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SÉMINAIRE DEEP TECH

9-10 AVRIL 2024

CHÂTEAU LOUISE DE LA VALLIÈRE
REUGNY, INDRE-ET-LOIRE

LES TECHNOLOGIES QUANTIQUES AU SERVICE DE L'ENVIRONNEMENT

Olivier Ezratty

les technologies quantiques au service de l'environnement

olivier ezratty
⟨ auteur | … ⟩
Tours, 9 avril 2024
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(https://france-science.com)

Adopter l'IA frugale : concepts, leviers et initiatives

septembre 7, 2023

Frugal Machine Learning

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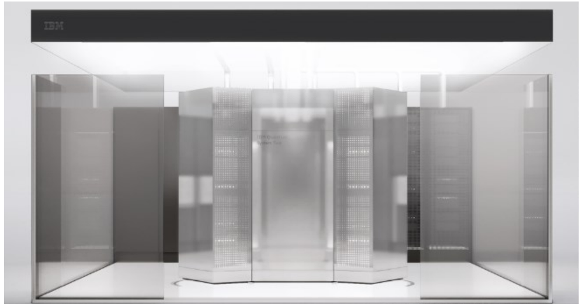
agenda



quantum technology applications

quantum technologies environmental impact

a future conjugated at the present tense

WORLDFUND

DANIJEL VISEVIC · JULY 22, 2022

Why we invested in IQM, the leading European company building superconducting quantum computers to help tackle the climate crisis

Eos

ABOUT SPECIAL REPORTS TOPICS PROJECTS NEWSLETTER SUBMIT TO *EOS*

How Quantum Computing Can Tackle Climate and Energy Challenges

The day is coming when quantum computers, once the stuff of sci problems that are proving intractable to classical computing.

By Annarita Giani and Zachary Goff-Eldredge 21 October 2022

HYUNDAI Brand Journal FIFA World Cup 2022™ Vehicles Company EN

Home > Company > Newsroom

Release 2022.01.19 22:00:00 No. 16785

IonQ and Hyundai Motor Partner To Use Quantum Computing To Advance Effectiveness Of Next-Gen Batteries

Learn to Leap: Green Business Building Edition #4

How quantum computing can help tackle global warming

May 27, 2022 | Interview

Jeremy O'Brien, PsiQuantum CEO

Share Print Download Save

identified case studies

Q4Climate

	Solar energy [11]	Wind energy [12, 13]	Batteries [14]	Industrial processes [15]	Materials for the grid [16]	Synthetic fuels (incl. electrolysis) [17]	CO_2 capture [18, 19]	Atmospheric science [20]	Nuclear power [21]	Structural materials [4]	Biological enzymes [22]	Plastics & circular economy	Agriculture
Gas-phase electronic structure [23]	-	-	-	●	-	●	●	●	-	-	-	•	●
Molecular dynamics [24]	-	-	•	●	-	●	●	●	-	-	●	•	•
Solution chemistry [25]	-	-	●	-	-	●	●	●	-	-	●	●	●
Transition metal elements [26]	●	●	●	●	●	●	-	-	•	•	●	●	-
Lanthanides & actinides [27]	●	●	•	•	•	•	-	-	●	•	-	-	-
Electronic band structure [28]	●	-	●	-	-	●	-	-	-	-	-	-	-
Electron/hole diffusion constants [28]	●	-	●	-	-	●	-	-	-	-	-	-	-
Vibrational and vibronic structure [29, 30]	•	-	•	•	-	•	•	●	-	-	●	-	●
Magnetism [31]	•	●	-	•	●	-	-	-	•	-	-	-	-
Nuclear structure and reactions [32]	-	-	-	-	-	-	-	-	●	-	-	-	-
Excited states of a Hamiltonian [33–36]	●	-	-	•	-	•	-	●	•	-	•	•	•

