the energetics challenges of FTQC

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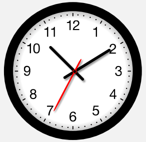
#QEI

the quantum energy initiative

potential quantum computing benefits

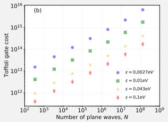


- **computing faster than classical systems.**

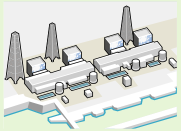
or

- **solving problems inaccessible to classical computers.**

- **reducing required training data**, particularly for machine learning tasks.



- **improving results quality**: chemical accuracy, better heuristics, etc.



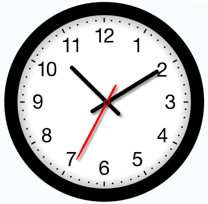
- **energy advantage** (NISQ).

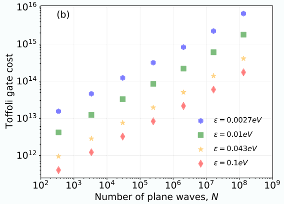
or

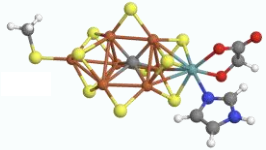
- **energy acceptability** (FTQC).

- **usefulness**: which depends on the stakeholder (fundamental research, governments, industry).

practical benefits



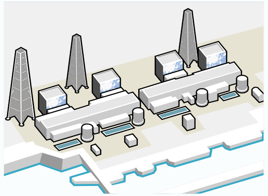




speedup | results quality | required data

costs (TCO)

€ $ £



capex + other opex | **energy, power**

economical benefits (EB)

increased revenue
reduced costs
improved service quality
competitiveness

return on investment (ROI)

