Q2B

the energetics challenges of FTQC

#QEI
the quantum energy initiative

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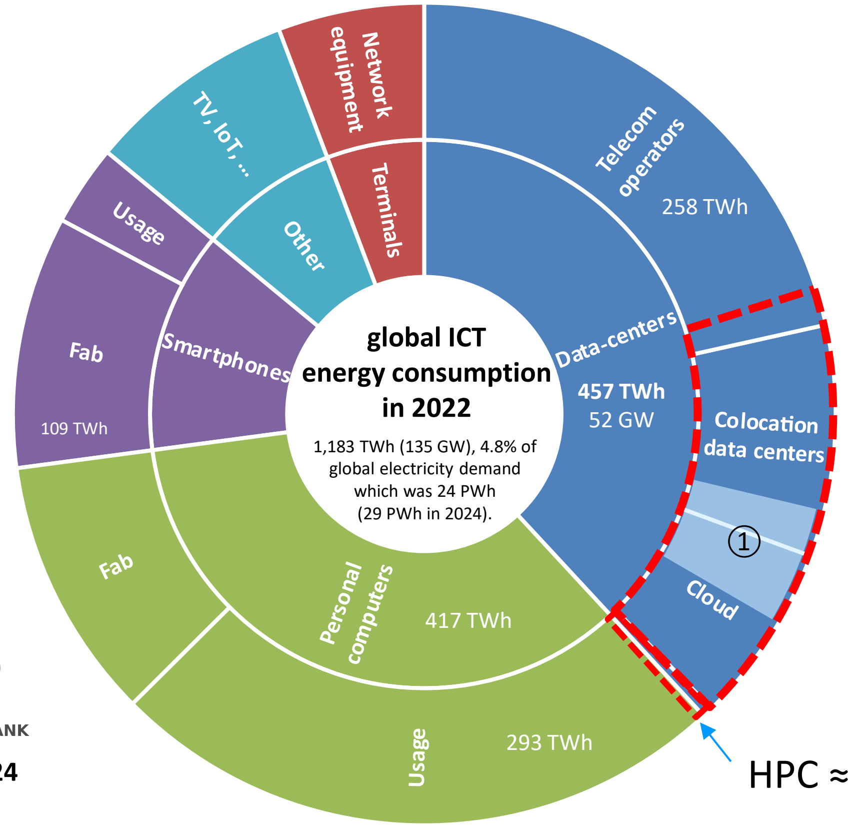
Q2B, Santa Clara, December 9th, 2025

sizing QCs potential energetic impact



HPC ≈ 0.4%

THE WORLD BANK

March 2024 report

① ≈ 63 TWh and ≈ 7.2 GW
for Google, Microsoft and Meta

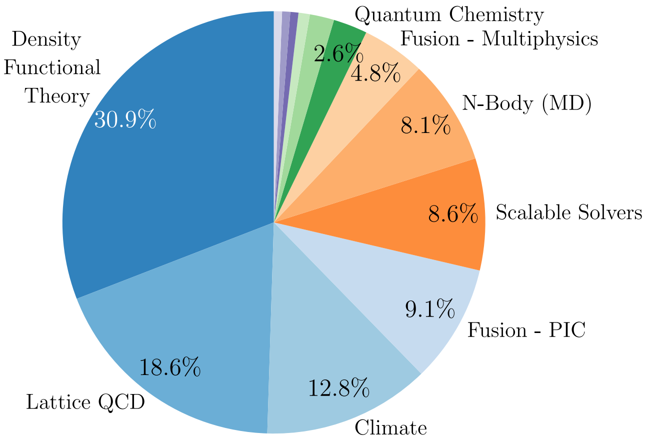
ICT electricity consumption growth driven by AI data centers.

