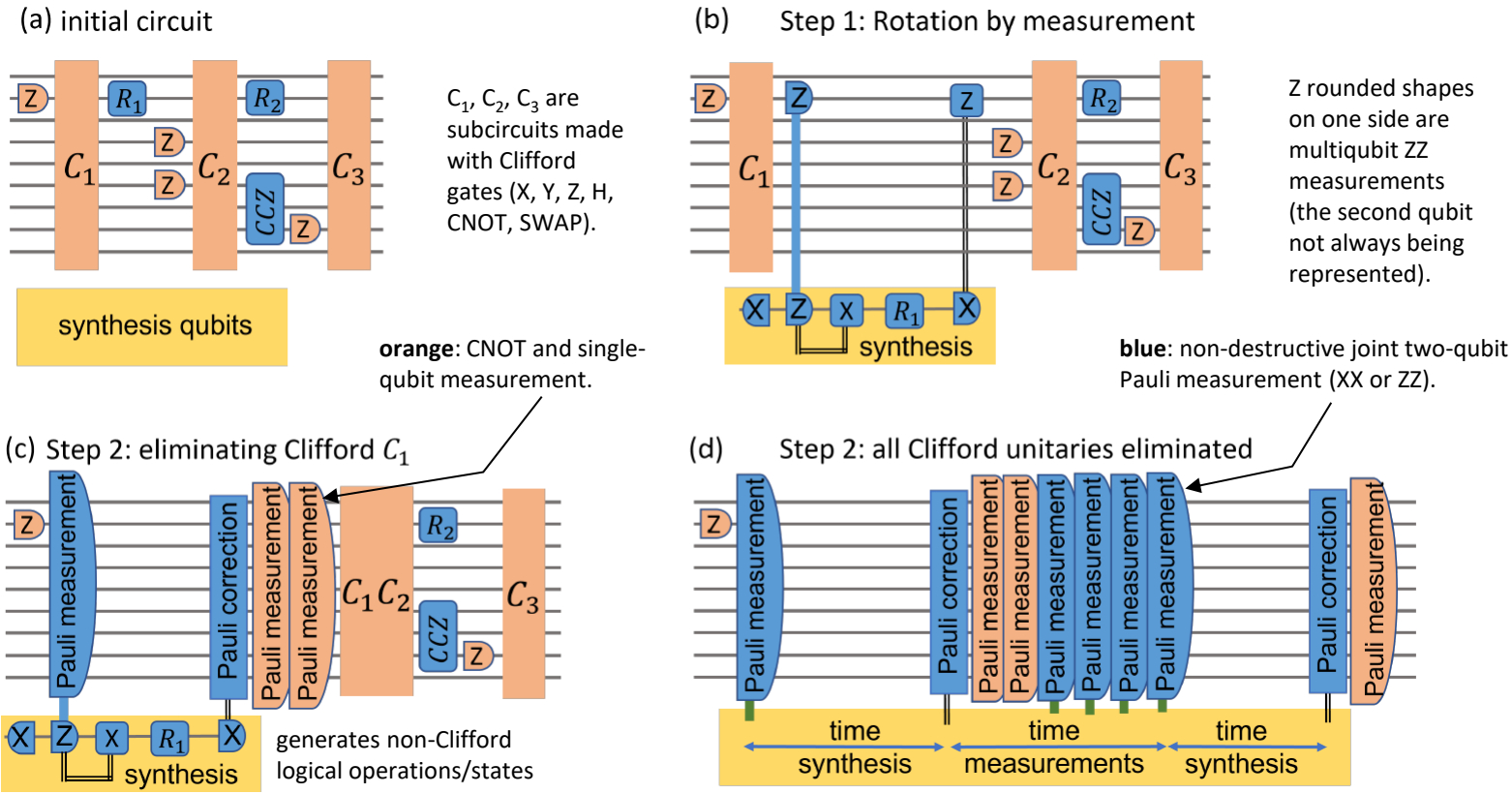
Molecule(s) & references	Algorithm	Logical qubits	T/Toffoli gates per sample	Number of samples
FeMo-co (nitrogen fixation) [38, 22, 24, 25, 62, 61]	2nd Q, THC qubitization, Gaussians 2nd Q, randomized compilation, Gaussian	2196 [25] $\sim$193 [62]	3.2×10^{10} [25] $\sim 3 \times 10^{12}$ [62]	7 $\sim$600
Cytochrome P450 (biological drug metabolizing enzyme) [63]	2nd Q, THC qubitzation, Gaussians	1434	7.8×10^{9}	7
Lithium-ion battery molecules [64, 7]	2nd Q, DF qubitization, Gaussians 1st Q, qubitization, plane waves	10^4–10^5 [64] 2000–3000 [7]	10^{12}–10^{14} [64] 10^{11}–10^{12} [7]	7 7
Chromium dimer [65]	2nd Q, sparse qubitization, Gaussians	$\sim$1300	$\sim 10^{10}$	7
Ruthenium catalyst (CO_2 fixation) [24]	2nd Q, DF qubitization, Gaussians	$\sim$4000	$\sim 3 \times 10^{10}$	7
Ibrutinib (drug molecule) [66]	2nd Q, Sparse qubitization, Gaussians	2207	1.1×10^{10}	7
Molybdenum catalysts (nitrogen fixation) [67]	2nd Q, DF qubitization, Gaussians	1000–8000	10^{11}–10^{12}	3–9[a]
Amyloid beta binding site fragment (Alzheimer's disease) [68]	2nd Q, DF qubitization, Gaussians	5000	10^{14}	7
Fullerene-encapsulated cyclic ozone (rocket fuel) [69]	2nd Q, DF qubitization, Gaussians 2nd Q, sparse qubitization, plane wave dual	10^3 10^4	10^{12}–10^{13} 10^{15}	7

"Quantum algorithms: A survey of applications and end-to-end complexities", Oct 2023-Aug2025
https://arxiv.org/abs/2310.03011

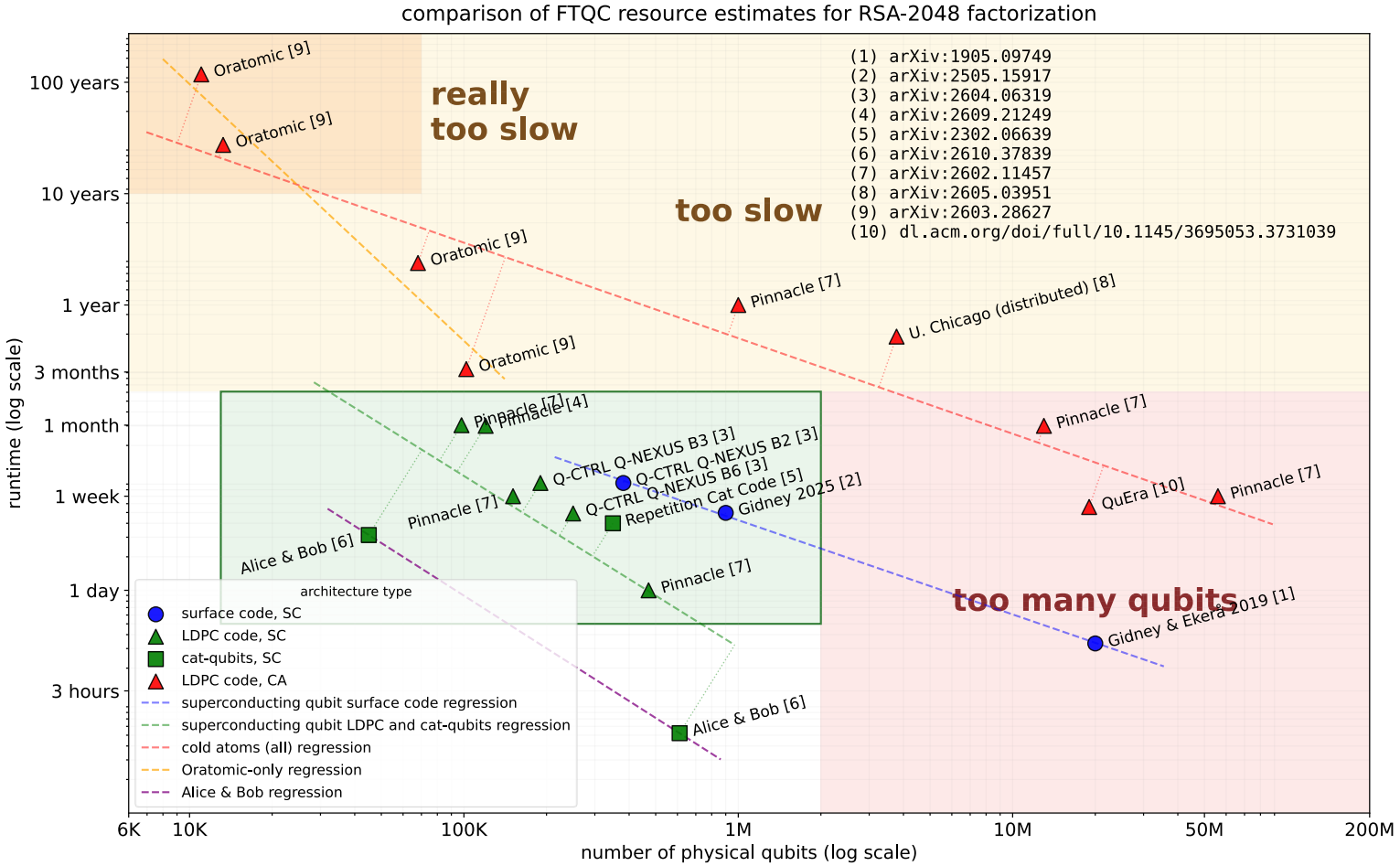


how FTQC ressource estimates work

circuit QEC “shape shifting” example



https://arxiv.org/abs/2211.07629

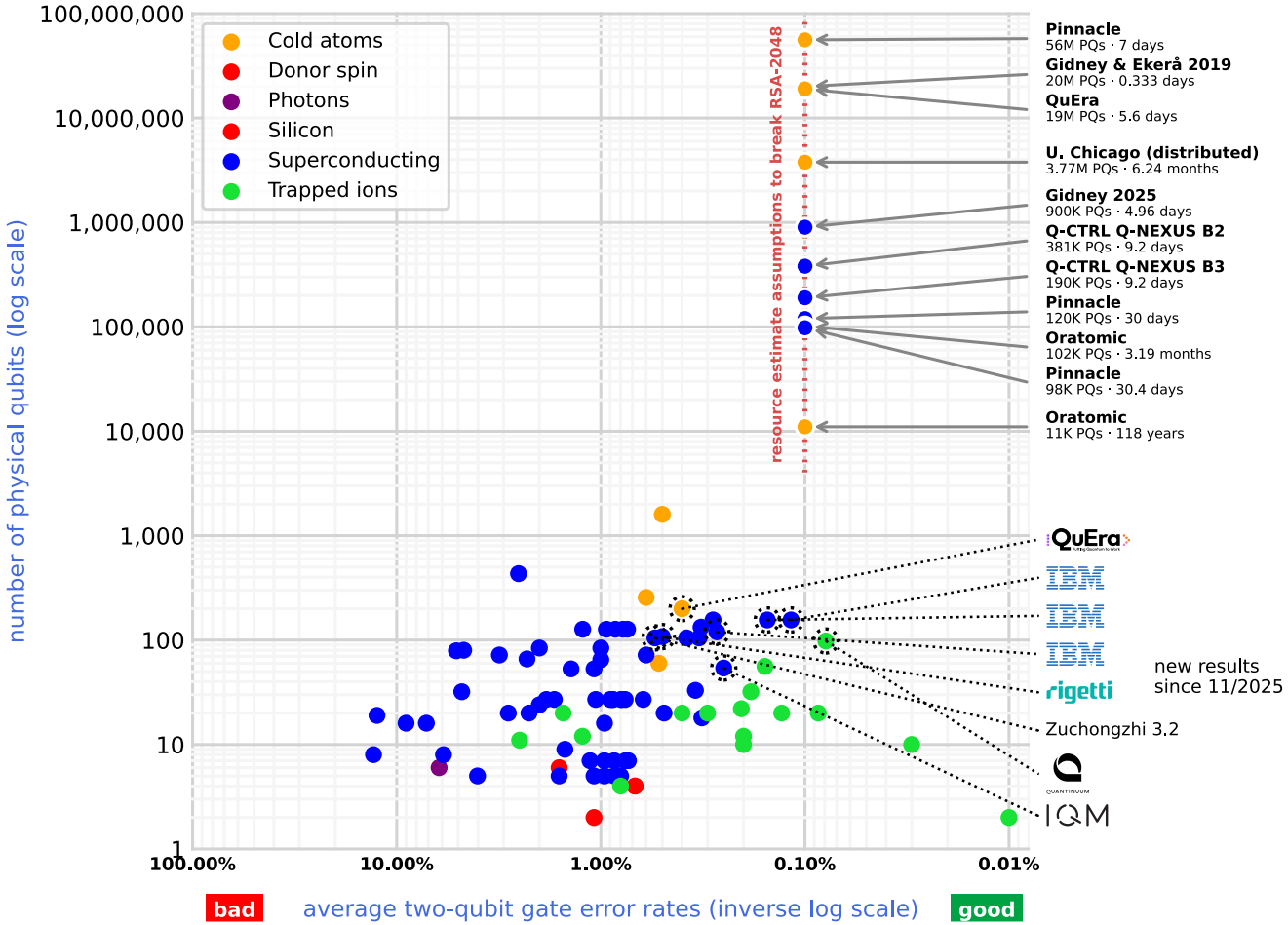

comparison of FTQC resource estimates for RSA-2048 factorization
really too slow
too slow
too many qubits
(1) arXiv:1905.09749
(2) arXiv:2505.15917
(3) arXiv:2604.06319
(4) arXiv:2609.21249
(5) arXiv:2302.06639
(6) arXiv:2610.37839
(7) arXiv:2602.11457
(8) arXiv:2605.03951
(9) arXiv:2603.28627
(10) dl.acm.org/doi/full/10.1145/3695053.3731039
Oratomic [9]
Oratomic [9]
Oratomic [9]
Oratomic [9]
Pinnacle [7]
U. Chicago (distributed) [8]
Pinnacle [7]
Pinnacle [4]
Pinnacle [7]
Q-CTRL Q-NEXUS B3 [3]
Q-CTRL Q-NEXUS B2 [3]
Q-CTRL Q-NEXUS B6 [3]
Repetition Cat Code [5]
Gidney 2025 [2]
Pinnacle [7]
Alice & Bob [6]
Pinnacle [7]
QuEra [10]
Pinnacle [7]
Gidney & Ekerå 2019 [1]
Alice & Bob [6]
architecture type
surface code, SC
LDPC code, SC
cat-qubits, SC
LDPC code, CA
superconducting qubit surface code regression
superconducting qubit LDPC and cat-qubits regression
cold atoms (all) regression
Oratomic-only regression
Alice & Bob regression
runtime (log scale)
100 years
10 years
1 year
3 months
1 month
1 week
1 day
3 hours
number of physical qubits (log scale)
6K
10K
100K
1M
10M
50M
200M

physical error rate assumptions in QEC/FTQC resource estimates:

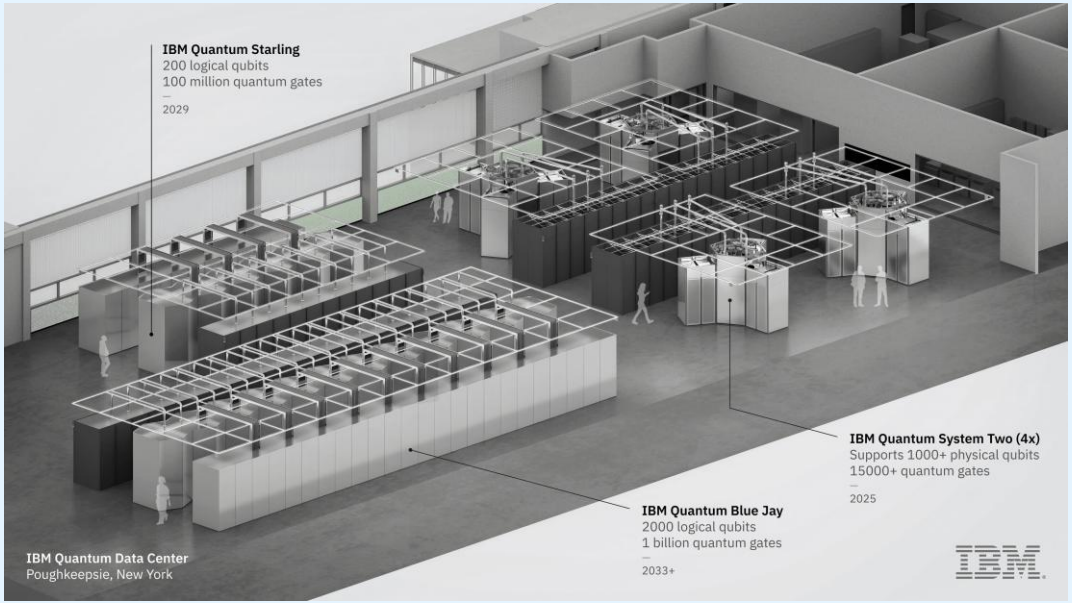
- 99.9% reset fidelity
- 99.9% single qubit gate fidelity
- **99.9% two qubit gate fidelity**
- 99.9% idle state fidelity
- **99.9% readout fidelity**
- usually, missing correlated noise sources + unknown noise sources at scale.

=>

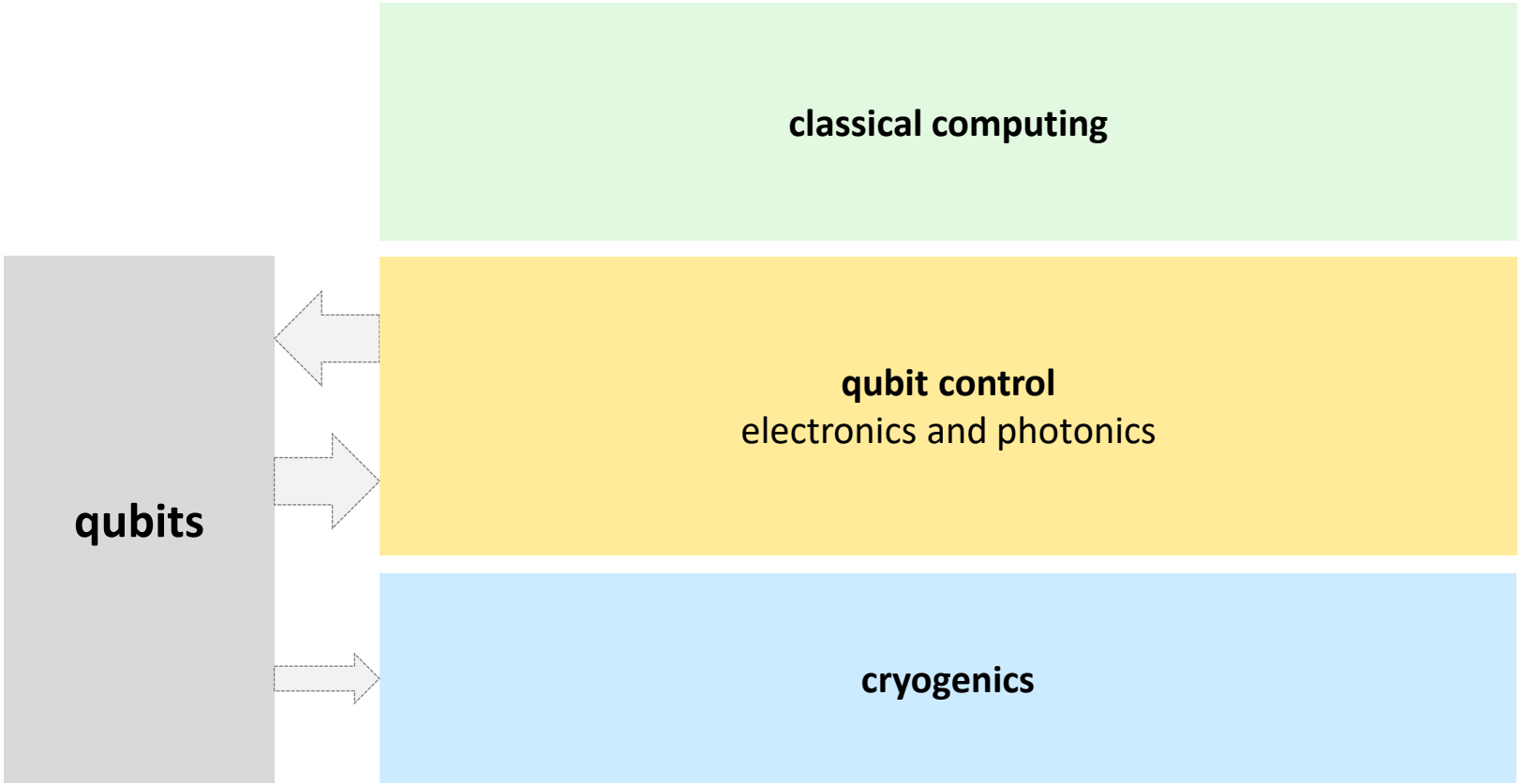
- quantum energetics.
- material sciences.
- high-quality manufacturing.
- high-quality qubit control.
- QPU interconnect overhead.



quantum computing energetics

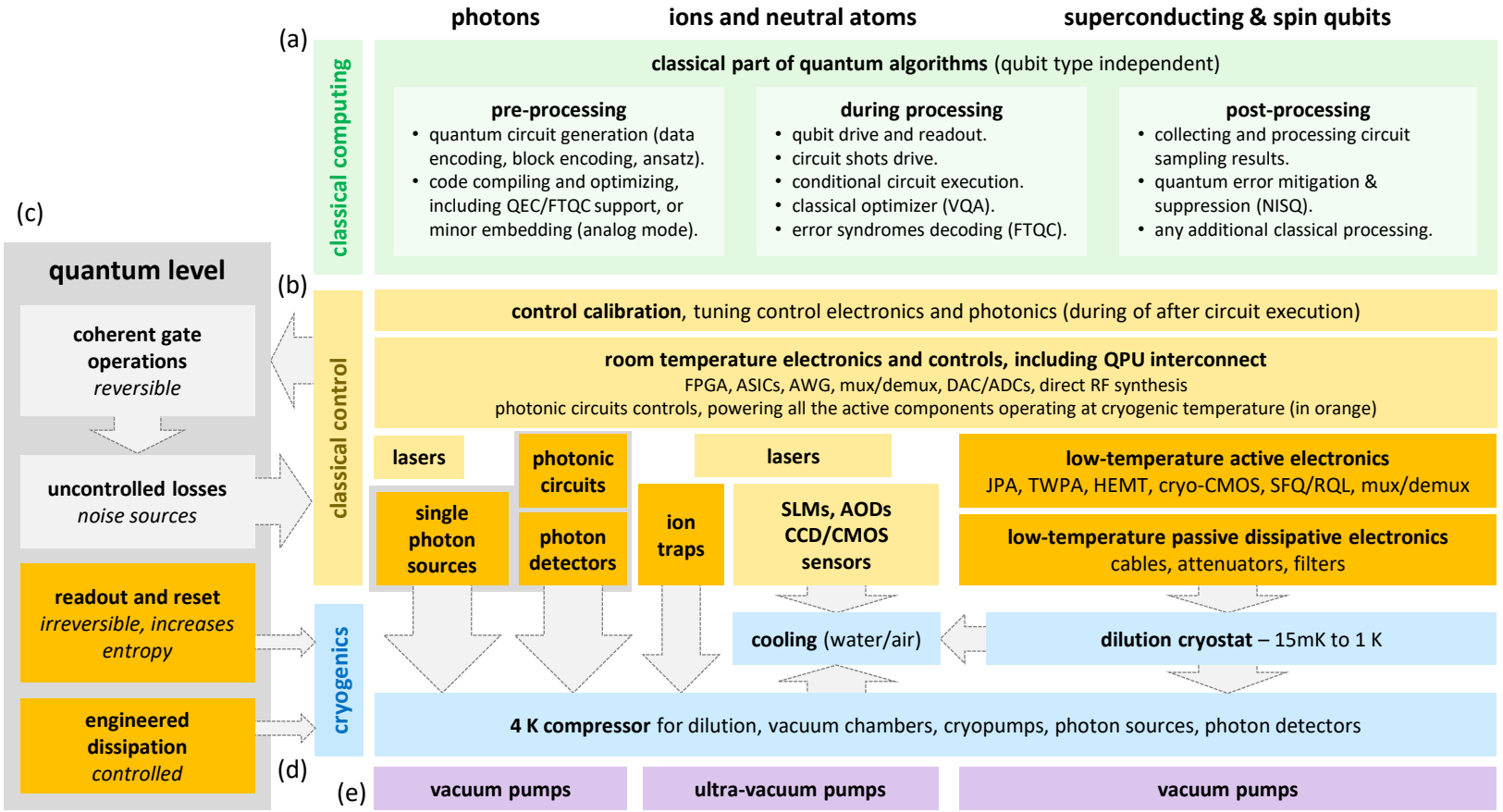


energy consumption sources



source: Olivier Ezratty, October 2026

quantum ↔ macroscopic costs



source: Understanding Quantum Technologies 2026, Olivier Ezratty, September 2026

quantum energetics scientific fields

quantum technologies energetics

full-stack approaches to model, optimize, and benchmark the energy resources required to implement useful quantum technologies, under specified performance constraints.

macroscopic scale	classical computing software engineering quantum information science all classical enabling technologies classical thermodynamics
quantum scale	quantum electrodynamics, semiconductor spin physics, quantum optics. open quantum system theory, quantum control theory, noise modelling. materials science and semiconductor manufacturing. fundamental quantum energetics. quantum thermodynamics.