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

decreases

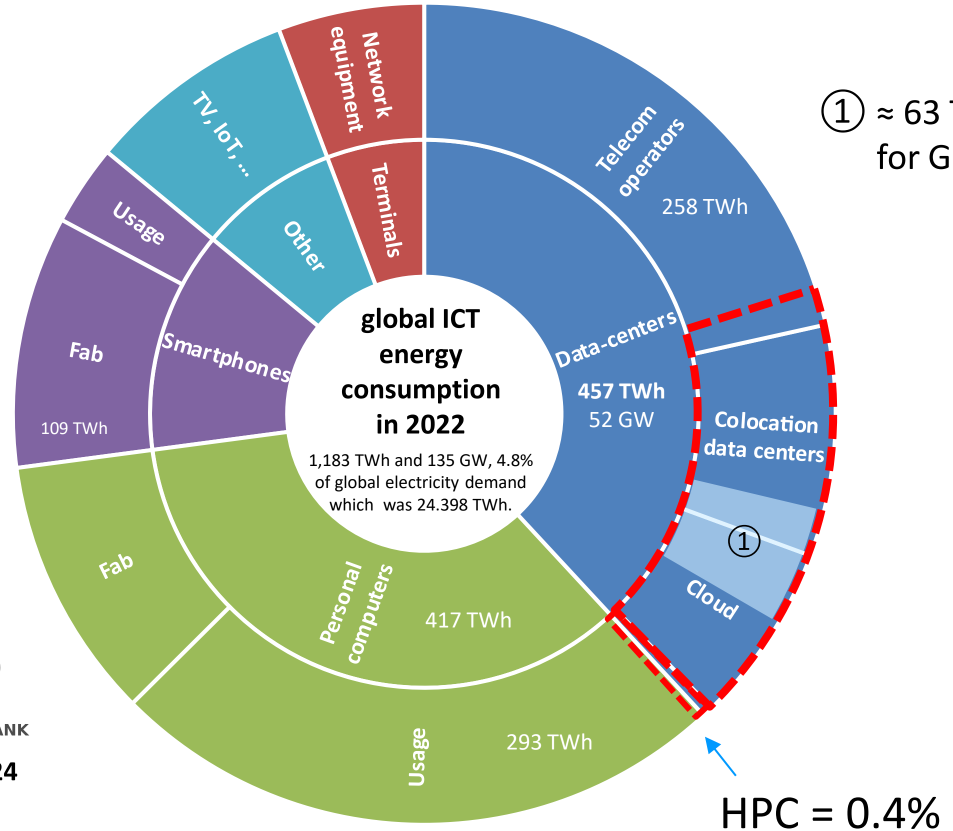
versatility and platform effects

improves

externalities, including economies of scale

TCO = total cost of ownership

sizing QPU's energetic impact…



THE WORLD BANK

March 2024 report

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

quantum computing energetic footprint base references

with business operations applications (larger base)

with fundamental and applied research applications (smaller base)

ions and neutral atoms	photons	superconducting & spin qubits

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)

classical electronics

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

low-temperature passive electronics losses
cables, attenuators, filters

impacts

cooling and vacuum

laser cooling (water/air)

dilution cryostat – 15mK to 1K

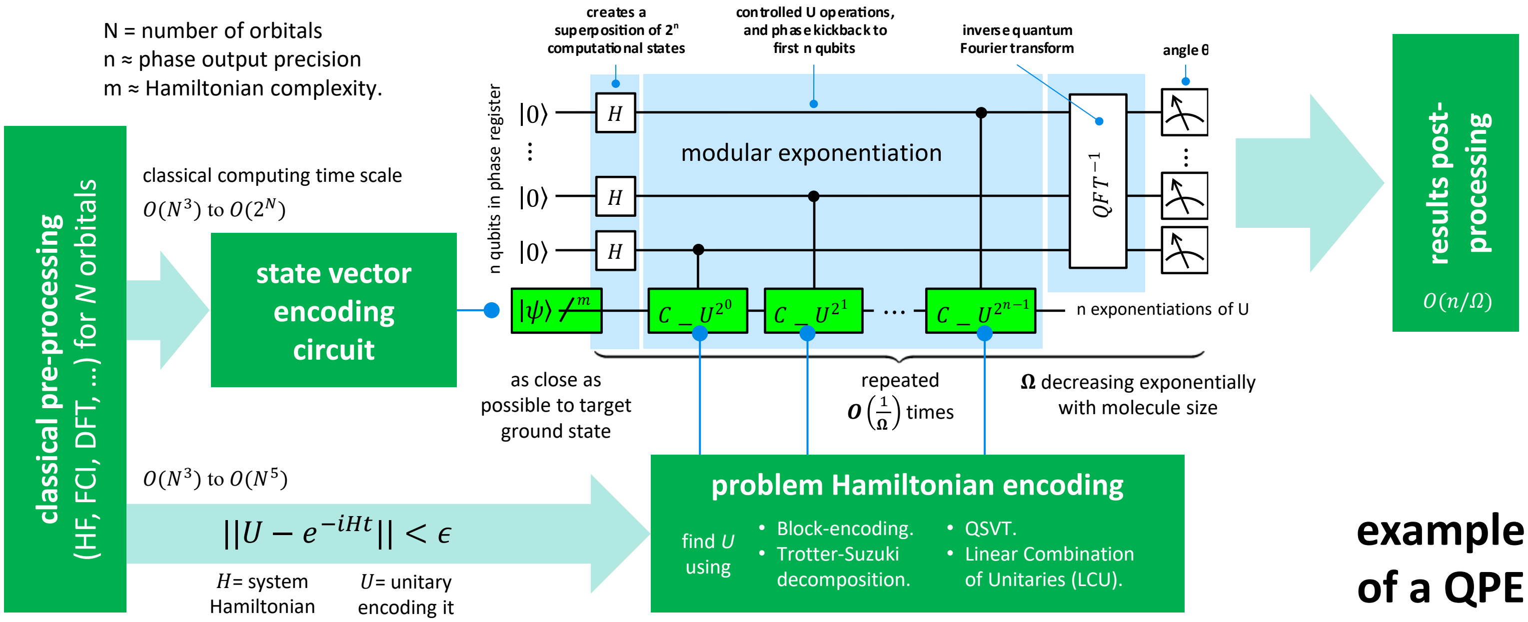
4K compressor for dilution, vacuum chambers, cryopumps, photon sources, photon detectors