quantum computing energetic footprint base references

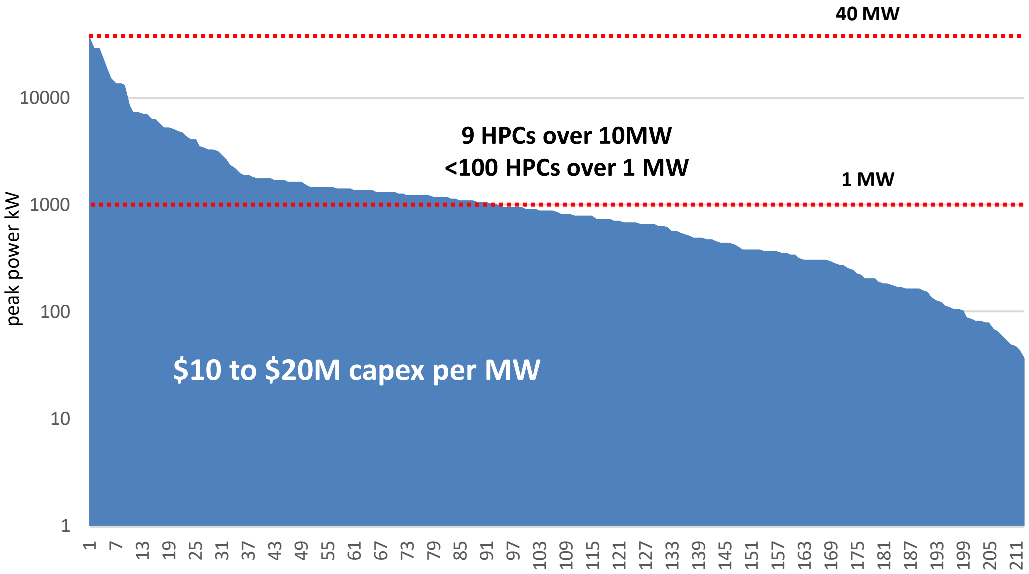
with business operations applications (larger base)

with fundamental and applied research applications (smaller base)

current largest HPCs power consumption



classical applications run on
DoE supercomputers. Source: NERSC.
https://arxiv.org/abs/2509.09882



distribution of the top documented 211 HPC peak power in the TOP500 as of June 2025

HPC market drivers assumptions

usage and value
scientific computing and ML

funding
majority of academic research public investments

systems capex and opex
energy opex ≈ annualized capex

why

- ICT energy consumption is growing in an uncontrolled way.
- energetics are usually an afterthought, like with LLMs.
- it's time to work on this as quantum technologies are being designed.

Perspective

PRX QUANTUM **3**, 020101 (2022)

Quantum Technologies Need a Quantum Energy Initiative

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(Received 18 November 2021; revised 11 April 2022; published 1 June 2022)

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

#QEI

the quantum energy initiative

what

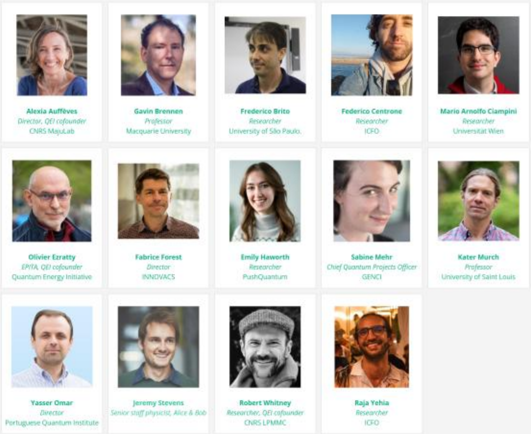
- build new science and engineering.
- create full-stack methodologies to evaluate, optimize, and benchmark QT energy consumption.

where

- academic and industry QEI workshops: Singapore (2023), Grenoble (2025), Barcelona (2026).
- APS 2025, ICQE 2025, France Singapore Symposium (Paris, 2025), Q2B Paris and Santa Clara (2025).
- online seminars, website.

who

- 4 cofounders.
- 14 scientific board members.



- 500+ community in >90 countries.
- >30 industry and academic partners.

IBM, Quandela, quobly, Pasqal, IQM, Alice & Bob, diraq, Microsoft, C12, Quantum Brilliance, Qilimanjaro Quantum Tech, Vigthor, Radiall, Atem, river lane, aQuantum Software Engineering, parityqc, KIPU Quantum, Eviden an atos business, BTQ, OVHcloud, nami

how

first methodology (2023)

PRX QUANTUM 4, 040319 (2023)

Optimizing Resource Efficiencies for Scalable Full-Stack Quantum Computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3,4] Yvain Thonnart,[5] Hui Khoon Ng,[6,3,7,†]
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(Received 29 November 2022; accepted 31 July 2023; published 30 October 2023)

OECQ flagship project with EDF, Quandela, Alice&Bob, and CNRS (2023-*)

Accueil > Actualité

Lancement du projet "Optimisation Énergétique des Circuits Quantiques", avec le CNRS, EDF, Quandela et Alice & Bob

25 septembre 2024 INNOVATION

putting quantum technologies energetic in the EU Quantum Strategy agenda (ongoing).