an emerging research field

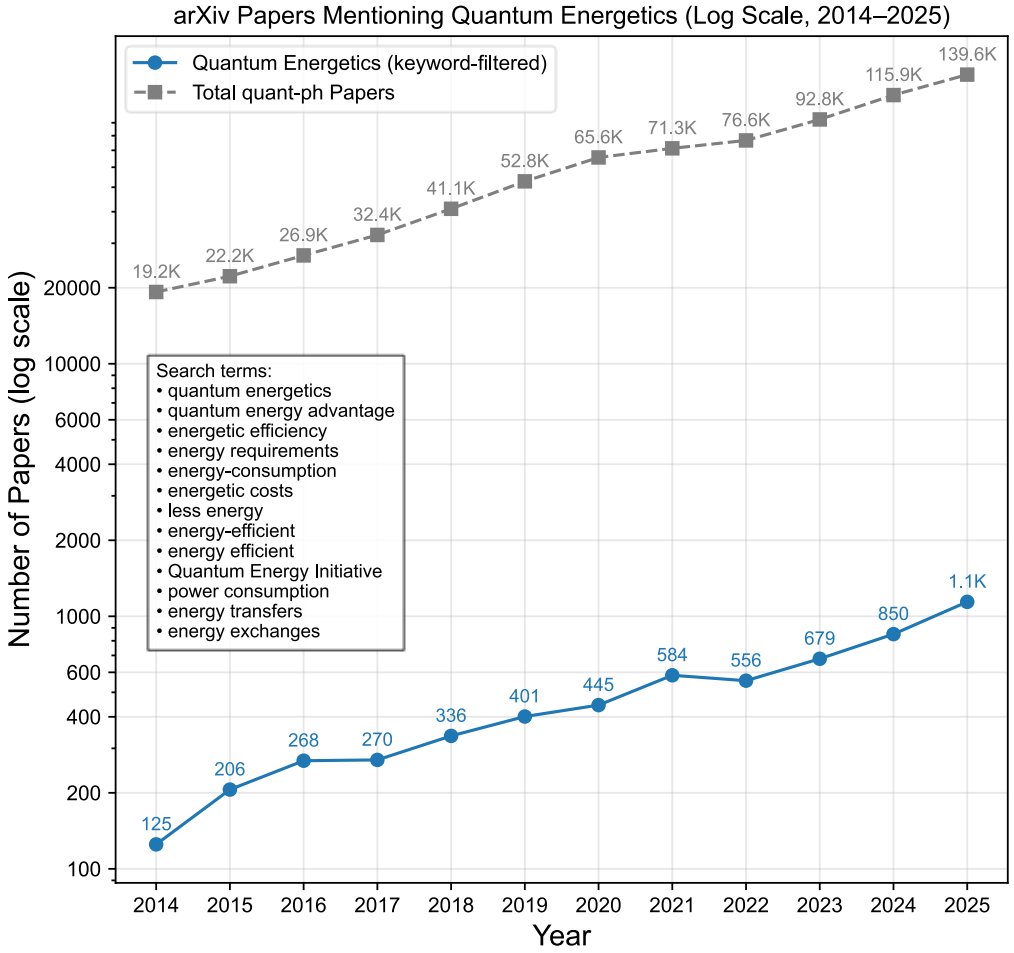
PHYSICAL REVIEW X **16,** 011016 (2026)

Powering Quantum Computation with Quantum Batteries

Yaniv Kurman,[1] Kieran Hymas,[1] Arkady Fedorov,[2] William J. Munro,[3] and James Quach[1,*]
[1]*Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton, Victoria 3168, Australia*
[2]*School of Mathematics and Physics, The University of Queensland, Brisbane, QLD 4072, Australia*
[3]*Okinawa Institute of Science and Technology Graduate University, Onna-son, Kunigami-gun, Okinawa, 904-0495, Japan*

(Received 3 July 2025; revised 7 October 2025; accepted 7 January 2026; published 26 January 2026)

https://journals.aps.org/prx/abstract/10.1103/l39v-jwwz



QT energetics related research examples

methodology

Auffèves QEI vision paper: prxquantum 3.020101
Fellous-Asiani resources constraints: prxquantum 2.040335
Fellous-Asiani MNR: arxiv 2112.04022
Jaschke energy quantum advantage estimate: iopscience 10.1088/2058-9565

fundamentals

Buffoni thermo laws & QC scaling: PhysRevLett.129.150602
Alimuddin erasure cost ICFO: arxiv 2512.05761
Zhao state erasure: arxiv 2504.07341
Aifer QSL and gates: iopscience 10.1088/1367-2630
Ikonen energy efficiency: arxiv 1609.02732
Latune autonomous quantum systems: arxiv 2601.01272
Piccione measurement costs: arxiv 2311.11870
Kurman qc with quantum batteries: prx 10.1103/l39v-jwwz
Chattopadhyay computation thermos: arxiv 2102.09981
Chattopadhyay Landauer in quantum: arxiv 2506.10876
Roadmap on quantum thermodynamics: arxiv 2504.20145
Harrington engineered dissipation: arxiv 2202.05280
Meir fundamental bounds: arxiv 2305.11212

quantum communications

Yehia communication protocols cost: arxiv 2410.10661
Horodecki entanglement distribution cost: arxiv 2507.23108
Nötzel optical fiber cost: arxiv 2201.12397
Vokes optical tracking in space comm: arxiv 2602.22160

trapped ions energetics

Goïs: arxiv 2404.11572

cold atoms energetics

Alves: arxiv 2601.03141
Dauphin (Pasqal): arxiv 2511.20388
Sorani (Planqc): link

superconducting qubits energetics

Fellous-Asiani: prxquantum 4.040319
Dassonneville measurement: arxiv 2501.17069
Ramos cat-qubits energetics arxiv 2605.19854

silicon spins energetic

Steinacker (Diraq): arxiv 2607.11846
Santos (Quobly): arxiv 2610.22199
Koteva: in prep.

photon qubits energetics

de Buy Wenniger QD energy: arxiv 2202.01109, arxiv 2603.13152
Maffei spin-photon QND: quantum-journal-2023-08-31-1099/
Emeriau boson sampling: arxiv 2601.08068
Laverick, qubit entanglement, arxiv 2603.16225
Volpato, SPAM energy, arxiv 2402.16603

cryogenics and control

Manifold (OQC): arxiv 2503.10775
NREL cooling cryogenic electronics: link

NISQ and FTQC

Carrasco-Codina NISQ energy efficiency arxiv 2605.15090
McCollum uncertain quantum computing ScienceDirect
Fellous-Asiani FTQC energetic challenges: in prep

application specific

Calero quantum circuits: nature s42254-025-00846-0
Desdendato trade-offs: sciencedirect S0164121224002103
Tao QPE: arxiv 2511.05458
Tu linear systems: arxiv 2502.11239
Paler Shor estimate: acm 10.1145/3490172
Pratapsi half adder: arxiv 2210.10470
Moutinho full adder: arxiv 2206.14241
Verma VQE optimization: in prep
Fellous-Asiani magic state cost arxiv 2411.01880
Flores-Garrigos (Kipu) LLM: arxiv 2510.24509
Flöther Gen AI: arxiv 2508.20720
Thompson quantum agent: arxiv 2503.19896
Kearney Blockchain mining: arxiv 2306.03321
Amin Blockchain mining D-Wave: arxiv 2503.14462
Orun Cryptos mining: arxiv 2401.10902
Brenner emulation cost: arxiv 2509.18854
Li emulation cost: arxiv 2307.05510

economics

Cordier life cycle assessment: arxiv 2411.00118
Arora Carbon lifecycle assessment: arxiv 2408.05679

Standardizing the evaluation of power & energy consumption



(Brief explanation of the goal)

IEEE QEI Workgroup: standardizing the evaluation of energy & power consumption

https://sagroups.ieee.org/qei/

Chair: Marco Fellous-Asiani (myself)
Vice-Chair: Dash Liu
Secretary: Harshit Verma



Affiliation of some participants:

Disclaimer

In this presentation, I speak in my own personal capacity.

What is presented = not an official position of neither the working group or IEEE

-> No official vote on the technical draft occurred yet; still WIP

IEEE QEI Workgroup: standardizing the evaluation of energy & power consumption

What are the challenges in standardization (in a nutshell):

1. Make sure consumption is **defined in a scientifically rigorous manner**

E.g: Important to relate consumption to computational performance

« FTQC consumes X MW, E Joules, to solve problem Y **at an accuracy Z** with a time T »

2. To provide **set of rules** of what to include in the total bill, and **how** (methodology)

Examples of issues that could occur: *why a methodology is needed*

- **Standard aims to be applicable to any platform.**
  => How to make platform-agnostic rules?
- **Significant part of consumption could be OUTSIDE of compute.**
  => E.g. qubit's calibration.
- **Not all consumption = electrical.**
  => E.g. factory producing cryogenic fluids.
- **How is « quantum computer » even defined?**
  => Surrounding classical HPC also needed.

Standardization must adress all these issues

IEEE QEI Workgroup: Timeline

- **Technical document (with all the precise rules): Under finalization.**
  We target a public review in early 2027. **Interested in technical feedbacks!**

- Standardization ≠ benchmarking.
  However it OPENS the way to (energy) benchmark (natural follow-up)

Disclaimer

In this presentation, I speak in my own personal capacity.

What is presented is not an official position of neither the working group or IEEE

sizing the challenge

New Scientist

Technology

Some quantum computers might need more power than supercomputers

A preliminary analysis suggests that industrially useful quantum computers designs come with a broad spectrum of energy footprints, including some larger than the most powerful existing supercomputers

By Karmela Padavic-Callaghan

8 January 2026

https://www.newscientist.com/article/2509492-some-quantum-computers-might-need-more-power-than-supercomputers/

PT PHYSICS TODAY

NEWS / ARTICLE

How much electricity does a quantum computer need?

JUN 15, 2026

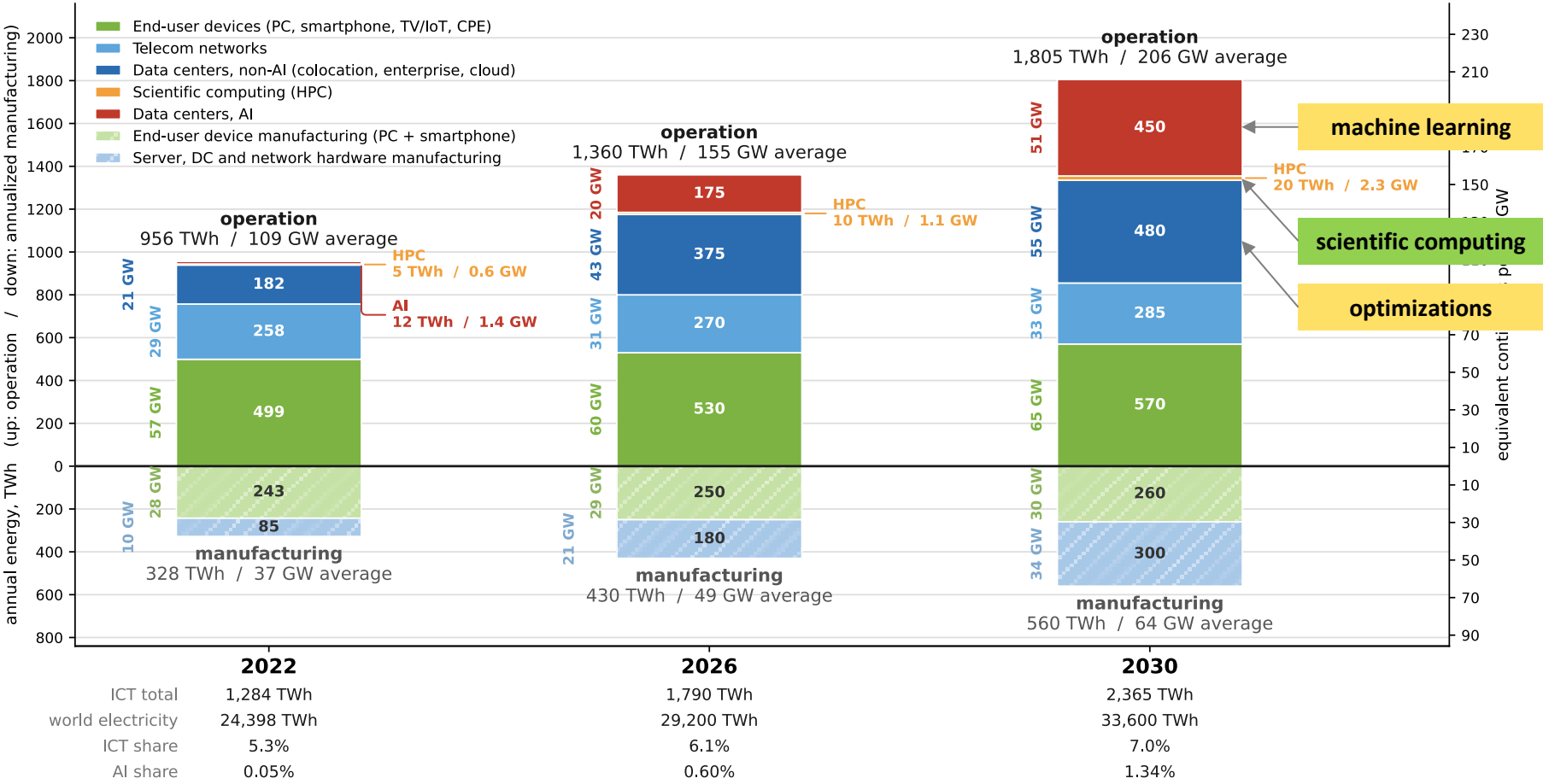
The question is attracting attention amid rising energy use by classical computing data centers.