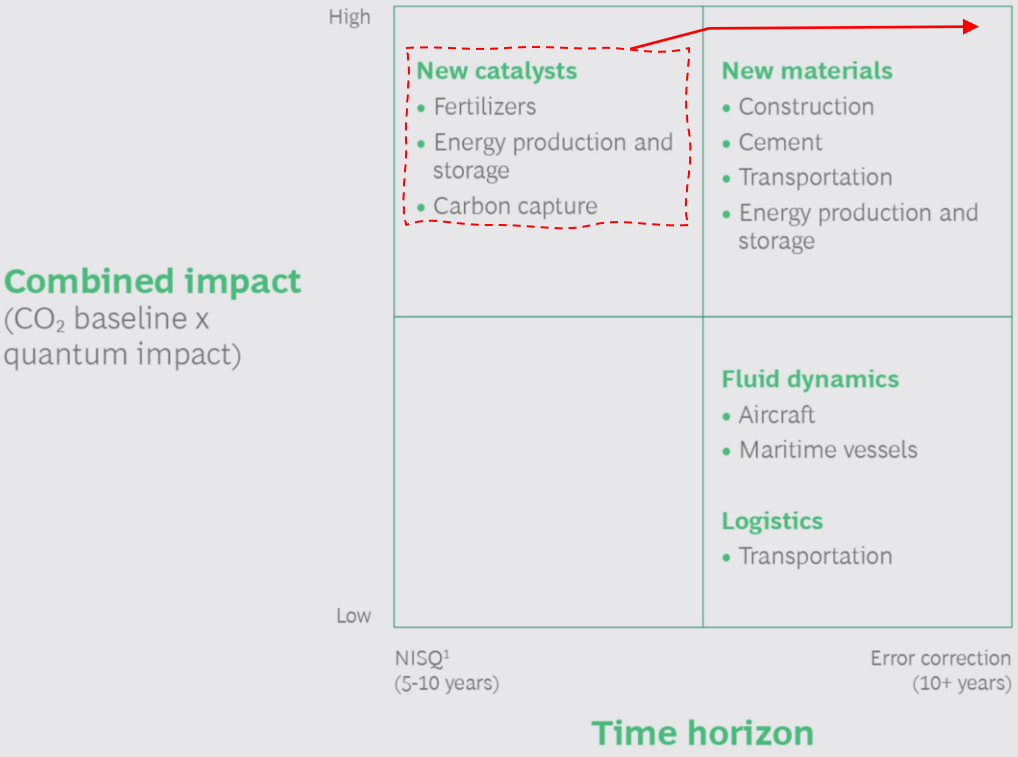
source: Quantum technologies for climate change: Preliminary assessment by Casey Berger, Agustin Di Paolo, Tracey Forrest, Stuart Hadfield, Nicolas Sawaya, Michał Stęchły, and **Karl Thibault**, arXiv, June 2021 (14 pages).

the typical view on how quantum computing could solve some hard problems related to climate change

the promise lies with potentially finding new chemical processes inspired by nature to produce fertilizers, cement, capture carbon and the likes

most case studies require **1000s logical qubits**

EXHIBIT 1 | New Solutions Can Help Fight Climate Change

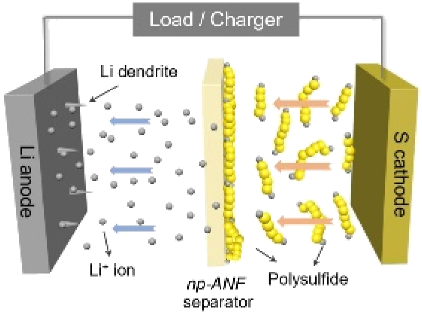


Source: BCG analysis. 2020
[1]Noisy intermediate-scale quantum.

assessing QC case studies

criteria	case 1	case 2	case 3	case 4
problem sizing	small scale	larger scale	large scale	very large scale
resource estimates	tested with <30 qubits		>1,000 logical qubits	>10K logical qubits
quantum advantage	results quality energetic costs		speedup	
QPU type	NISQ or emulator	analog	FTQC	large FTQC
	equivalent to a classical computing case	approaching quantum advantage	long-term applicability	very long-term applicability

simulate matter for…



quantum digital twins to create better batteries

MITSUBISHI CHEMICAL

battery simulation

lithium-oxygen

source: IBM

Mercedes-Benz

battery simulation

estimating the cost of electrolyte simulation on PsiQuantum's future QPU.

source: PsiQuantum, Mercedes-Benz

HYUNDAI

battery simulation

model lithium oxide to understand how batteries age over time

source: Hyundai, IonQ

DAIMLER

battery simulation

lithium-sulfur battery design

source: IBM

SAMSUNG

battery simulation

simulating magnetism and spins

source: Samsung, Honeywell

TotalEnergies

battery materials design

simulating Mott insulator transitions in battery electrode materials and ceramic superconductors and discharge curve of Li_xCoO_2.

source: Total, Pasqal

Li-Ion battery chemical simulation

needs…

6,652 logical qubits

10^{-12} error rate

computing times in months/years

VOLKSWAGEN

XANADU

source: Simulating key properties of lithium-ion batteries with a fault-tolerant quantum computer by Alain Delgado et al, April-September 2022 (31 pages).

PHYSICAL REVIEW A **106**, 032428 (2022)

Simulating key properties of lithium-ion batteries with a fault-tolerant quantum computer

Alain Delgado,[1,*] Pablo A. M. Casares,[2,*] Roberto dos Reis,[1,3] Modjtaba Shokrian Zini,[1] Roberto Campos,[2,4] Norge Cruz-Hernández,[5] Arne-Christian Voigt,[6] Angus Lowe,[1] Soran Jahangiri,[1] M. A. Martin-Delgado,[2,7] Jonathan E. Mueller,[6] and Juan Miguel Arrazola[1,†]