EuQIC European Quantum Industry Consortium

#QEI the quantum energy initiative

this talk's focus

FTQC energetics paper (in preparation).

The energetic challenges of fault-tolerant quantum computing

Marco Fellous-Asiani,[1] Pierre-Emmanuel Emeriau,[2] Jeremy Stevens,[3]
Marco Pezzutto,[4,5,6] Yasser Omar,[4,5,6] and Olivier Ezratty[7,8,*]

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IEEE P3329 Quantum Energy Initiative (QEI) Working Group (2023-*)

IEEE

European Commission

QUANTUM EUROPE STRATEGY

July 2025

BACQ benchmarking project (2023-*)

BACQ - Application-oriented Benchmarks for Quantum Computing

Delivering an application-oriented benchmark suite for objective multi-criteria evaluation of quantum computing performance, a key to industrial uses

QEI roadmap (in preparation).

full-stack energetic costs decomposition

ions and neutral atoms | **photons** | **superconducting & spin qubits**

quantum physics & quantum energetics

qubit gates and readout operations

cost of fighting noise with error correction

engineered dissipation

…

classical computing

classical part of quantum algorithms
ansatz preparation, data loading, block encoding, cost function computing, data access, networking, post-processing

code compiling (or minor embedding in analog modes) and **run-time execution drive** (including number of shots)

error syndromes detection and QEC drive (FTQC) and/or **quantum error mitigation & suppression** (NISQ)

electronics and photonics

gate calibration, tuning control electronics

room temperature electronics and controls, including QPU interconnect
FPGA, ASICs, DAC/ADCs, AWG, mixers, tone pulses generation; lasers, SLMs, AODs, CCD and photonic circuits controls

lasers

SLMs, AODs
CCD/CMOS sensors, ion traps

photon sources and detectors

low-temperature active electronics
JPA, TWPA, HEMT, cryo-CMOS, SFQ, mux/demux

low-temperature passive electronics
cables, attenuators, filters

cooling and vacuum

laser cooling (water/air)

dilution cryostat – 15mK to 1K

4K compressor for dilution, vacuum chambers, cryopumps, photon sources, photon detectors

4K compressor cooling (water/air)

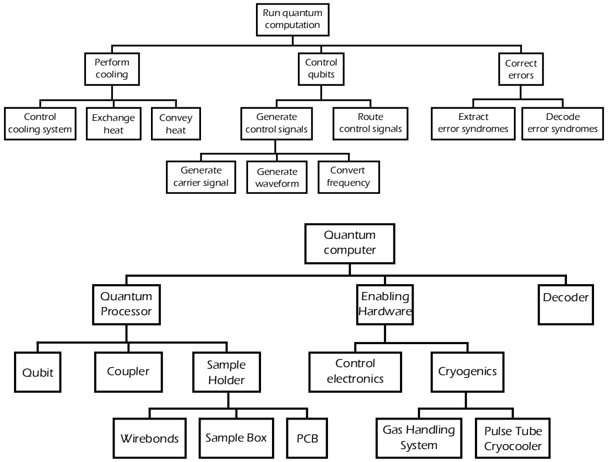
ultra-vacuum pump

vacuum pump

energetic systems architecture approach

1. **functional and product breakdowns** →
2. **estimate baseline resources**
3. **optimize energy efficiency under constraints**
4. **mix reductionist and holistic approaches**
5. **handle operational trade-offs**
6. **measure and benchmark**
7. **integrate an economical view**

detailed in next slide



credit: Jeremy Stevens, Alice&Bob

FTQC energetics paper (in preparation).