4K compressor cooling (water/air)

ultra-vacuum pump

vacuum pump

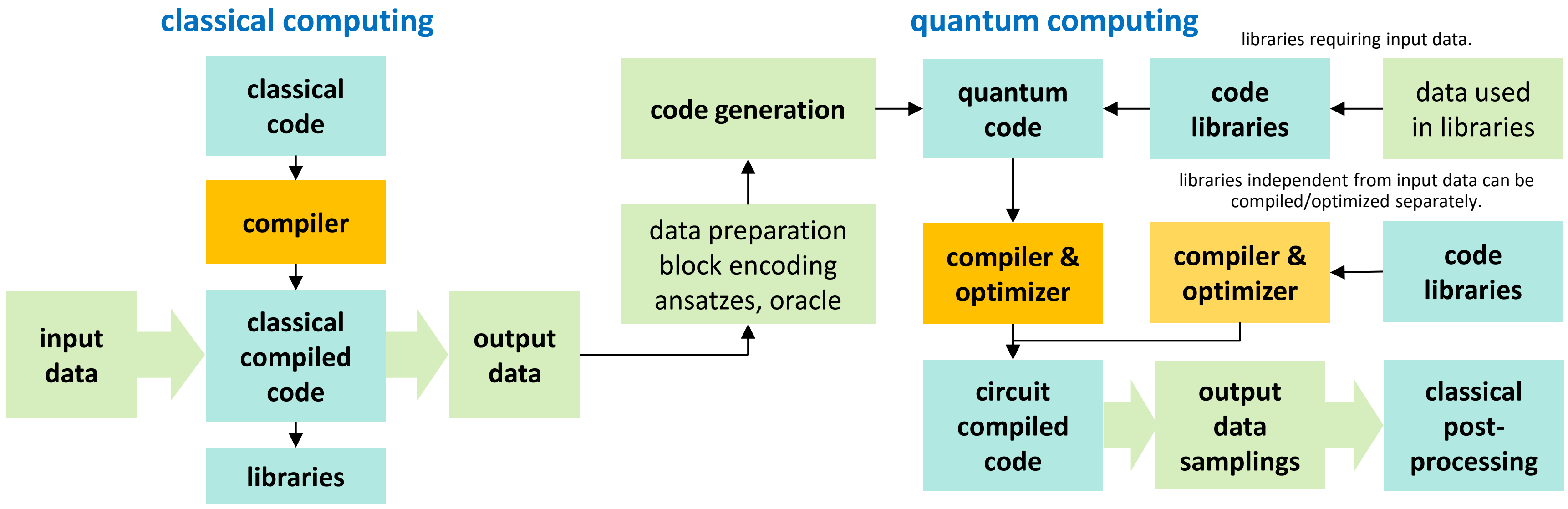
classical costs: **pre- and post-processing**



example of a QPE

inspired by Quantum chemistry, classical heuristics, and quantum advantage by Garnet Kin-Lic Chan, arXiv, July 2024 & On the feasibility of performing quantum chemistry calculations on quantum computers by Thibaud Louvet, Thomas Ayral, and Xavier Waintal, arXiv, June 2023-October 2024.