DOI: 10.1063/pt.41fbb5d95c

Jenessa Duncombe

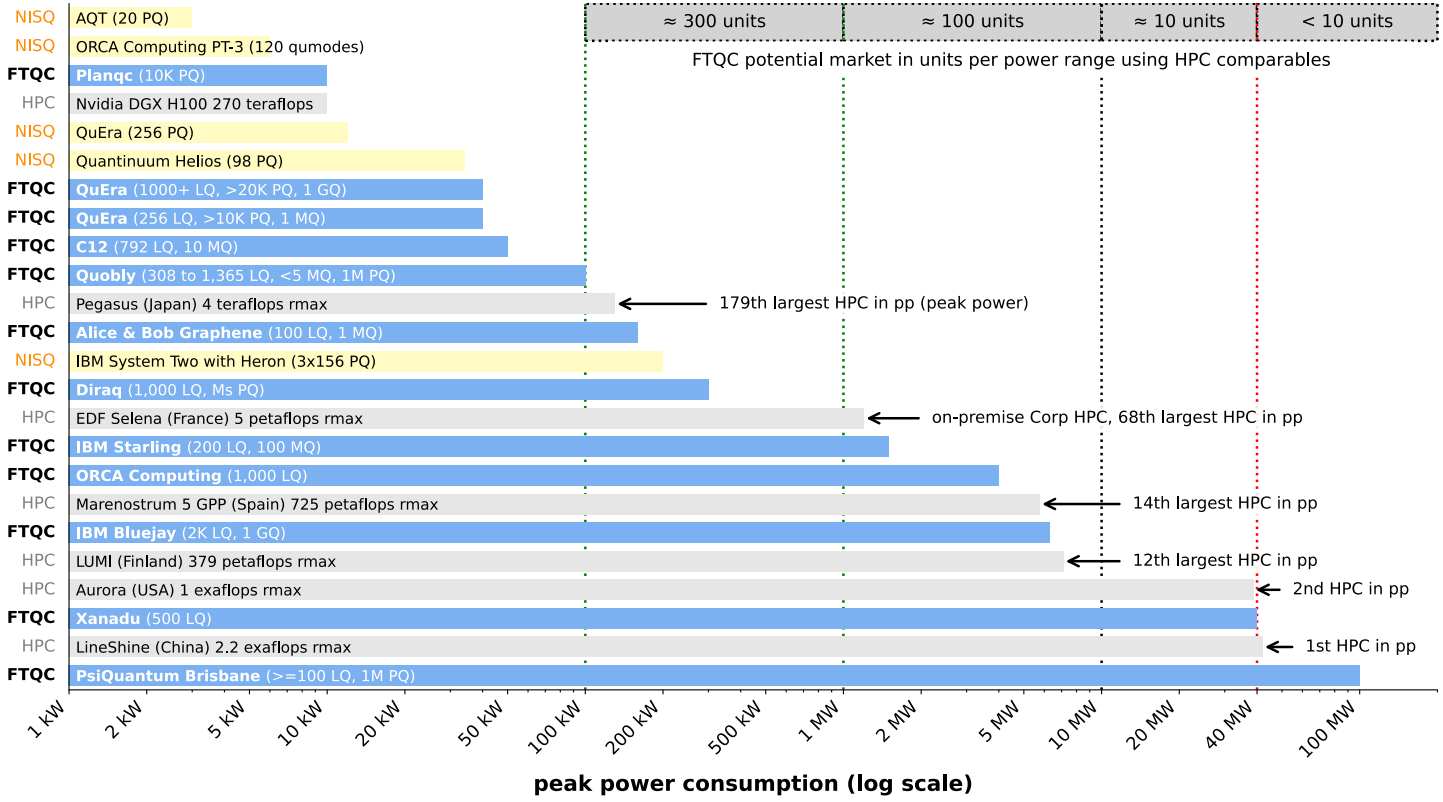


https://physicstoday.aip.org/news/how-much-electricity-does-a-quantum-computer-need



source: Understanding Quantum Technologies 2026, Olivier Ezratty, September 2026

NISQ-FTQC-HPC power comparables



estimate base power for various FTQCs and actual for existing largest HPCs WW and NISQ QCs. HPC source: TOP 500 and Nvidia. FTQC sources: vendor data or data reconciliation.
PQ: physical qubits
LQ: logical qubits.
MQ: megaquop (logical operations).
TQ: teraquop.

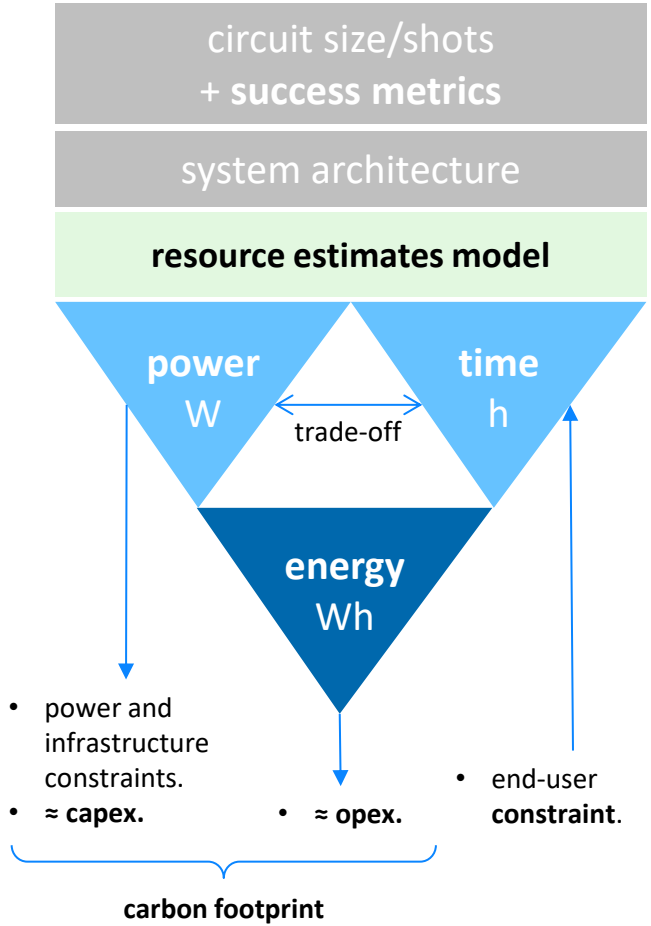
these are based on multiple unverifiable and usually optimistic assumptions (physical error rates, error models, …).

power comparable warnings

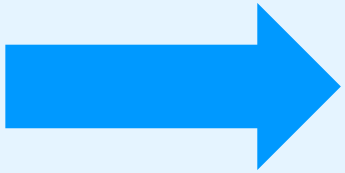
1. **vendor numbers give some indication of the potential power/energy needs for future FTQC systems.**
2. **the distribution and comparison with HPC systems gives an indirect indication of a potential market size.**
3. **numbers are based on multiple optimistic assumptions:**
   - circuit sizes and optimistic physical error rates: 99.9% for all operations.
   - incomplete error models: leakage, losses, correlated errors at scale, variability.
   - not accounting for the overhead of quantum interconnect.
   - quantum algorithm success metrics (accuracy, …).
   - enabling technologies efficiencies: cryogenics, electronics, photon losses, QEC.
4. **they do not account for the speed difference between systems.**
   - these differences play a key role when comparing the energy consumption and computing times for specific quantum computing workloads.

why look at both energy and power?

1. **broad range of expected power consumption**
   - 1 to 1000 range under usual optimistic assumptions.
   - maximum = 2,5 the largest exaflops HPCs and 10% of an average nuclear reactor (1 GW).
2. **power consumption**: indication of feasibility.
3. **energy consumption**: potential platform Darwinism through energy-efficiency, « survival of the fittest »?
4. **global environmental footprint**: will depend on # of practical use cases.



modelling and ~~evaluate~~ optimizing quantum computing energetics



focus on power (for pedagogy)…
(whole logic is similar for energy)

The path toward realistic energetic models

Making realistic energetic models of full-stack quantum computers:



~~Difficult~~ **impossible** today.

- Algorithmic resource estimates: rely on crucial assumption regarding noise (uncorrelated, stochastic, …) => **High chances of being unreliable.**

- Energy estimates: need **additional** assumptions on hardware.
  => Even less reliable!



If we don't know if models are reliable:
why making them?

Why making models if they are unreliable?

- Optimistic/idealistic assumptions => lower bounds the actual cost
  => **Can rule out not scalable architectures** (think about >100MW!)

- **Idealistic** but well chosen assumptions:

  - ~~Realistic quantitative estimate~~

  - **What dominates** the bill => Clear research goals of what to optimize
  - How consumption **scales** as function of key parameters

- Can connect fundamental physics to engineering.
  - Key to **benefit from physics' hardware breakthrough** to optimize consumption

Idealized energetic models: can be strategic for roadmaps

THE DIFFERENCE BETWEEN ESTIMATING AND OPTIMIZING CONSUMPTION

Estimating power consumption: how done in practice

Inputs: $(N_L, Q_L, p, \epsilon_{Target})$

- N_L: #logical gates
- Q_L: #logical qubits
- p: Physical error-rate
- ϵ_{Target}: Algorithm's targetted error rate

Logical error-rate: $p_L(p, d)$

« Code distance »

#Physical qubits: $Q_P(d) = Q_L \times f(d)$

p≤ $p_{threshold}$: d↗ ⇒ $p_L(p,d)$↘ ☺ & $Q_P(d)$↗ ☹

Impose:

$$\epsilon_{Algo} = p_L(p,d) \times N_L \leq \epsilon_{Target} \ (1)$$

Then: Minimize d (thus Q_P) so that (1) is true

↓

Q_P^{Min}

↓

Power *per* qubit

Deduce: $P_{tot} = q \times Q_P^{Min}$

This is power for MIN qubit count.
This is *NOT* MIN power

Estimating power consumption: how done in practice

Inputs: $(N_L, Q_L, p, \epsilon_{Target})$

- N_L: #logical gates
- Q_L: #logical qubits
- p: Physical error-rate
- ϵ_{Target}: Algorithm's targetted error rate

Logical error-rate: $p_L(p, d)$

« Code distance »

#Physical qubits: $Q_P(d) = Q_L \times f(d)$

$p \leq p_{threshold}$: $d \nearrow \Rightarrow p_L(p,d) \searrow$ ☺ & $Q_P(d) \nearrow$ ☹

Impose:

$$\epsilon_{Algo} = p_L(p,d) \times N_L \leq \epsilon_{Target} \ (\mathbf{1})$$

Then: Minimize d (thus Q_P) so that (1) is true

$$Q_P^{Min}$$

Power *per* qubit

Deduce: $P_{tot} = q \times Q_P^{Min}$

Constant p & q:
assumes a SPECIFIC strategy in how power is used.
Typically NOT optimal

Optimizing power consumption: how done in practice (general case)

p: physical error rate. q: consumption/physical qubit

Faithful algorithm:

$$\epsilon_{Algo} = p_L(p, d) \times N_L \leq \epsilon_{Target}$$

Total power consumption:

$$P_{tot} = q \times Q_P(d)$$

Code distance d ↗ ⇒ p_L ↘ ☺ Q_P ↗ ☹

First possibility: lower q without impacting p (therefore keep same Q_P)
=> Sometimes possible, but difficult in general

Optimizing power consumption: how done in practice (general case)

p: physical error rate. q: consumption/physical qubit

Faithful algorithm:

$$\epsilon_{Algo} = p_L(p,d) \times N_L \leq \epsilon_{Target}$$

Total power consumption:

$$P_{tot} = q \times Q_P(d)$$

Code distance d ↗ ⇒ p_L ↘ ☺ Q_P ↗ ☹

More general case: exploit tradeoffs between q & p

Change:
- Physical gate speed.
- Qubit's temperature
- Amount of multiplexing
- …

→ (generally) changes p AND q

Example: Qubit's temperature ↗ ⇒ q ↘ & p ↗

Exploit such ENERGY/NOISE tradeoffs to reduce consumption:

↘ q ☺ => p ↗ ☹ => MORE QEC ☹ => ↗ Q_P ☹ → Small q; Large Q_P

↗ q ☹ => p ↘ ☺ => LESS QEC ☺ => ↘ Q_P ☺ → Large q; Small Q_P

$P_{tot} = q \times Q_P$ → Non-trivial optimum

Optimizing power consumption: how done in practice (general case) [1]

Faithful algorithm:

$$\epsilon_{Algo} = p_L(p,d) \times N_L \leq \epsilon_{Target}$$

Total power consumption:

$$P_{tot} = q \times Q_P(d)$$

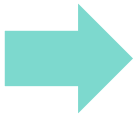
$$\underbrace{\epsilon_{Algo}(\{Architecture\}) \leq \epsilon_{Target}} \qquad P_{tot}(\{Architecture\})$$

$\{Architecture\}$

- QEC code distance
- Physical gate speed.
- Qubit's temperature
- Amount of multiplexing
- …

Find $Min[P_{tot}(\{Architecture\})]$

so that $\epsilon_{Algo}(\{Architecture\}) \leq \epsilon_{Target}$



Optimal architecture found minimizing consumption

[1] Fellous-Asiani, Chai, Thonnart, Y., Ng, Whitney, Auffèves, A. *PRX Quantum 2023*

Optimizing power consumption: how done in practice (general case) [1]

Faithful algorithm:

$$\epsilon_{Algo} = p_L(p,d) \times N_L \leq \epsilon_{Target}$$

Total power consumption:

$$P_{tot} = q \times Q_P(d)$$

$$\epsilon_{Algo}(\{Architecture\}) \leq \epsilon_{Target}$$

$$P_{tot}(\{Architecture\})$$

Requires to relate full-stack architecture to algo performance.
=> **open quantum systems**

Optimizing for consumption:
not only an engineering problem.
For a big part: physics' problem

Find $Min[P_{tot}(\{Architecture\})]$
so that $\epsilon_{Algo}(\{Architecture\}) \leq \epsilon_{Target}$

Optimal architecture found minimizing consumption

[1] Fellous-Asiani, Chai, Thonnart, Y., Ng, Whitney, Auffèves, A. *PRX Quantum 2023*

Optimizing power consumption: how done in practice (general case) [1]

Explained in different (equivalent) terms:

This approach = « **Metric Noise Resource** » methodology. Developped in [1]

- **Metric** = Computational accuracy.
- To evaluate it: you need to model **Noise**
- **Resource** = what you want to minimize (energy or power)

=> Express Metric/Noise/Resource as a function of $\{Architecture\}$

$\{Architecture\}$

- QEC code distance
- Physical gate speed.
- Qubit's temperature
- Amount of multiplexing
- …

Then: solve

$Min[Resource(\{Architecture\})]$

So that $Metric(Noise(\{Architecture\})) \geq M_{Target}$

One equation describes the full computer

=> Enables **holistic optimization of the machine**

[1] Fellous-Asiani, Chai, Thonnart, Y., Ng, Whitney, Auffèves, A. *PRX Quantum 2023*

Metric Noise Resource [1]: applied in a **highly idealized** full-stack superconducting quantum computer model with **concatenated QEC**.