The energetic challenges of fault-tolerant quantum computing

Marco Fellous-Asiani,[1] Pierre-Emmanuel Emeriau,[2] Jeremy Stevens,[3] Marco Pezzutto,[4,5,6] Yasser Omar,[4,5,6] and Olivier Ezratty[7,8,*]

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from baseline estimates to optimizations

what

baseline resources

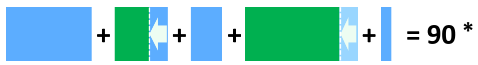
- use state of the art existing technologies.
- adding individual components resources.
- evaluate or measure idle, average and peak power.

examples

- all active components.
- classical computing (circuit preparation, compiler, error correction, post-processing, …).

reductionist optimizations

- account for future enabling technology developments.
- component level optimization.
- doesn't affect other components performance.
- doesn't add more noise.

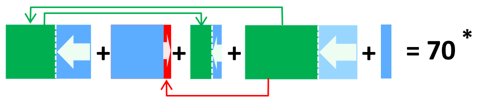


examples

- cryogenics.
- control electronics.
- cable dissipation.
- compiler efficiency.

holistic optimizations

- interdependent optimizations.
- side effects on noise and task success metrics.
- various energy vs computing time or space-time trade-offs.



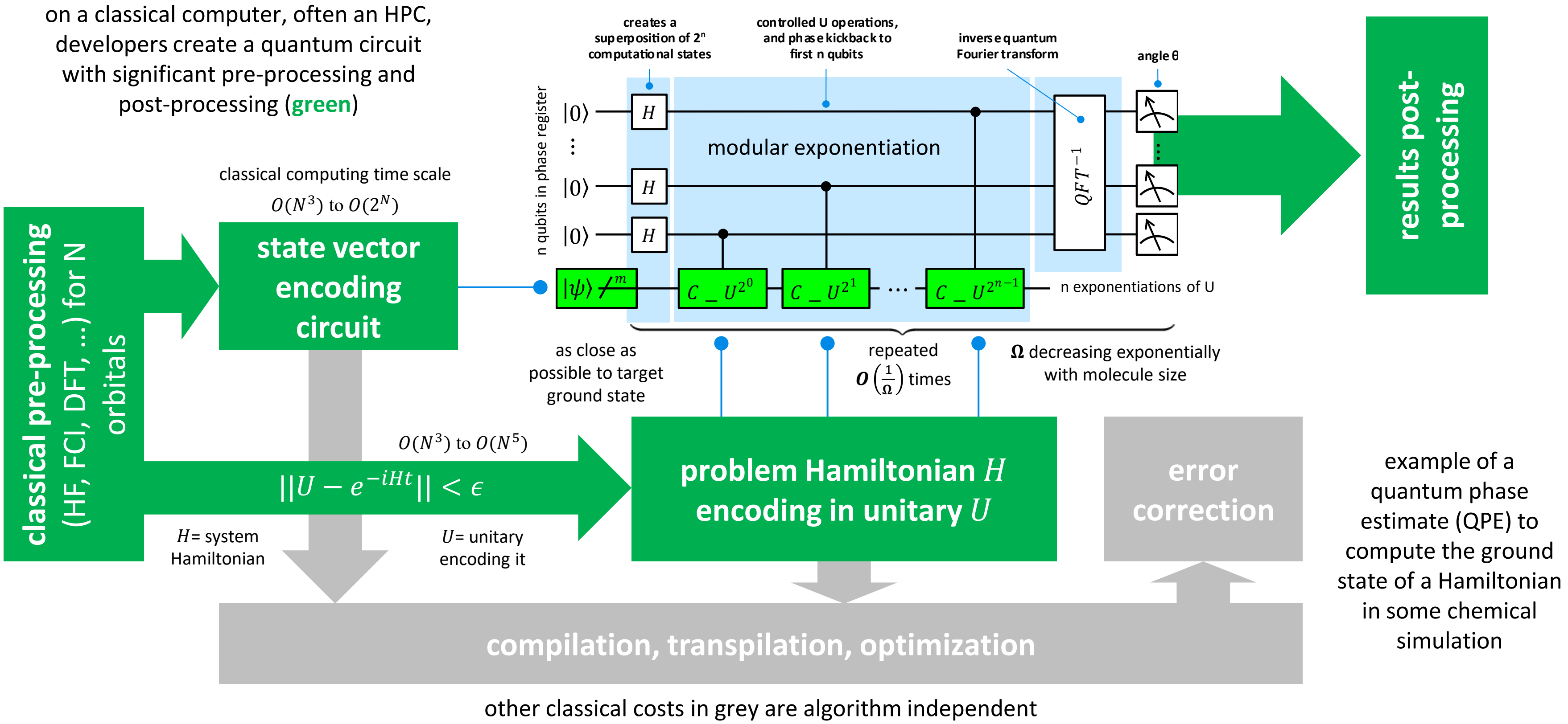
examples

- moving electronics at cryogenic temperatures.
- using SFQ control electronics.
- changing qubit temperature.