classical costs: **compilation**

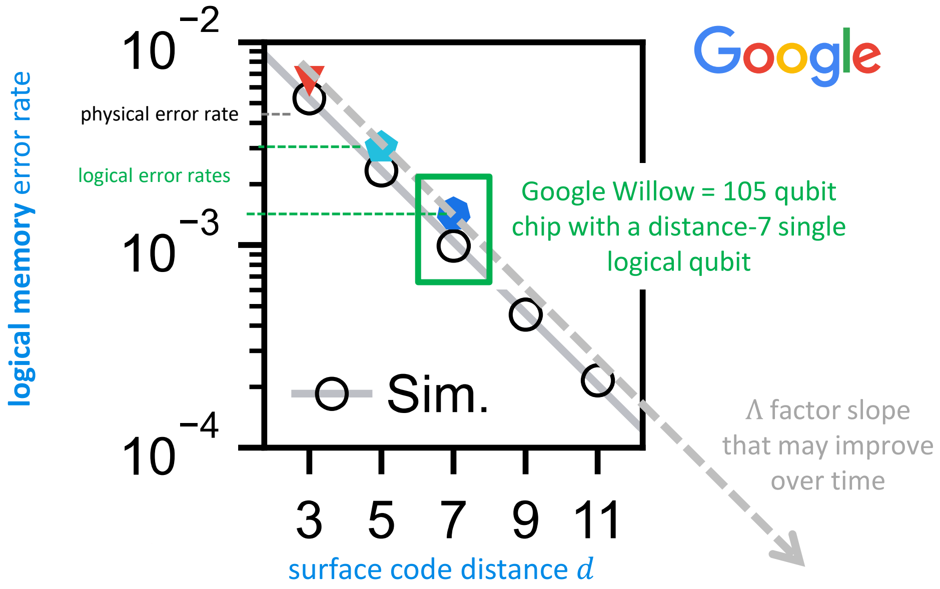


architecture	Von Neuman / Princeton	in-memory processing.
classical compilation cost	fixed cost vs data.	variable cost vs data
libraries & data	used by the compiled code.	embedded *in* circuits/models.
classical data-ingestion	fast.	slow.
compilation	done once.	NP hard circuit optimization.

research & engineering questions:

- compilation cost estimations with large-scale algorithms?
- practical optimization?
- impact on business operations applications with fast duty cycles?

beyond the first breakeven logical qubits



number n_q of physical qubits per logical qubit

$$n_q = 2d^2 - 1$$

[Quantum error correction below the surface code threshold](#) by Rajeev Acharya, Frank Arute, Michel Devoret, Edward Farhi, Craig Gidney, William D. Oliver, Pedram Roushan et al, Google, arXiv, August 2024.

$$\boldsymbol{d} = 2\,\frac{\ln(p_L/A)}{\ln(p/p_{thr})} - 1$$

$$\boldsymbol{N_{phys}} = 2d^2 - 1 \qquad \Lambda = \varepsilon_d/\varepsilon_{d+2} \approx p_{thr}/p$$