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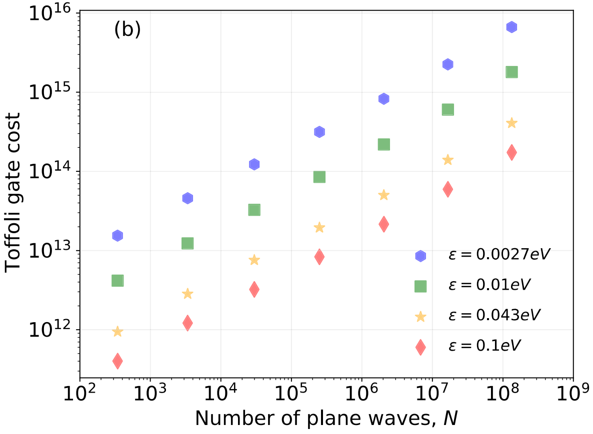
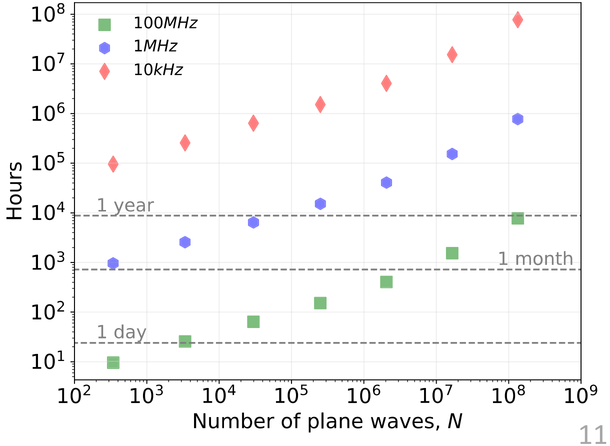
(Received 27 April 2022; revised 14 July 2022; accepted 10 August 2022; published 26 September 2022)





LNO battery simulation

Google

$LiNiO_2$ chemistry simulation

from 75K to 3M logical qubits and 91M to 6G physical qubits

requires physical qubits with 0.01% error rates

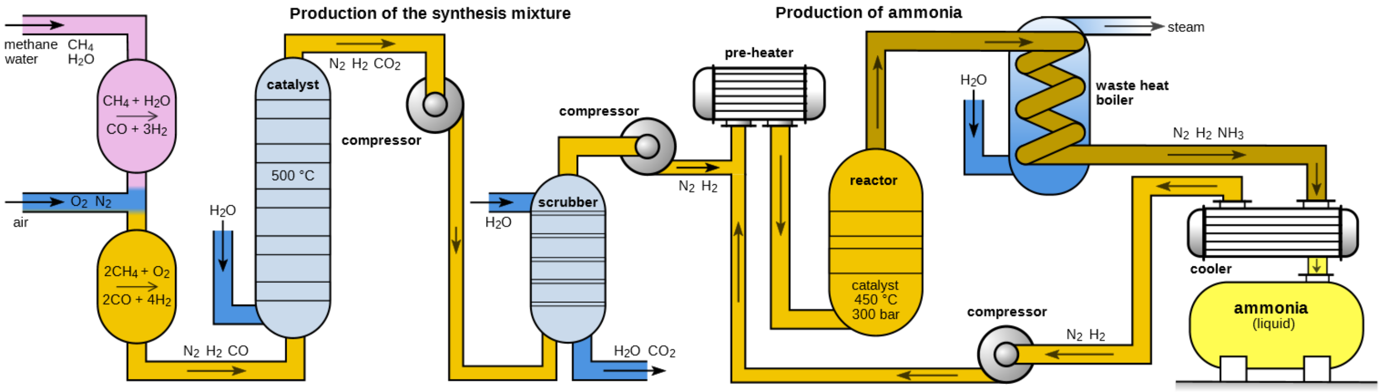
computing time from one year to 2,739 years

source: Fault-tolerant quantum simulation of materials using Bloch orbitals, Nicholas C. Rubin, Ryan Babbush et al, February 2023 (58 pages).