system generic (power) or **task dependent with a success metric** (energy)

* % of baseline power or energy, for the sake of demonstration

pre- and post-processing classical costs

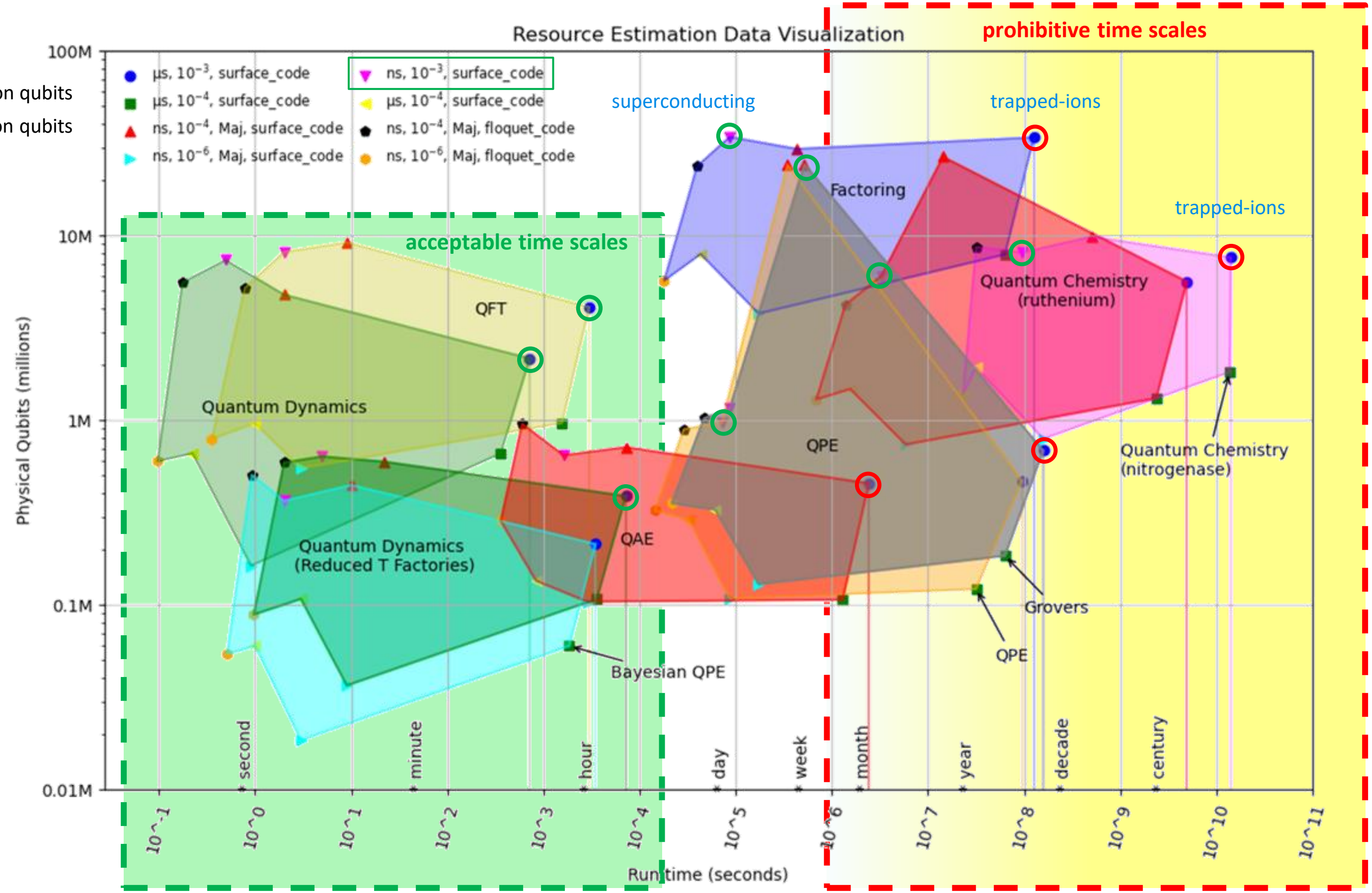


µs gate times: trapped ion qubits

ns gate times: superconducting and silicon qubits

several scenarios are used with different physical qubit error rates and gate times. The realistic ones are with 99.9% fidelities and µs readout cycle times.

one ultimate challenge will be actual computing times!