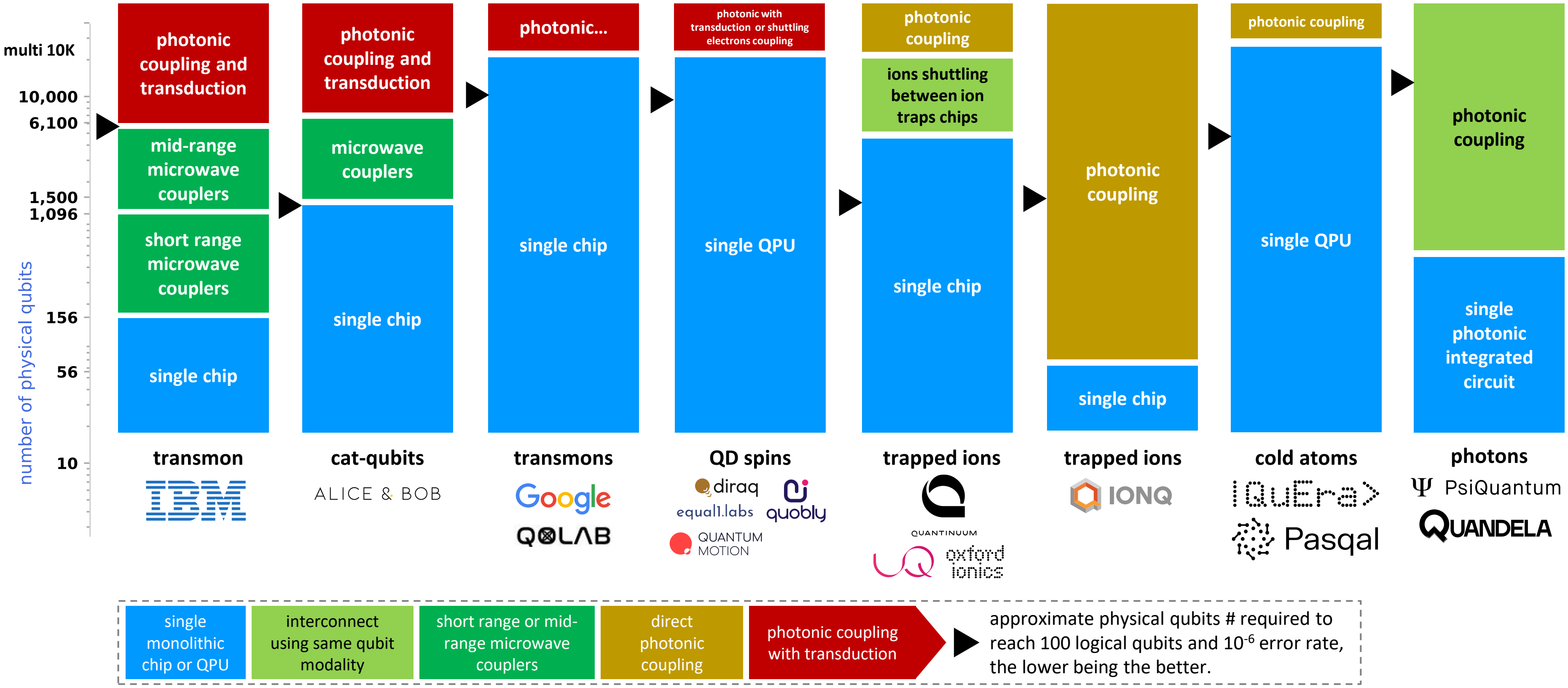
d	=	surface code distance
N_{phys}	=	number of physical qubits
N_{phys}-opt	=	number of physical qubits with optimization
N_{phys}-total	=	number of physical qubits with FTQC
p	=	physical error rate
A	=	between 0.03 and 0.1
p_{thr}	=	threshold error rate
p_L	=	target logical error rate
Λ (lambda)	=	error reduction factor when growing d by 2

p_L	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}
d	27	33	39	45	51	57	63	69
N_{phys}	1,483	2,211	3,082	4,099	5,260	6,565	8,015	9,609
N_{phys}-opt	742	1,106	1,542	2,050	2,630	3,283	4,008	4,805
N_{phys}-total	**1,457**	N/A	N/A	N/A	N/A	N/A	N/A	N/A

10K qubit chips → **QPU interconnect**

extra qubits are needed to perform syndrome extraction, interconnect logical qubits, and support operations like state injection and distillation