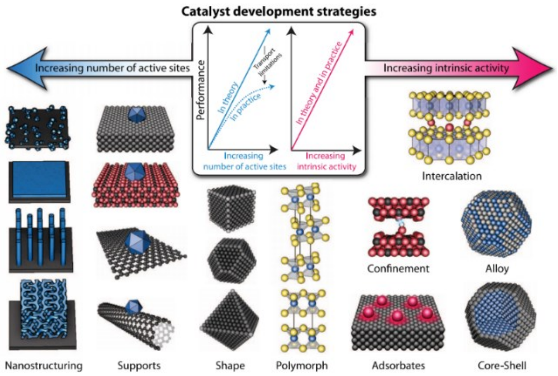
System	LCU	k-mesh	λ	Num. Spin-Orbs.	Toffolis	Logical Qubits	Physical Qubits [M]	run time [days]
$R\bar{3}m$	Sparse	[2, 2, 2]	120382.037	116	6.16×10^{13}	166946	242.72	1.51×10^{4}
		[3, 3, 3]	718377.133	116	3.57×10^{15}	1625295	2808.82	9.82×10^{5}
	SF	[2, 2, 2]	183778.821	116	7.86×10^{13}	89162	129.77	1.93×10^{4}
		[3, 3, 3]	2966279.293	116	4.60×10^{15}	404723	699.68	1.27×10^{6}
	DF	[2, 2, 2]	10730.422	116	4.97×10^{12}	149939	180.16	1.08×10^{3}
		[3, 3, 3]	44794.803	116	7.28×10^{13}	598286	869.02	1.79×10^{4}
$C2/m$	Sparse	[2, 2, 1]	58422.522	116	1.03×10^{13}	83532	100.47	2.53×10^{3}
		[4, 4, 2]	893339.394	116	5.37×10^{15}	3051285	5272.93	1.48×10^{6}
	SF	[2, 2, 1]	95803.204	116	2.05×10^{13}	44657	53.90	5.05×10^{3}
		[4, 4, 2]	2899609.300	116	5.23×10^{15}	405310	700.69	1.44×10^{6}
	DF	[2, 2, 1]	4873.648	116	1.18×10^{12}	75178	90.44	2.56×10^{2}
		[4, 4, 2]	51416.281	116	9.82×10^{13}	598736	869.68	2.41×10^{4}
$P2/c$	Sparse	[1, 1, 1]	84977.359	464	2.06×10^{13}	99918	120.21	5.07×10^{3}
		[2, 2, 2]	1627121.892	464	1.67×10^{16}	3182362	6454.14	4.59×10^{6}
	SF	[1, 1, 1]	201894.726	464	8.74×10^{13}	92786	135.04	2.15×10^{4}
		[2, 2, 2]	5666363.179	464	2.07×10^{16}	839487	1450.95	5.68×10^{6}
	DF	[1, 1, 1]	2753.901	464	9.72×10^{11}	75834	91.23	2.11×10^{2}
		[2, 2, 2]	40788.113	464	1.40×10^{14}	1192900	1732.40	3.44×10^{4}
$P2_1/c$	Sparse	[1, 2, 1]	105584.297	232	3.39×10^{13}	182864	265.83	8.34×10^{3}
		[2, 4, 2]	1714723.913	232	1.50×10^{16}	3116825	6321.24	4.12×10^{6}
	SF	[1, 2, 1]	271178.934	232	8.92×10^{13}	96882	140.98	2.19×10^{4}
		[2, 4, 2]	7798992.981	232	2.13×10^{16}	438080	757.32	5.85×10^{6}
	DF	[1, 2, 1]	3958.111	232	1.27×10^{12}	75383	90.69	2.76×10^{2}
		[2, 4, 2]	46189.645	232	1.23×10^{14}	1192758	1732.20	3.02×10^{4}

TABLE VI. Quantum Resource estimates for all four LNO structures normalized by the number of formula units represented in each simulation cell. $R\bar{3}m$ and $C2/m$ are both one formula unit while $P2/c$ is four formula units and $P2_1/c$ is two formula units. The sparse threshold is selected to be 1.0×10^{-4}, the SF the auxiliary index is truncated at eight times the number of molecular orbitals, and the DF the second factorization is truncated at 1.0×10^{-4}.