Goal=**<u>proof of principle of applicability @full-stack level</u>**.

Shor's algorithm (RSA-2048). Result obtained in one of the studied architectures

$10GW = 10\times$  $\times 1/5000$ $2MW =$ 

During 1h34 — During 1h34

« Usual » approach
(Minimize qb count, deduce consumption)
Fixed error rates

This approach:
Specifically optimize for consumption
Adaptative error rates

One of the explanations:

Qubits LESS COLD (↗ noise) — BUT Competition — <u>MORE</u> QEC (↘ errors)

Bigger computer…ending up being **MORE energy-efficient**

=> Because PER-QUBIT consumption = lower

[1] Fellous-Asiani, Chai, Thonnart, Y., Ng, Whitney, Auffèves, A. *PRX Quantum 2023*

What physics' can do, in addition to engineering & computer-science to ~~estimate~~ optimize consumption

The role of physics on optimizing FTQC energetics:
1) quantitatively understand noise-energy tradeoffs

I. Regarding **physical noise *strength***

=> Model: $p(\{Architecture\})$ (full-stack + open quantum system theory)

For important architecture parameters w.r.t. consumption:

(Temperature, Physical gate speed, Attenuation, Multiplexing, …)

II. Regarding **physical noise *structure***

- Global qubit driving: can lower consumption per qubit ☺

  (often) introduce correlated noise ☹ => more QEC ☹ => **TRADEOFF**

The role of physics on optimizing FTQC energetics:
2) Optimize the $\hbar\omega$ scale gate consumption

Why should we care? This is tiny!

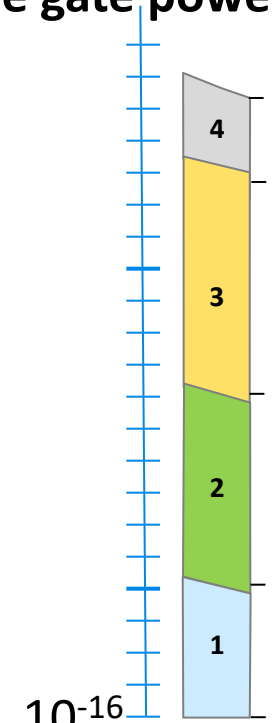


Can be a misleading argument!

The role of physics on optimizing FTQC energetics:
2) Optimize the $\hbar\omega$ scale gate consumption

superconducting qubit

single-qubit microwave gate power consumption [Watts]



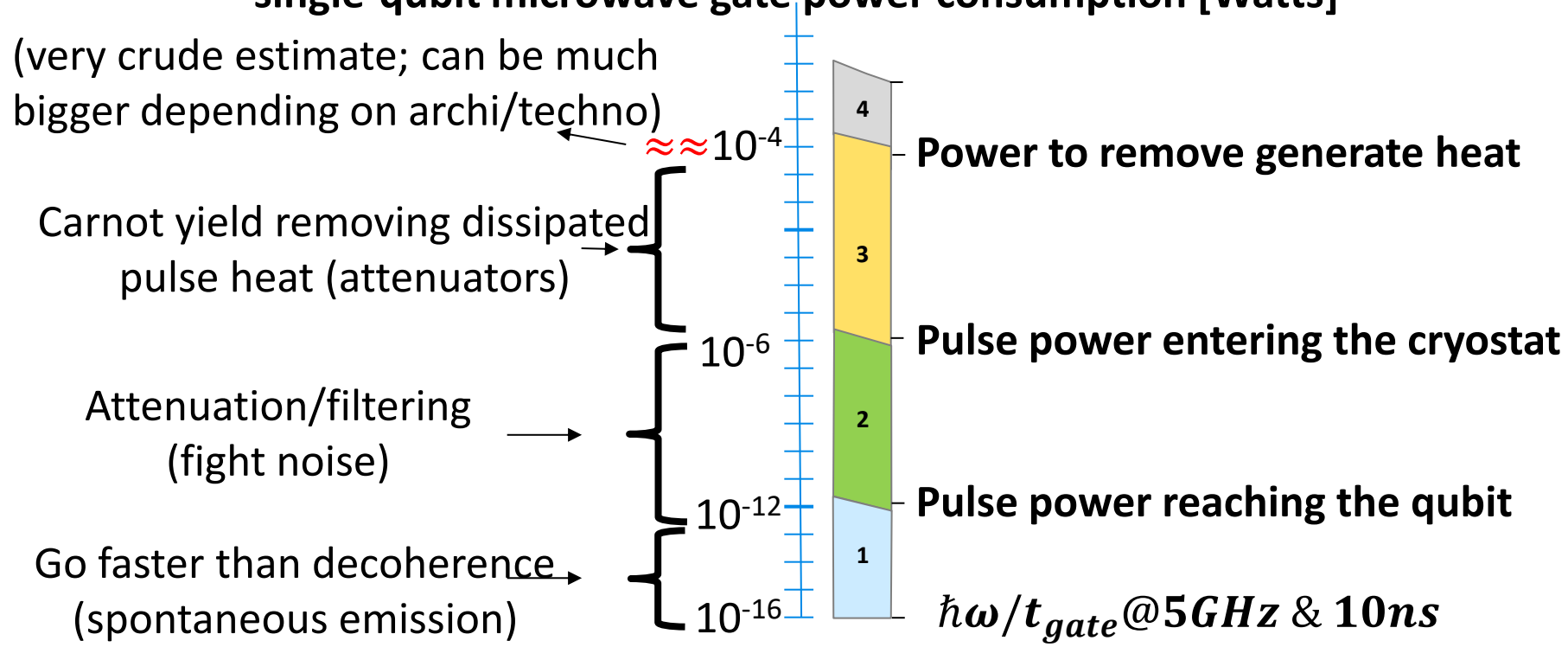
Power « strictly » needed by qubits to go from |0> to |1>

$\hbar\omega/t_{gate}$@$5GHz$ & $10ns$

The role of physics on optimizing FTQC energetics:
2) Optimize the $\hbar\omega$ scale gate consumption

superconducting qubit

single-qubit microwave gate power consumption [Watts]

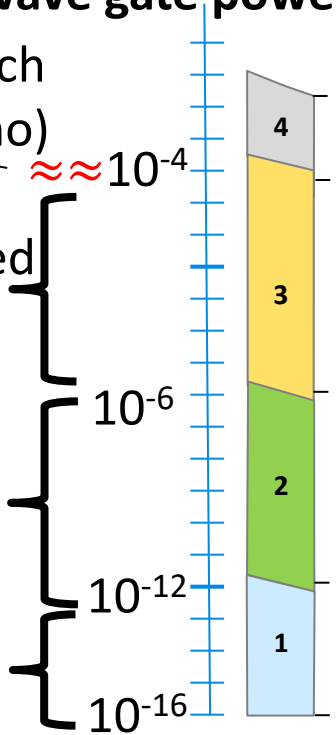


The role of physics on optimizing FTQC energetics:
2) Optimize the $\hbar\omega$ scale gate consumption

superconducting qubit

single-qubit microwave gate power consumption [Watts]

(very crude estimate; can be much bigger depending on archi/techno)



Carnot yield removing dissipated pulse heat (attenuators)

Attenuation/filtering (fight noise)

Go faster than decoherence (spontaneous emission)

Will divide by 10x here (proportional)!

$\hbar\omega$ scale reduction could impact macroscopic consumption!

Divide by 10x here…

=>Pure quantum physics' problem!

The role of physics on optimizing FTQC energetics:
3) Help engineers designing components

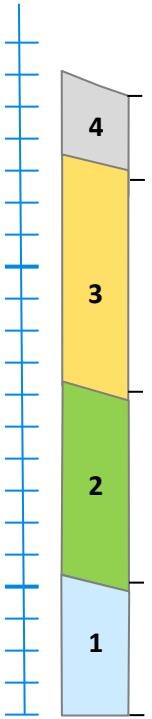
Electronics generating the signal ≈≈10

Why?!
Suggests big reductions opportunities!

Huge gap!

Generated pulse → 10^{-6}

10^{-16}



Often: big cost to generate accurate signals.
Possibly(?): **exploit noise/energy tradeoff there**

Lower (a bit) signal's quality & compensate with noise suppression techniques (QEC or QEM).

counter intuitive insights



cryogenics

- all qubit types rely on cryogenics.
- it's usually a variable cost vs physical qubit #.
- cryogenics may not be the dominant energetic cost for some qubit modalities.

science vs engineering

- still room for progress at the fundamental level.
- enabling technologies key role.
- many interdependencies and potential counterintuitive optimizations.



electronics and photonics

- control electronics and photonics may become the dominant energetic cost in solid state platforms.

classical computing

- classical energetic costs must be considered before, during and after a quantum circuit run.
- compilation is a variable cost vs the problem data.



error correction

- error syndrome detection may dominate energetic costs for some qubit modalities.

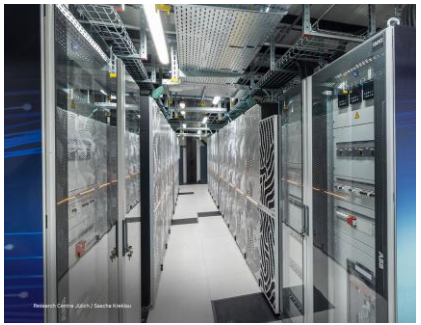
economics

- energy could represent >30% of an FTQC TCO.
- energy = power (infra) × time (user constraints).
- power is a proxy for all environmental footprint.

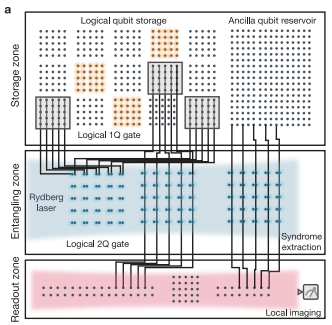
optimization trade-off examples



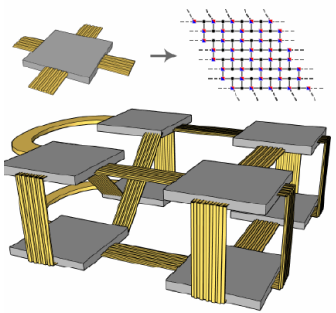
qubit temperature vs **QEC cost**



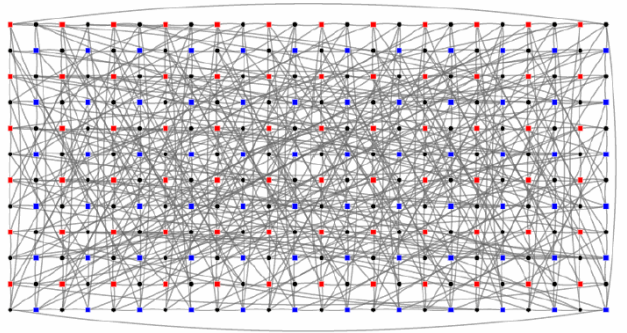
classical cost vs **quantum computing cost**



global driving vs **correlated errors**



scale-in vs **scale-out**



non-local high-rate codes vs **syndrome decoding**

optimization options

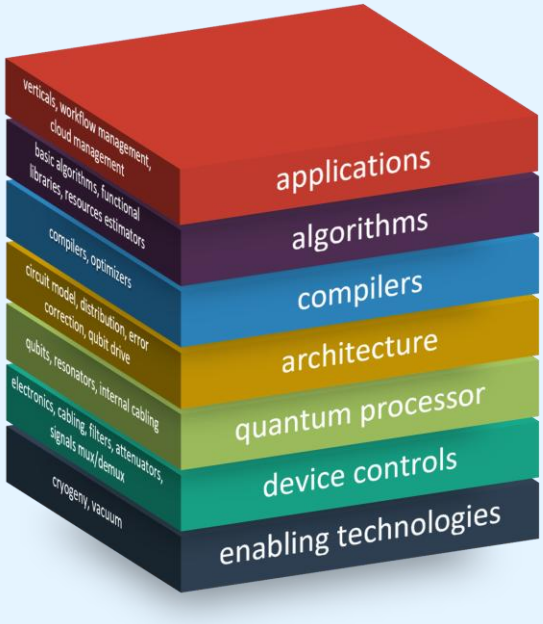
holistic optimizations

reductionist optimizations

- optimize the consumption of individual components in the stack, without introducing more noise on the processor.
- key for enabling technologies.

- interdependent optimizations.
- typically, can involve trade-offs between spending less energy and introducing more noise.
- can be highly counter-intuitive.
- requires a full-stack approach and modelling.

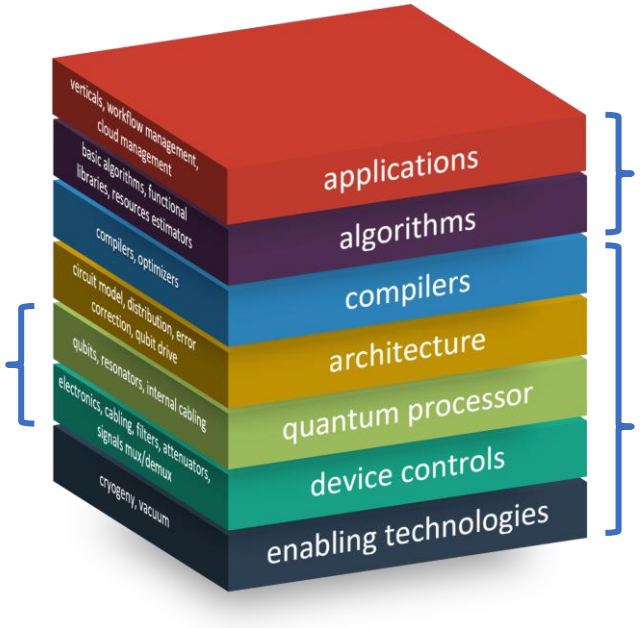
an example of full-stack approach



QECQ project

quantum computing energy efficiency optimization
2024-2028 project funded by Bpifrance i-demo

- theoretical models.
- fundamental bounds.
- optimization model PRX Quantum 2023.