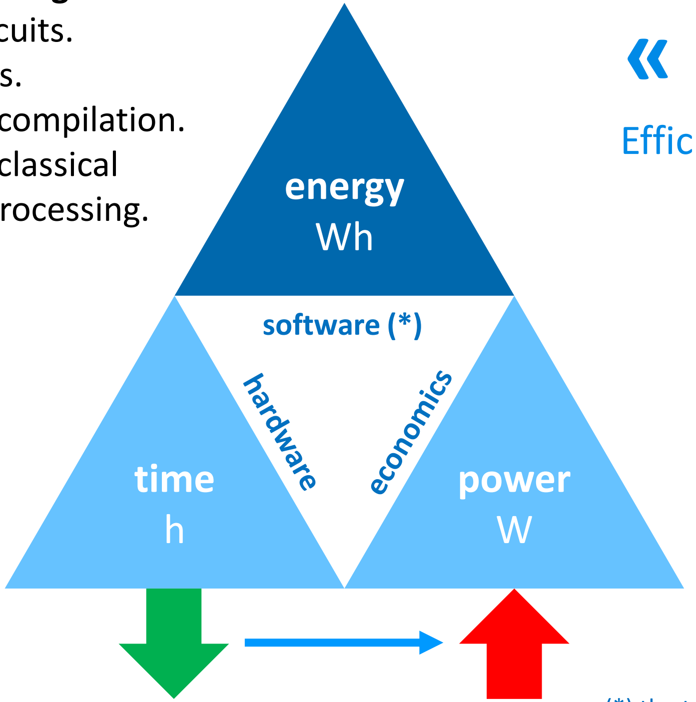
[The GQI Quantum Resource Estimator Playbook - Quantum Computing Report](#)
by Doug Finke, Quantum Computing Report, August 2024.

computing time optimization options

more Efficient algorithms

❶

- smaller circuits.
- fewer shots.
- optimized compilation.
- optimized classical pre/post-processing.



« EFP »

Efficient-Faster-Parallel

Faster computing

❷

- faster gates and readout, constrained by various limitations.
- faster classical-quantum cycles, including QEC, classical-quantum drive efficiencies.