simulate matter for…



producing fertilizers with less energy



FeMoCo role in nitrogen fixation

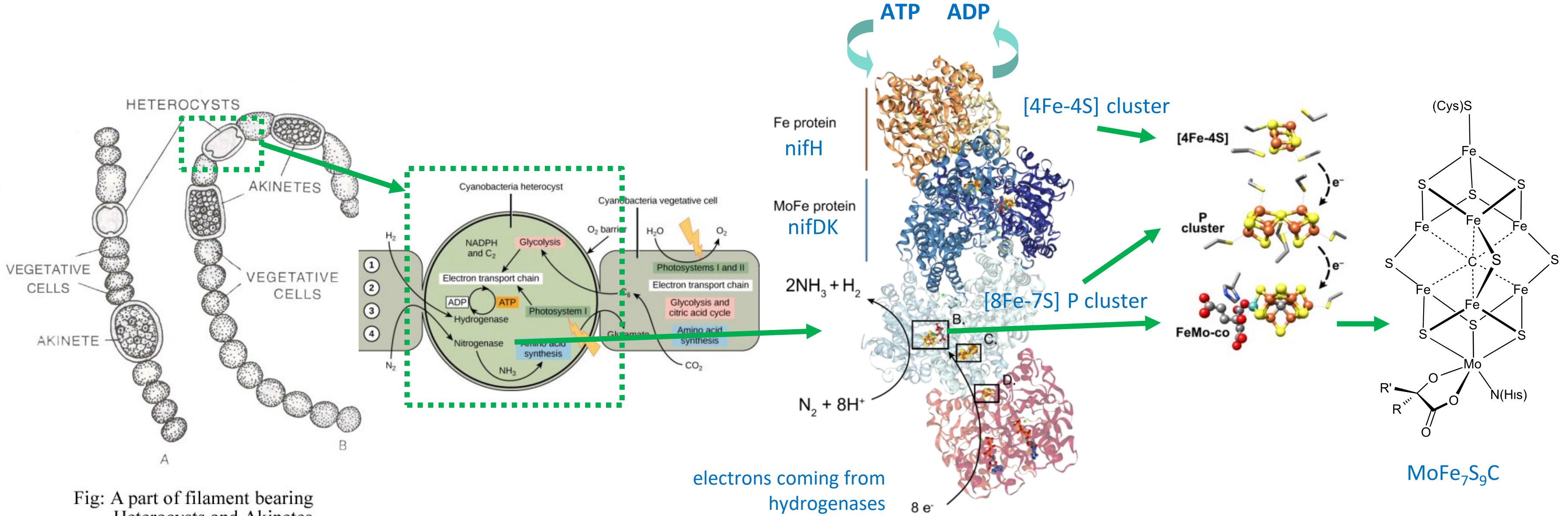


Fig: A part of filament bearing Heterocysts and Akinetes.

cyanobacteria

bacteria producing ammonia in soil and water or legume plants root nodules

heterocyst

cell within cyanobacteria that support the chemical pathways producing ammonia using dinitrogen

nitrogenase

protein complex producing ammonia in heterocyst cells

FeMoCo complex

part of the two nidDK proteins in some nitrogenases that is involved in ammonia production

simulating FeMoCo

need…

2,142 logical qubits

4M physical qubits

4 days computing time

real need:

- **simulate full NH_3 creation chemical pathway.**
- **design a new industry-grade pathway.**
- **simulate it with a lot of tries.**
- **optimize it with real-life scenario.**

PRX QUANTUM **2,** 030305 (2021)

Even More Efficient Quantum Computations of Chemistry Through Tensor Hypercontraction

Joonho Lee,[1,*,§] Dominic W. Berry,[2,†,§] Craig Gidney,[3] William J. Huggins,[3] Jarrod R. McClean,[3] Nathan Wiebe,[4,5] and Ryan Babbush[3,‡]

[1] *Department of Chemistry, Columbia University, New York, New York, USA*
[2] *Department of Physics and Astronomy, Macquarie University, Sydney, NSW, Australia*
[3] *Google Quantum AI, Venice, California, USA*
[4] *Department of Physics, University of Washington, Seattle, Washington, USA*
[5] *Pacific Northwest National Laboratory, Richland, Washington, USA*

(Received 12 December 2020; revised 7 April 2021; accepted 24 May 2021; published 8 July 2021)

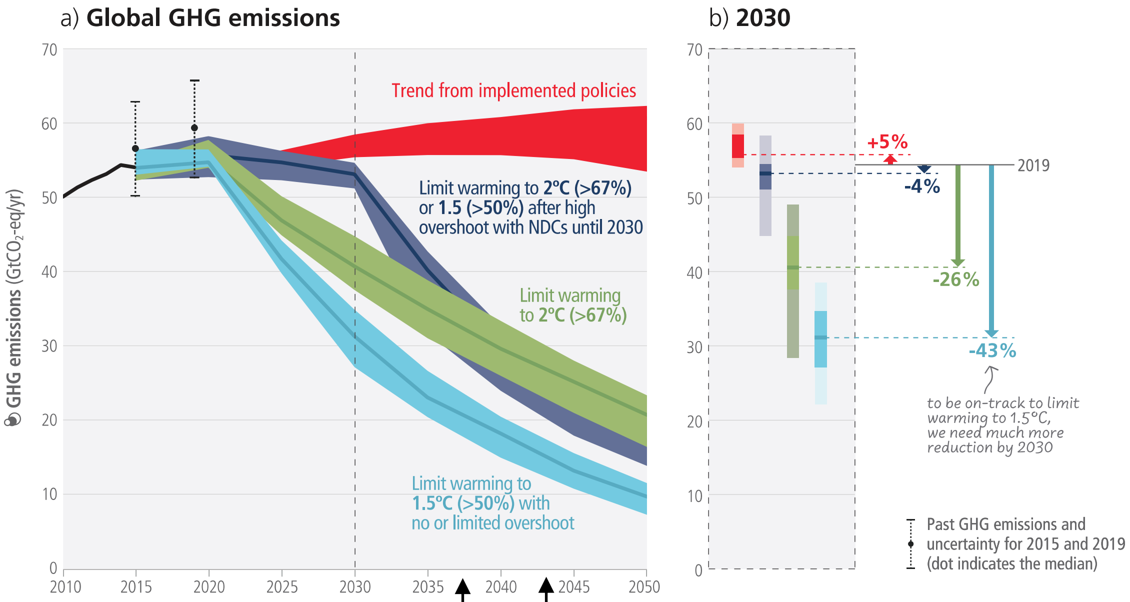
	Reiher *et al.* FeMoCo [23]		Li *et al.* FeMoCo [36]	
Algorithm	Logical qubits	Toffoli count	Logical qubits	Toffoli count
Reiher *et al.* [23] (Trotter)	111	5.0×10^{13}	—	—
Campbell and Kivlichan *et al.* [52,53] (qDRIFT) (D16), (D17)	288	5.2×10^{27}	328	1.8×10^{28}
qDRIFT with 95% confidence interval (D34)	270	1.9×10^{16}	310	1.0×10^{16}
Berry *et al.* [9] (single factorization) (B16), (B17)	3,320	9.5×10^{10}	3,628	1.2×10^{11}
Berry *et al.* [9] (sparse) (A17), (A18)	2,190	8.8×10^{10}	2,489	4.4×10^{10}
von Burg *et al.* [10] (double factorization) (C39), (C40)	3,725	1.0×10^{10}	6,404	6.4×10^{10}
This work (tensor hypercontraction) (44) (46)	2,142	5.3×10^{9}	2,196	3.2×10^{10}