- define practical industry relevant use cases (materials, PDEs).
- HPC energy consumption comparable references.

- FTQC systems full-stack architecture.
- resource estimations.
- energy footprint optimization.

#QEI the quantum energy initiative

- sharing best practices with the QEI community.
- extending models to other qubit modalities.

Quandela at a glance

35+
years of research

2017
year of incorporation (1st quantum computing startup in France)

5
main locations worldwide : Canada, France, Germany, South Korea, USA

150+
people

50+
people with PhD

Senior scientists:
P. Senellart: Acad. of Science
A. Aspect: Nobel Prize winner

> 40
scientific articles & patents

Lead scientists with:

> 150
scientific articles

> 30 000
citations

Full stack approach

Quandela Cloud

Quantum Algorithms

Open-source prog. framework

Quantum Processors

Hardware Manufacturing



[1] First in the world manufacturing plant (pilot-line) for semiconductor photonic qubit devices | [2] Factory for assembly and test of quantum computers. | [3] www.cloud.quandela.com

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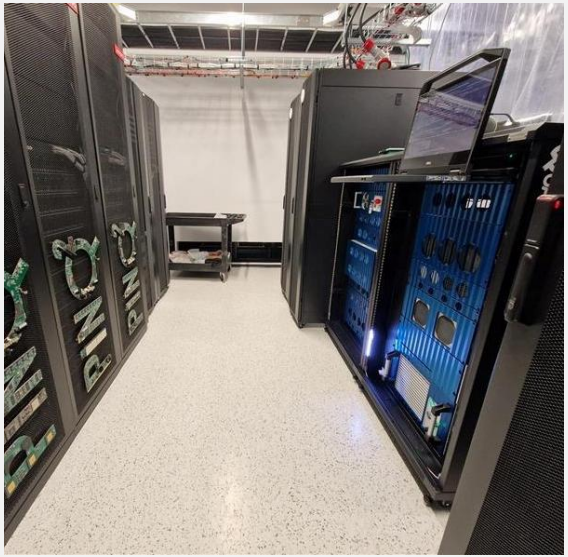
we deliver HPC-ready Quantum Processor Units (QPU)



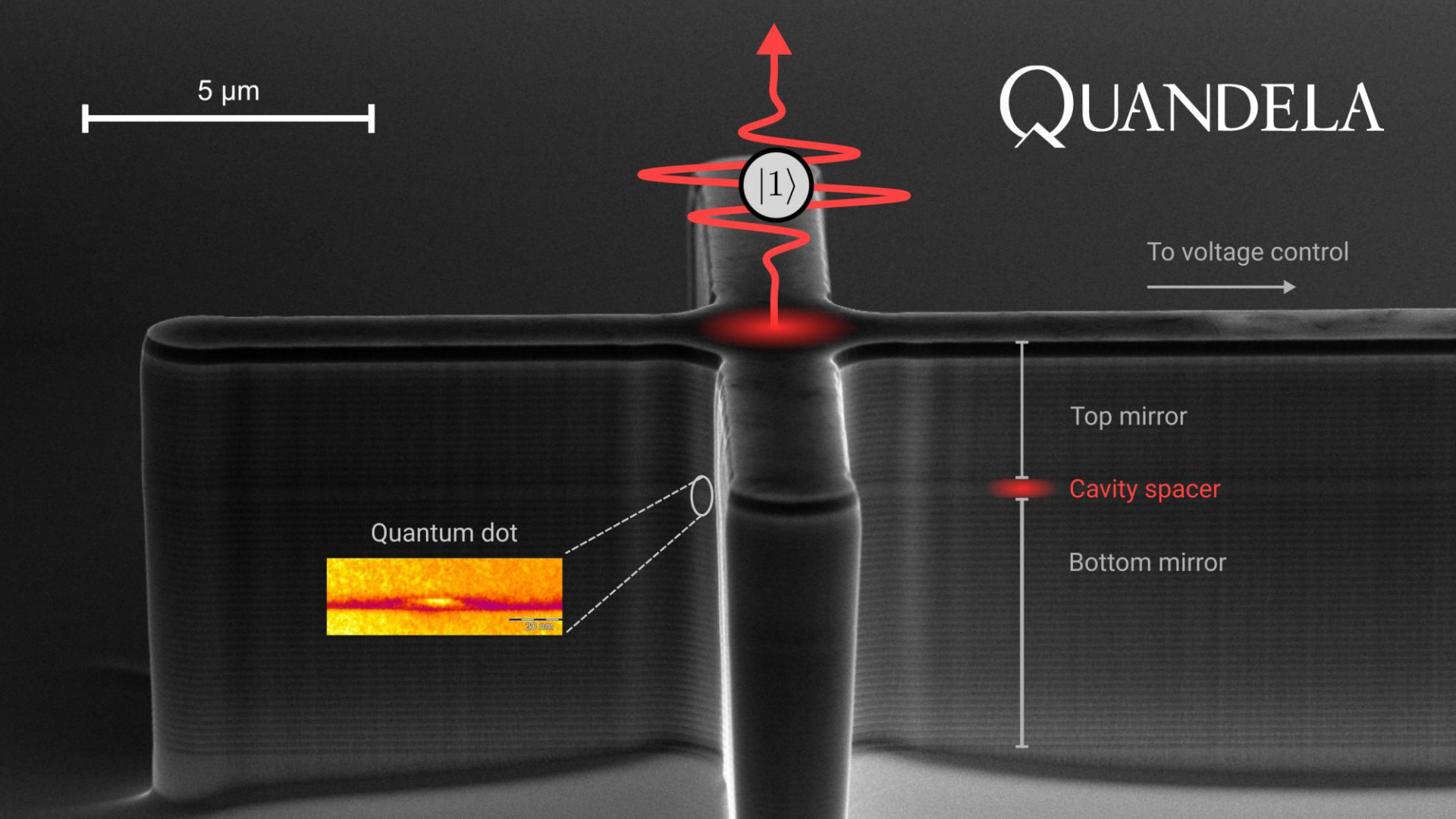
QPU installed at OVH-Cloud data-center in 2023 (France)



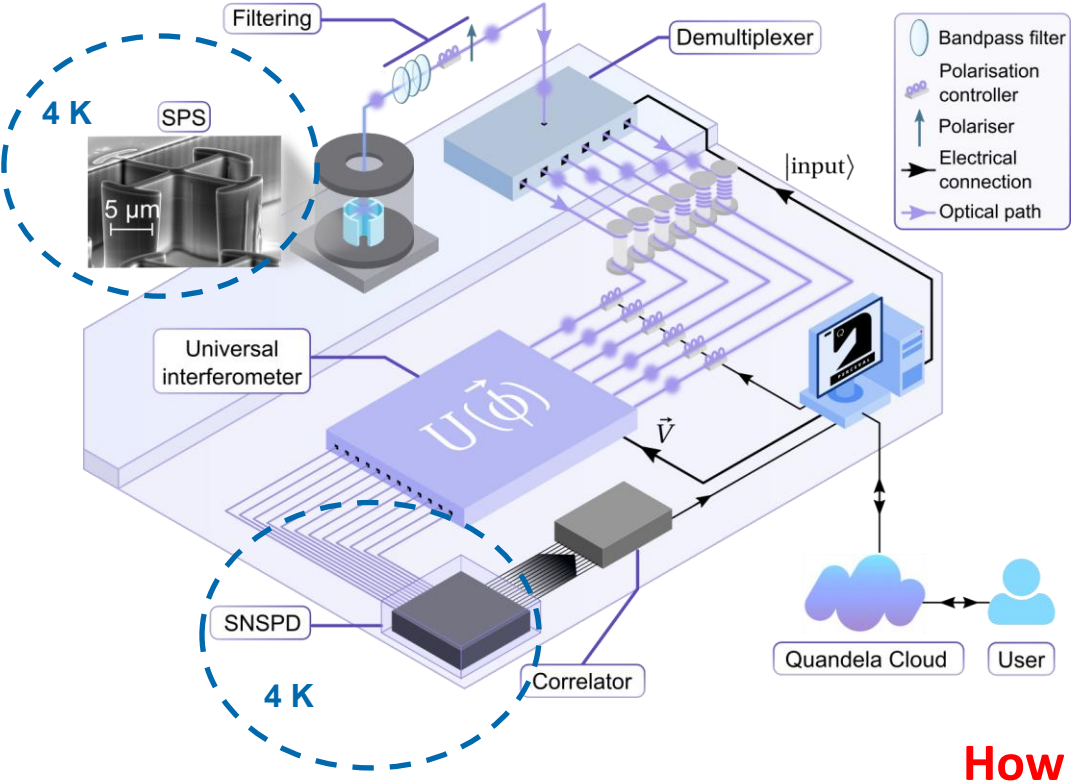
QPU integrated at Exaion's datacenter in Sherbrooke (Canada) in 2025



Deployed in October 2025 at TGCC (France) and operated by CEA, Lucy is the most powerful universal photonic quantum computer available in Europe.


5 µm
QUANDELA
|1⟩
To voltage control
Top mirror
Cavity spacer
Bottom mirror
Quantum dot
20 nm

6 photon Quantum Processor



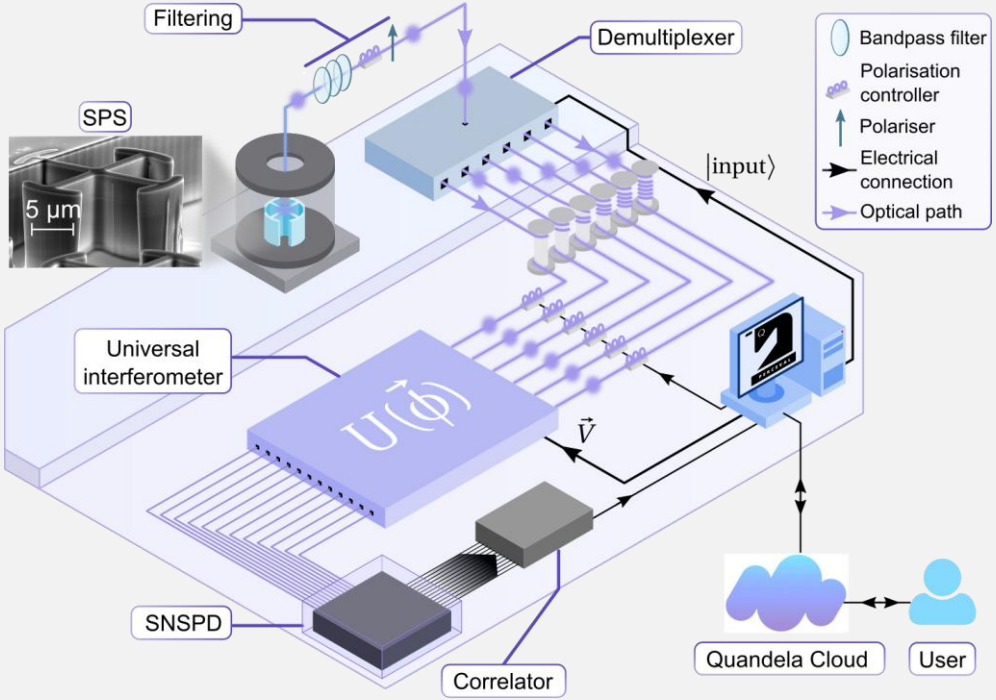
- Single photon source: 4 K
- Circuit (interferometer): room temperature
- Total power: 3 kw

How to keep the energy low scaling up?