multiple QPUs interconnect options



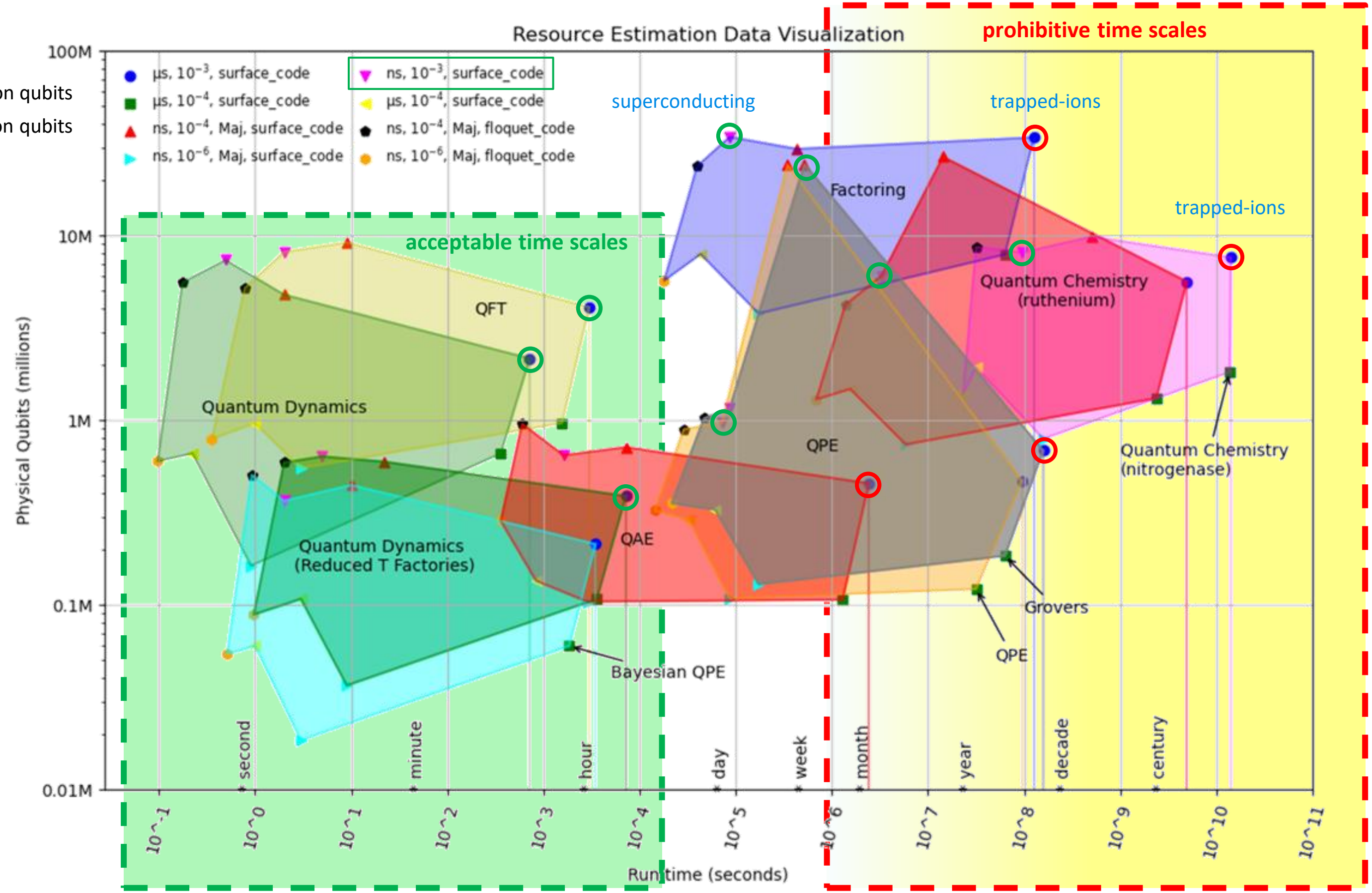
growing complexity with rough estimates thresholds requiring these techniques

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.