source: Even More Efficient Quantum Computations of Chemistry Through Tensor Hypercontraction by Joonho Lee, Craig Gidney et al, July 2021 (62 pages).
https://journals.aps.org/prxquantum/pdf/10.1103/PRXQuantum.2.030305

weighing global warming

Projected global GHG emissions from NDCs announced prior to COP26 would make it *likely* that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C

source: Climate Change 2023 Synthesis Report, IPCC, 2023.



potential advent of large scale FTQC

industrial deployment of any new solution

greenhouse gas contribution of synthetic nitrogen fertilizers production:
2.1% of global GHG

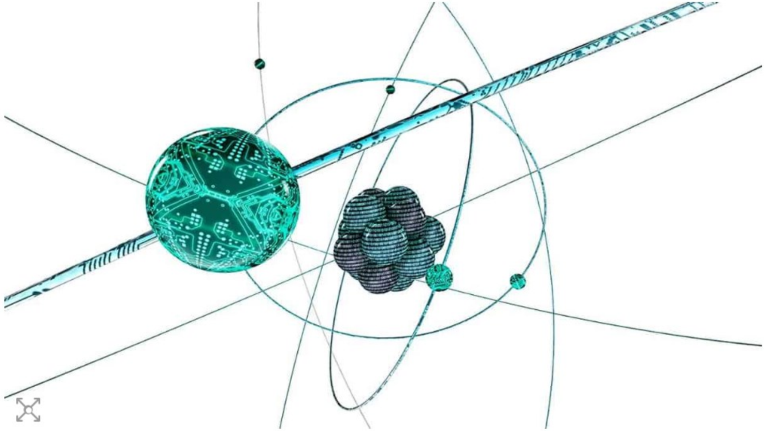
source: Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture, Stefano Menegat et al, Nature Research, 2022.

CO2 capture

QUANTUM | RESEARCH UPDATE

Carbon-capture technology could benefit from quantum computing

05 Apr 2023



Quantum chemistry: artistic conception of a molecule being simulated by a quantum computer. (Courtesy: iStock/thelightwriter)

Description of reaction and vibrational energetics of CO_2–NH_3 interaction using quantum computing algorithms

Cite as: AVS Quantum Sci. **5**, 013801 (2023); doi: 10.1116/5.0137750
Submitted: 5 December 2022 · Accepted: 30 January 2023 ·
Published Online: 14 March 2023

Manh Tien Nguyen,[1,2] Yueh-Lin Lee,[1,3] Dominic Alfonso,[1] Qing Shao,[2] and Yuhua Duan[1,a),b)]

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[3]NETL Support Contractor, Pittsburgh, Pennsylvania 15236, USA

[a)]Author to whom correspondence should be addressed: yuhua.duan@netl.doe.gov
[b)]Tel.: 412-386-5771