18, 603–609 (2024)

methodology: Metric Noise Resource

Fellous-Asiani et al., Optimizing Resource Efficiencies in Sacalable Full-Stack Quantum Computers, PRX Quantum

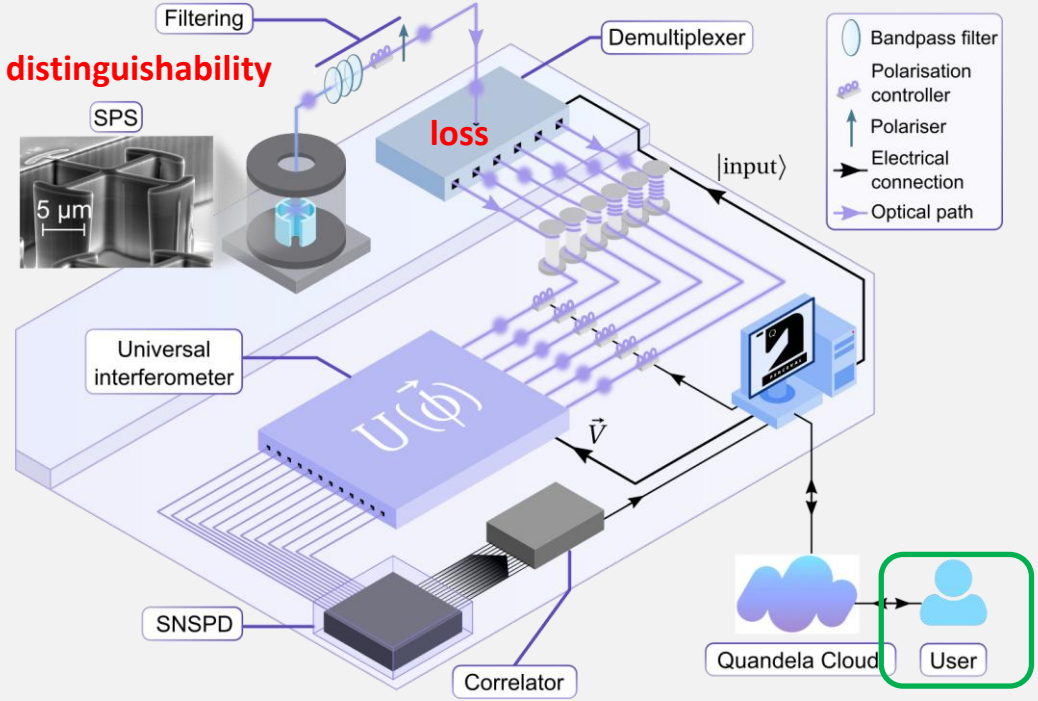


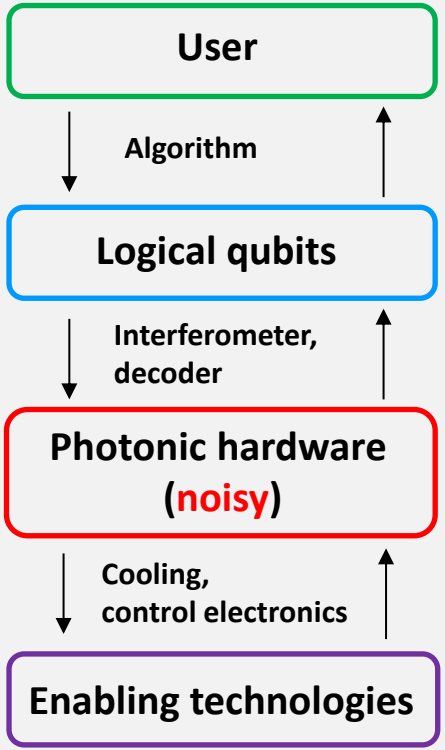
modelize….

Control parameters → equations → Metric, Noise, Resource

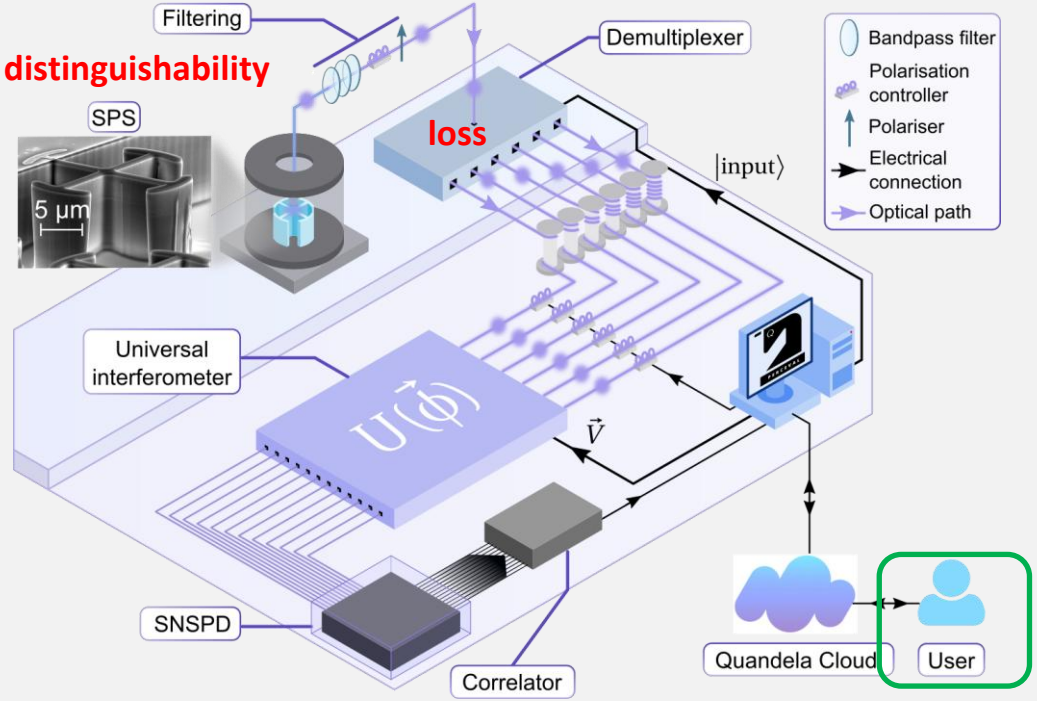
…and optimize

Metric-Noise-Resource for Quandela's QPU





Metric-Noise-Resource for Quandela's QPU



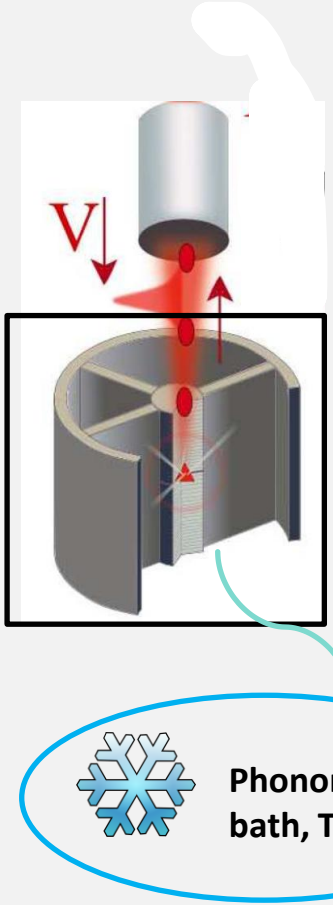
Control parameters: Photon number, Temperature

equation

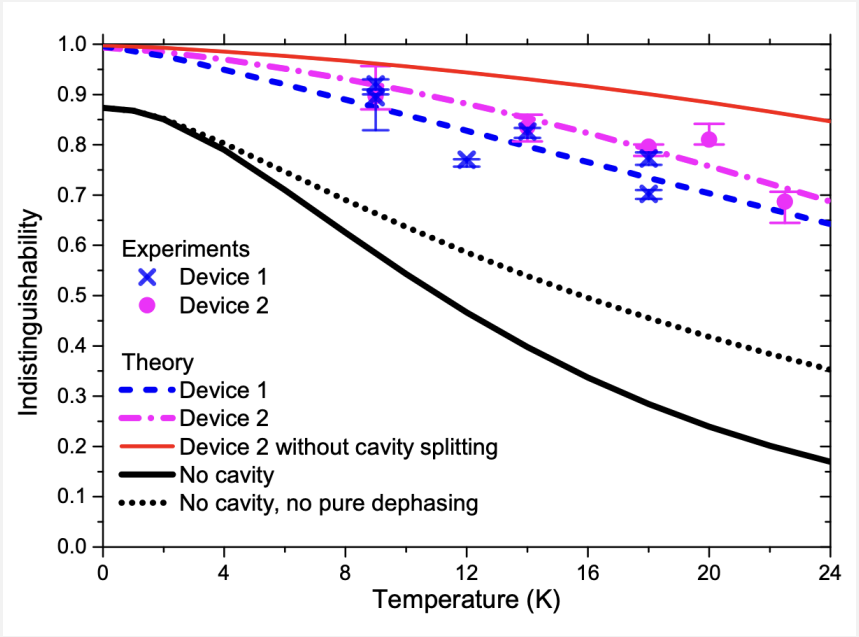
Noise: loss, distinguishability

Resource: cryo power, classical power

photon distinguishability



Distinguishability can be expressed as a function of temperature

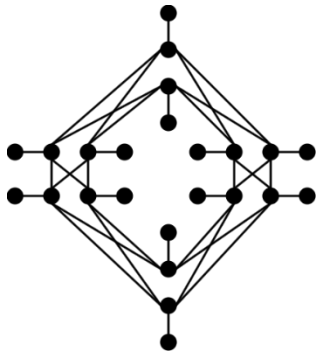


T. Grange et al, doi.org/10.1103/PhysRevLett.118.253602

usecase: Resource State Generation

- **Collaboration between Majulab (Nathan Shettell, Alexia Auffèves, Harshit Verma) and Quandela (AS, Pierre-Emmanuel Emeriau, Katia Hakem, Grégoire de Gliniasty)**

- **Resource state: primitive for fault-tolerant quantum computing, using the fusion based quantum computing scheme [1]**



Resource state (state of light)

Apply fusions and measurements to perform fault tolerant computations

Metric: -log p

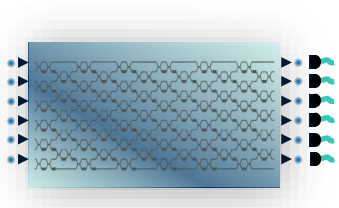
Logical error rate

[1] S. Bartolucci, *et al.* Fusion-based quantum computation. *Nat Commun***14**, 912 (2023

Technological key to Fault Tolerant Quantum Computing

Spin-Optical Architecture

Light-based (Linear Optical Quantum Computing)



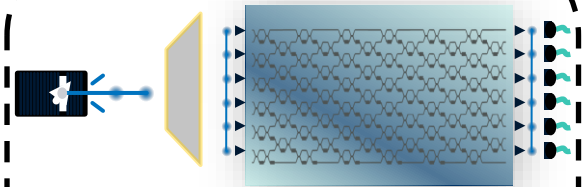
Pros:

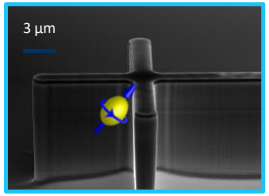
- **Fully modular**
- **Warmer operations**

Cons:

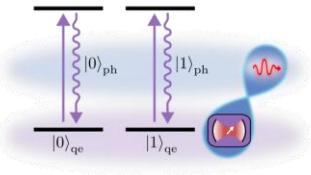
- **Probabilistic operations**
- **Destructive measurements**

Light-matter-based





- ✓ **Fully modular**
- ✓ **Warmer operations**
- ✓ **Deterministic operations**
- ✓ **Non-destructive measurements**



Recent publications: - G. de Gliniasty et al., *A Spin-Optical Quantum Computing Architecture*, Quantum 8, 1423 (2024)
- P. Hilaire et al., Enhanced Fault-tolerance in Photonic Quantum Computing: Floquet Code Outperforms Surface Code in Tailored Architecture, arXiv:2410.07065