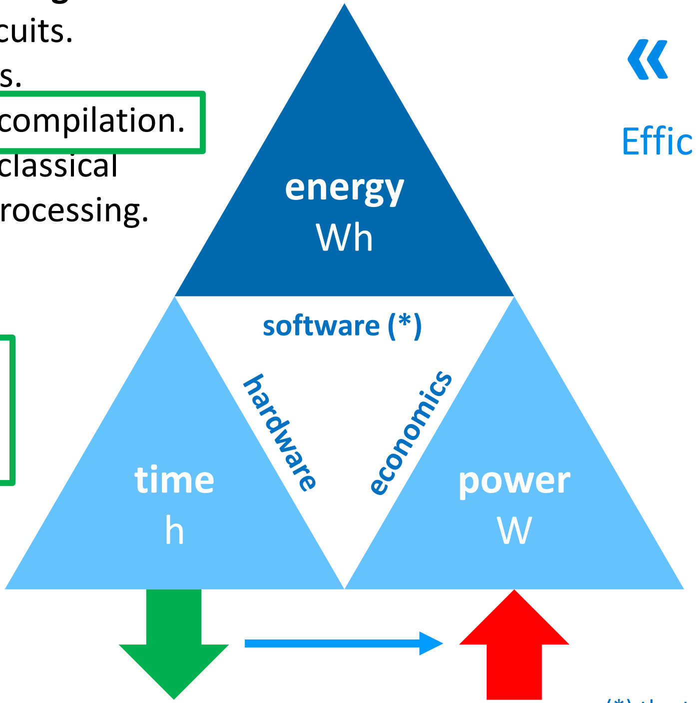
computing time optimization framework

« EFP »

Efficient-Faster-Parallel

❶ **more Efficient algorithms**

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



❷ **Faster computing**

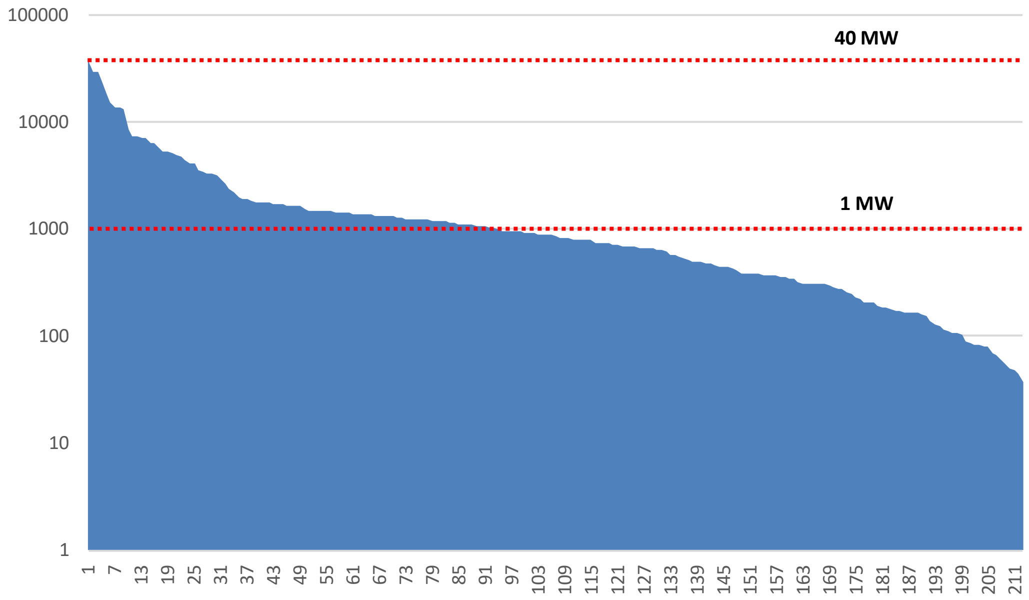
- faster gates and readout, constrained by various limitations.
- faster classical-quantum cycles, including QEC, classical-quantum drive efficiencies.

❸ **Parallelizing circuit shots on multiple similar QPUs**

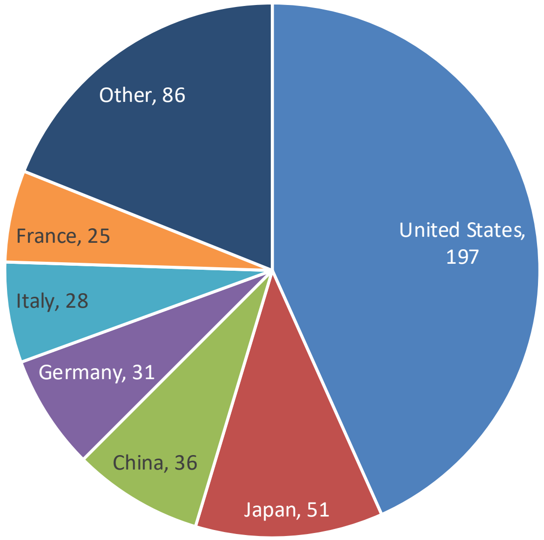
- affordable FTQC QPUs (cost and total carbon footprint).
- manage pressure on electricity grid.