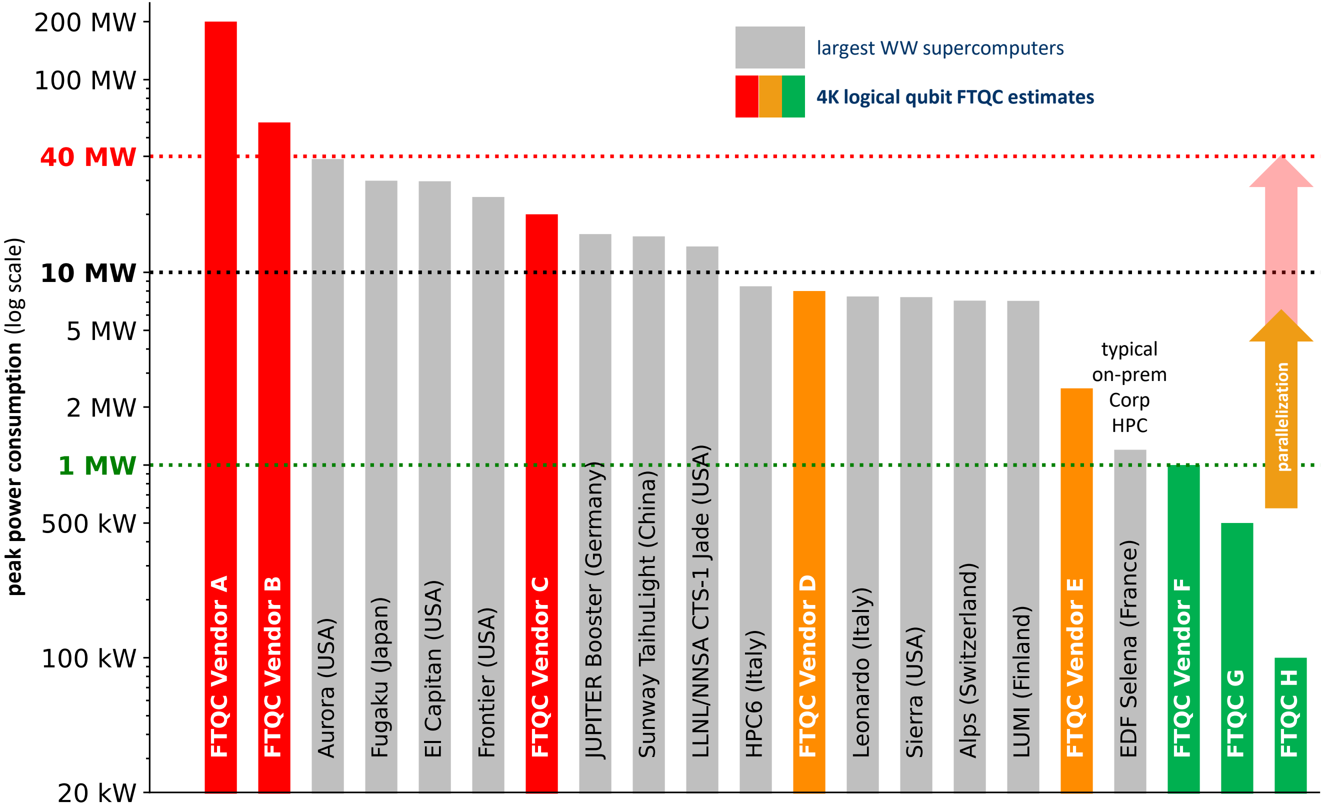
Parallelizing circuit shots on multiple similar QPUs

❸

- affordable FTQC QPUs (cost and total carbon footprint).
- manage pressure on electricity grid.

(*) the total energetic cost of computing depends on other parameters like the cost per physical gate. The EFP framework is focused here on computing time optimization.

FTQC vs HPC power baseline guesstimates



estimate base power for various FTQCs and actual for existing largest HPCs WW. HPC source: https://www.top500.org/lists/top500/2025/11/.
FTQC sources: official and unofficial vendor data, estimates with 4K logical qubits and 10^{12} gates support.

FTQC scenarios

<5 — **systems capex and opex**
range similar to largest HPCs

≈10

≈100 — **base scenario**
FTQC and HPC markets similar in size

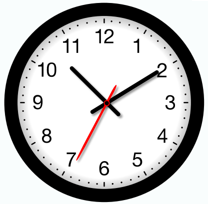
>300 — **optimistic scenario**
broad offering < 1 MW + viable business operations applications

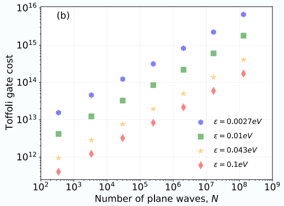
parallelization needs
will need multiple affordable FTQCs working in parallel to support heavy workloads like chemical simulations

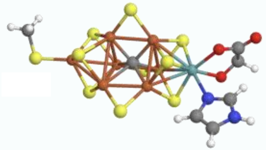
FTQC market in units using HPC comparables

technology and economics interplay

practical benefits



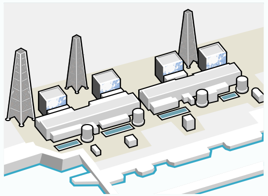




speedup | results quality | required data

total cost of ownership (TCO)

€ $ £



capex + other opex | energy, power

economical benefits (EB)

increased revenue
reduced costs
improved service quality
competitiveness

return on investment (ROI)

$$\mathrm{ROI} = \frac{\mathrm{EB}}{\mathrm{TCO}} \gg 1$$

versatility and platform effects

improves

externalities, including economies of scale

decreases costs

green: technology driven
black: economics driven

discussion

get the slides
now