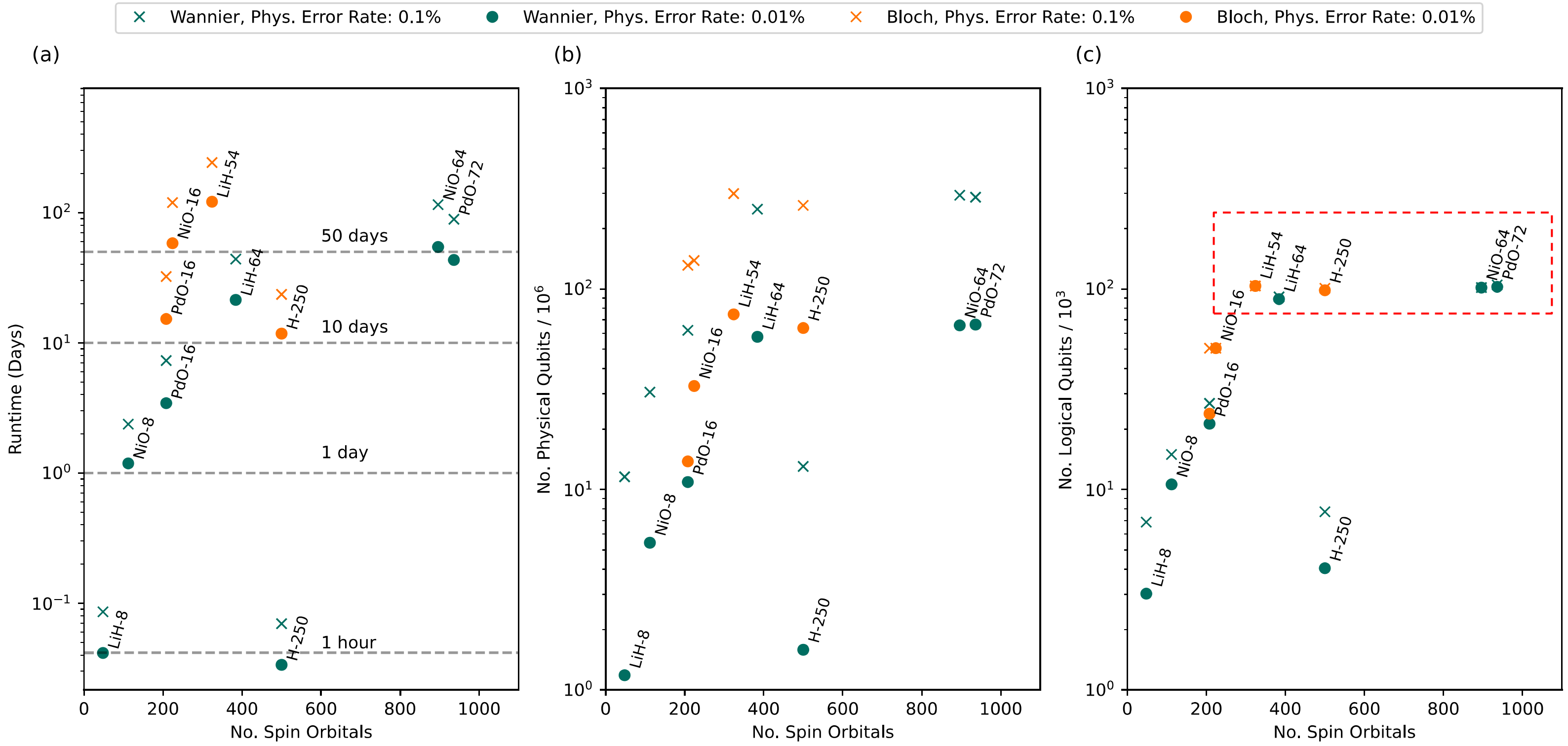
- **VQE algorithm tested on 20 qubits.**
- **not yet in a quantum advantage regime.**
- **not a solution for carbon capture.**

materials simulation

simulate nickel oxide and palladium oxide, which can be used in heterogeneous catalysis

Riverlane-Led Research Shows How Quantum Computers May Simulate Materials To Reduce Humanity's Impact On The Environment

Quantum Computing Business, Research, Uncategorized · Matt Swayne • March 24, 2023



100 000 logical qubits !

Quantum Computing for Fusion Energy Science Applications

I. Joseph, Y. Shi, M. D. Porter, A. R. Castelli, V. I. Geyko,
F. R. Graziani, S. B. Libby, J. L. DuBois
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, USA

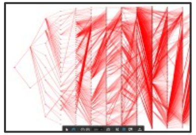
(*Electronic mail: joseph5@llnl.gov)

(Dated: 12 December 2022)

This is a review of recent research exploring and extending present-day quantum computing capabilities for fusion energy science applications. We begin with a brief tutorial on both ideal and open quantum dynamics, universal quantum computation, and quantum algorithms. Then, we explore the topic of using quantum computers to simulate both linear and nonlinear dynamics in greater detail. Because quantum computers can only efficiently perform linear operations on the quantum state, it is challenging to perform nonlinear operations that are generically required to describe the nonlinear differential equations of interest. In this work, we extend previous results on embedding nonlinear systems within linear systems by explicitly deriving the connection between the Koopman evolution operator, the Perron-Frobenius evolution operator, and the Koopman-von Neumann evolution (KvN) operator. We also explicitly derive the connection between the Koopman and Carleman approaches to embedding. Extension of the KvN framework to the complex-analytic setting relevant to Carleman embedding, and the proof that different choices of complex analytic reproducing kernel Hilbert spaces depend on the choice of Hilbert space metric are covered in the appendices. Finally, we conclude with a review of recent quantum hardware implementations of algorithms on present-day quantum hardware platforms that may one day be accelerated through Hamiltonian simulation. We discuss the simulation of toy models of wave-particle interactions through the simulation of quantum maps and of wave-wave interactions important in nonlinear plasma dynamics.

optimize operations

better production and distribution of renewable energies



safety probabilistic study

decision support tool for real time risk analysis, recalculates risk based on operation current state and maintenance operation, avoids roll back in case unintended events

source: EDF.

electric vehicle recharge station mapping optimization

optimization problem

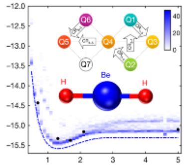
source: Atos.