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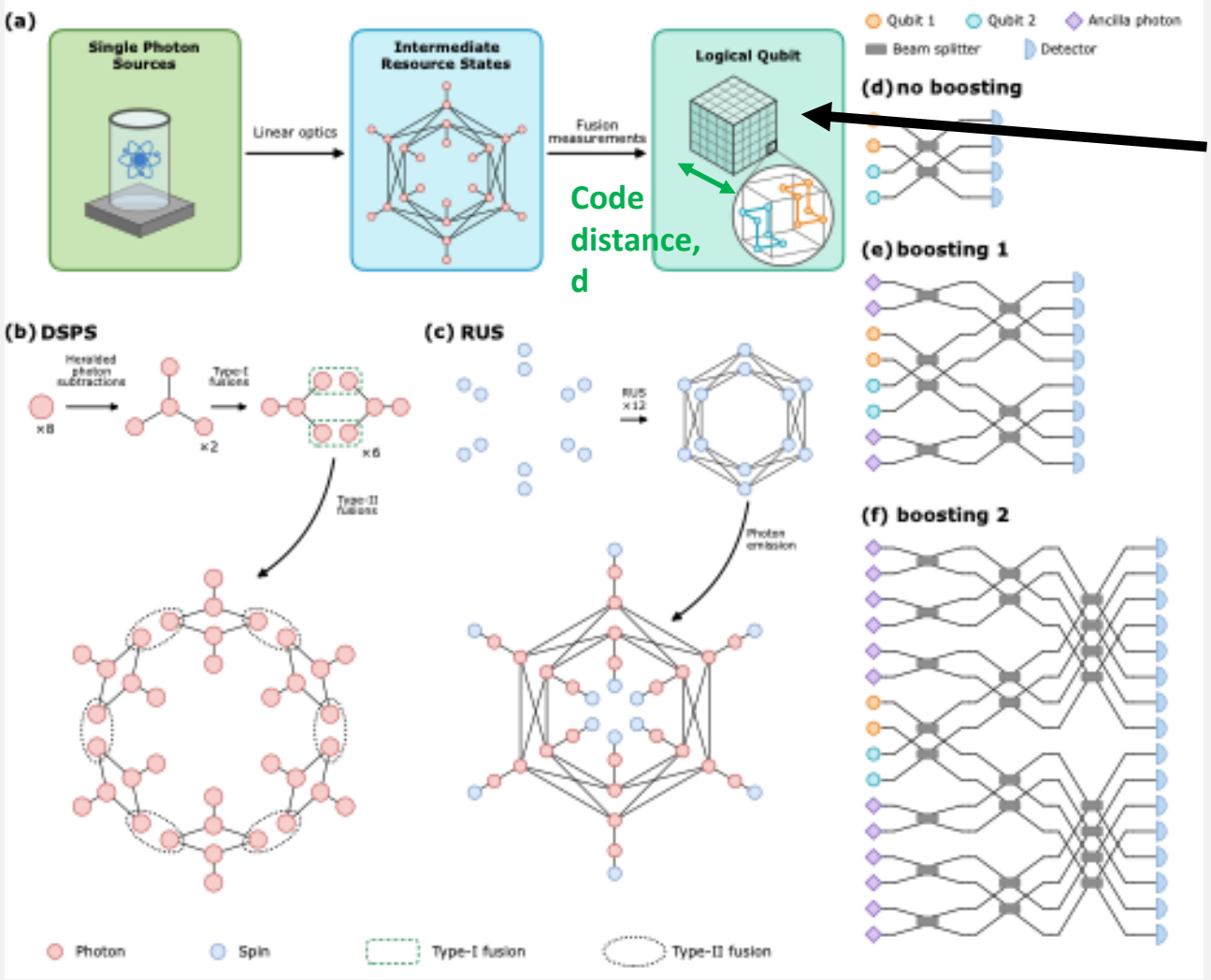
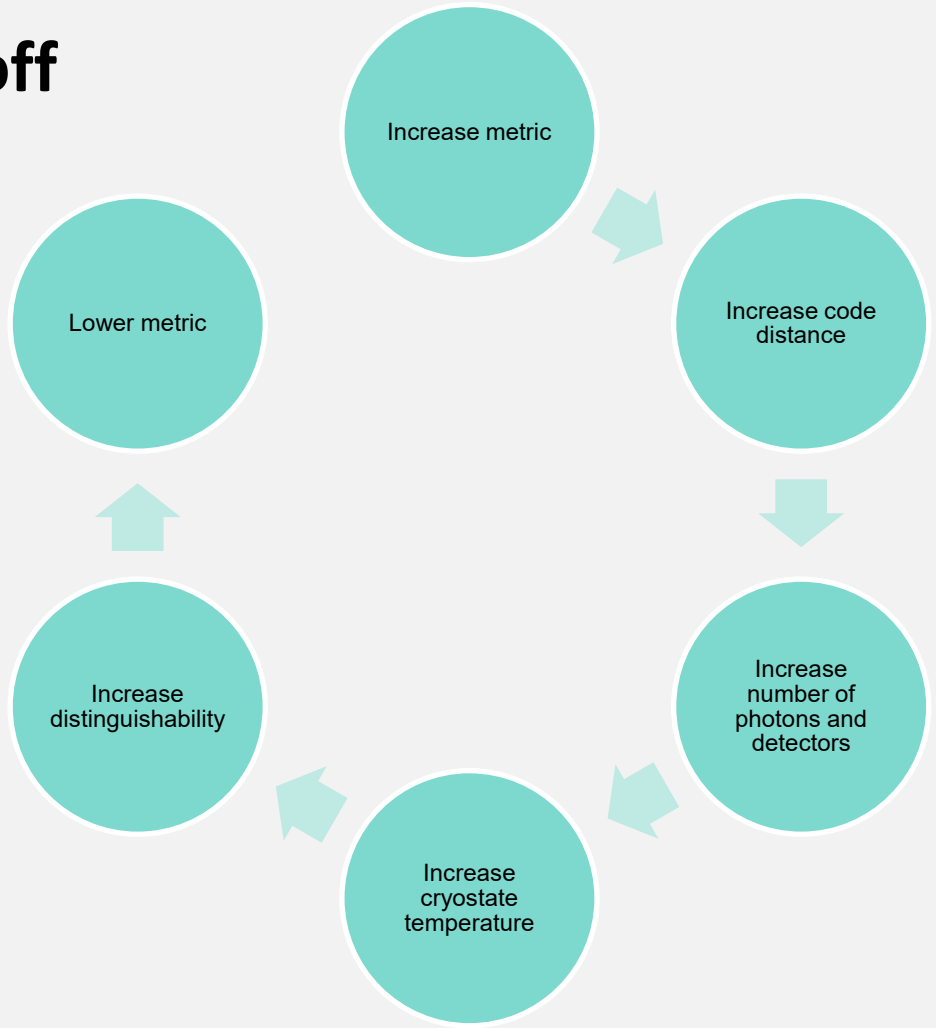
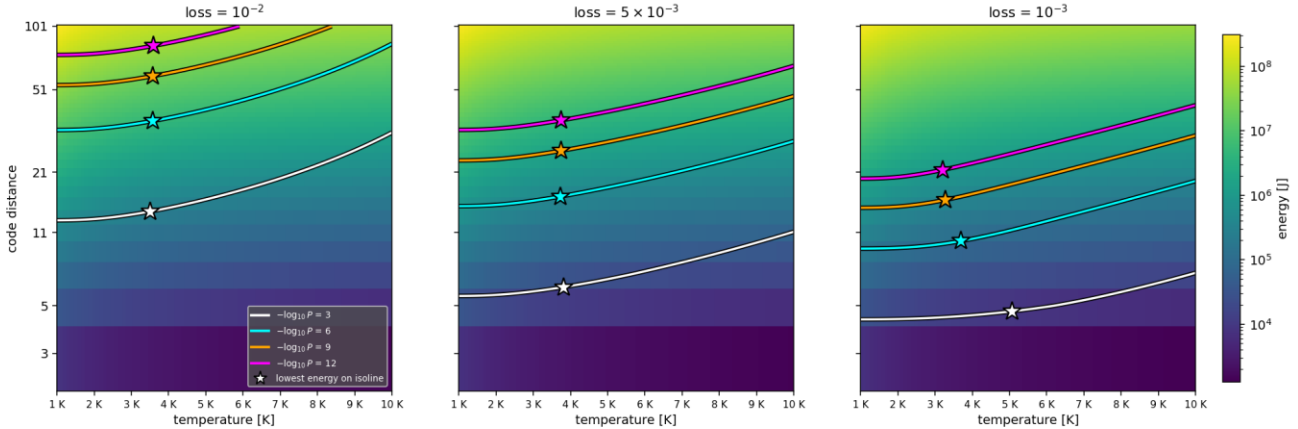


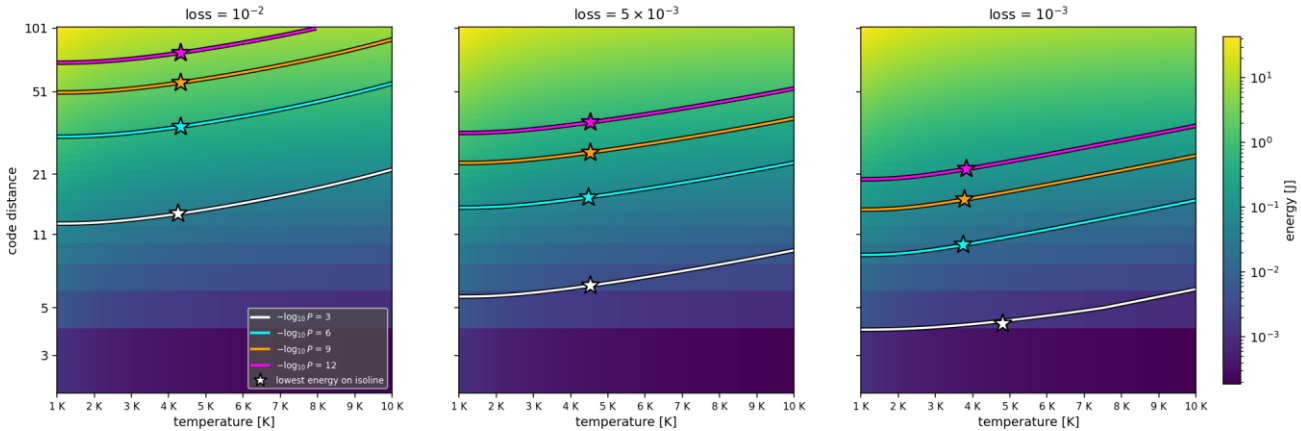
increasing the code distance lowers the logical error rate as long as the noise is below a given threshold

"Energy-Efficient Fault Tolerance in Fusion Based Quantum Computing", N. Shettell et. al, *draft in progress*

Metric/energy tradeoff




[heralded model] Ideal hardware | DSPS | fusion boosting 1, resource boosting 0
energy [J] (colour) and isolines of -log10 P_logical (model); star = lowest energy on each isoline
loss = 10^{-2}
loss = 5×10^{-3}
loss = 10^{-3}
code distance
temperature [K]
energy [J]
$-\log_{10} P = 3$
$-\log_{10} P = 6$
$-\log_{10} P = 9$
$-\log_{10} P = 12$
lowest energy on isoline


[heralded model] Ideal hardware | RUS | fusion boosting 1
energy [J] (colour) and isolines of -log10 P_logical (model); star = lowest energy on each isoline
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loss = 10^{-3}
code distance
temperature [K]
energy [J]
$-\log_{10} P = 3$
$-\log_{10} P = 6$
$-\log_{10} P = 9$
$-\log_{10} P = 12$
lowest energy on isoline

takeaways

- **full stack optimization** rather than part by part.
- **interdisciplinarity**: algorithm, quantum thermos, engineering.
- energy efficiency is a **performance metric**, complementary to computing speed and accuracy.

the quantum
computing
energetics
ecosystem



#QEI

the quantum energy initiative

quantum-energy-initiative.org/





QEI 2025 (Grenoble) and 2026 (Barcelona)

why

- ICT energy consumption is growing fast.
- most quantum technologies will add an incremental energetic cost to existing ICT.
- it is time to work on this as quantum technologies and applications are designed.
- responsible innovation imperative.

what

- build a **new** science and engineering field.
- create full-stack methodologies and standards to **evaluate**, **optimize**, and **benchmark** quantum technologies energy consumption.
- favor integrative **full-stack approaches**.

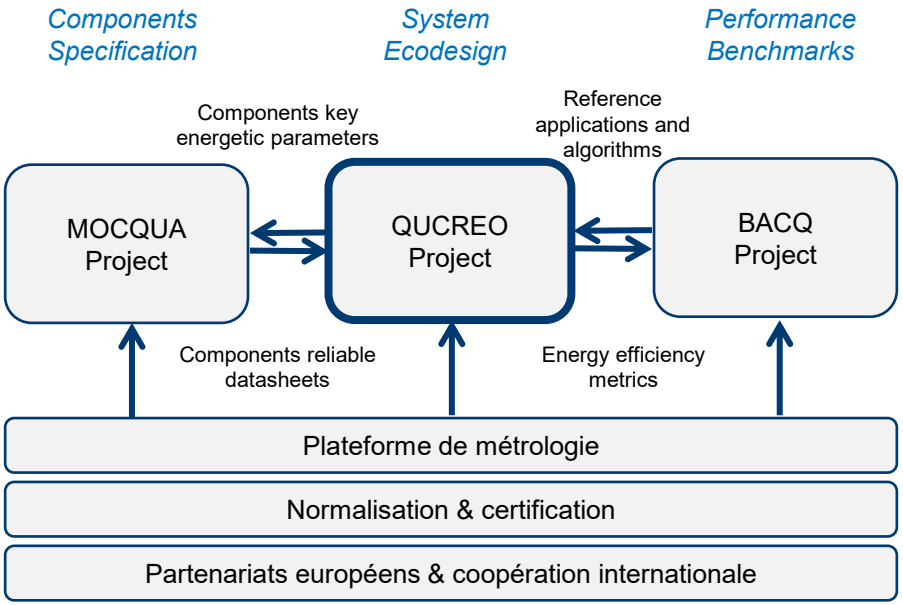
how

- QEI scientific board (10).
- QEI community (545 participants from 67 countries) *.
- QEI workshops (2023 in Singapore, 2025 in Grenoble, 2026 in Barcelona, 2027 in Lisbon).
- QEI IEEE standards Workgroup.
- ≈30 industry partners including IBM, Quandela, etc.

* : as of September 28th, 2026

QuCREO project

- creating a digital model for evaluating and optimizing the FTQC systems resource consumption including energy.
- will be open source, modular and support multiple qubit modalities.
- will enable composability.
- part of MetriQs II, the France national program on measurement, evaluation and standardization of quantum technologies.



MOCQUA – Metrological characterization of HW components for quantum computers
QUCREO – Resource estimation and optimization for quantum computing
BACQ – Application-oriented benchmarks for quantum computers

European Innovation Council

EIC Pathfinder Challenge call on quantum technologies energetics.

project grants up to 4M€ with up to 6-9 selected projects.

covers quantum computing, sensing and communications.

grants for fundamental and early-stage research (TRL 1 to 4).

proposal submissions by: September 29th, 2027.

https://eic.ec.europa.eu/eic-funding-opportunities/eic-pathfinder/eic-pathfinder-challenges-2027/quantum-energetics_en

An official website of the European Union How do you know?

European Innovation Council

Quantum Energetics

Page contents

Background and scope
Specific objectives
Expected Outcomes and Impacts
Portfolio approach and activities
EIC Work Programme 2027
How to apply

Background and scope

Quantum technologies hold the promise of transforming various sectors by, for example, delivering step changes in data processing capabilities, enhancing the security of communication, and through higher sensing capabilities. This promise has attracted significant public and private investments across the globe. However, large scale deployment may come with a significant energy and environmental footprint. Energy efficient quantum technology will bring a competitive advantage, and to develop this, key questions are how energy consumption scales with system size; what is the dependence on performance and the underlying technology; how does it compare to classical counterparts.

In full-stack quantum computers including qubits, error correction, control electronics, cooling systems, and supporting infrastructure energy usage differs fundamentally from current systems. For example, in superconducting systems, most of the energy is spent on maintaining the operating environment and not on the computation itself; the balance differs markedly across platforms. Superconducting quantum computers must operate at temperatures close to absolute zero. Their cooling systems, known as dilution refrigerators,

quantum energetics constituents



#QEI
the quantum energy initiative

building the quantum energetics community

IEEE

standardizing energetic costs inventory vs success metrics

academics, industry vendors & users

European Innovation Council

Quantum Act
FTQC calls

GDR TUNIQC

"Thermodynamics and Control at Ultimate Scales" academic community

QuCREO

QECQ

BACQ
MetriQs-France

algorithm resource estimates and benchmarking

models and optimizations

QuIC

discussion



get the slides, now!