(*) 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.

current HPC power consumption

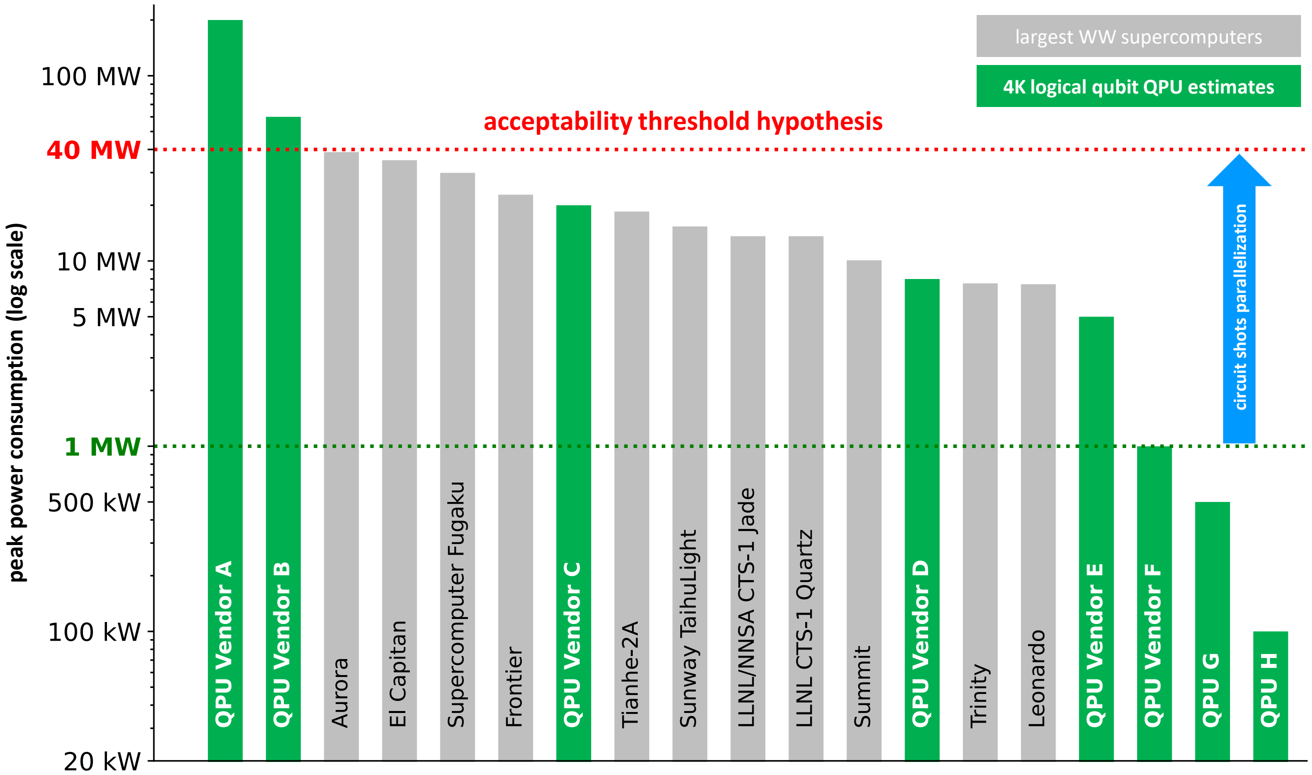


Power consumption distribution of the top documented 211 HPC in the TOP500 as of June 2025



Top500, June 2025
MW in peak power consumption

QPU vs HPC power scale guesstimates



estimate base power for various QPUs and actual for existing largest HPCs WW.
HPC source: https://www.top500.org/lists/top500/2024/06/.

#QEI
the quantum energy initiative

IEEE

IEEE P3329 Quantum Energy Initiative (QEI) Working Group

https://www.youtube.com/watch?v=rUcPLZeZxG0&t=3048s

discussion

get the slides

now