TotalEnergies

carbon capture

simulating interaction between CO^2 molecule and new complex materials to enable its storage, using MOFs (metal-organic frameworks like Al-Fu)

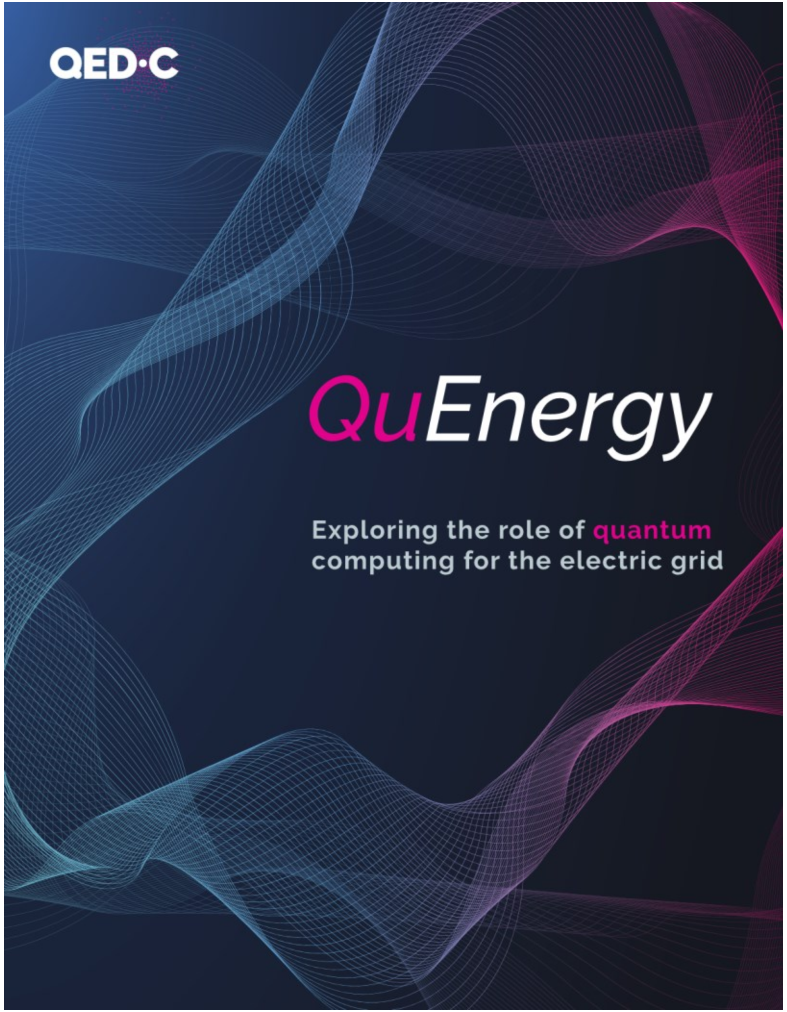
source: Atos, TotalEnergies, CQC



material ageing modelling

modelling ageing phenomena's with quantum physic laws, foresees material ageing patterns to gain operational margin.

source: EDF.



Key quantum computing use cases in the electric sector

	Use Case	Problem Type	Quantum Hardware Options		
			Gate	Annealing	Inspired
1	Real-Time Situational Awareness	Machine learning	✓	✓	✓
2	Energy Market Optimization	Optimization	✓	✓	✓
3	Distribution System Operation after Derecho Storm	Optimization, machine learning	✓	✓	✓
4	Load Modeling for Efficient and Effective Storage	Optimization, simulation, machine learning	✓	✓	
5	Discrete Choices with Nonlinear AC Physics	Optimization	✓	✓	
6	Prediction, Consistency with Observations	Machine learning	✓	✓	✓
7	Demand Modeling (and Prediction)	Simulation	✓		
8	Extreme Event Preparation	Optimization	✓	✓	✓
9	Energy Demand Forecasting	Machine learning	✓		
10	Rolling Blackout/Rare Event Prediction	Machine learning	✓		✓
11	Quantum Simulation of New Materials	Simulation, optimization	✓		
12	Optimization of Grid Resilience	Optimization	✓	✓	✓
13	Day-ahead Market	Optimization	✓	✓	✓
14	Coordinating Weather Events and Network Use Patterns	Optimization, machine learning	✓	✓	
15	Integrated Planning and Optimization	Simulation, optimization	✓	✓	✓
16	Integration Operations and Control	Simulation, optimization	✓	✓	✓
17	From Materials to Plant and Design	Simulation	✓		

Quantum Computers Can Now Interface With Power Grid Equipment

NREL and Atom Computing Debut Open-Source Application for Quantum-in-the-Loop Studies

July 17, 2023 | By Connor O'Neil | Contact media relations

Share

Test Setup and Technology

NREL and other research facilities regularly validate new power technologies with hardware in-the-loop, but quantum in-the-loop has never existed until now. The demonstration relied on several exceptional capabilities: NREL's provided nine digital real-time simulators, which communicated over the ESnet network to Atom Computing's quantum emulator and eventually to Phoenix, its prototype system. Linking the two sites was the newly developed interface—a software for interpreting, converting, and transmitting data from each end in real time.

PHASECRAFT

Won a £1.2M UK Government contract as part of the UK's Quantum Catalyst Fund. Phase One of the Fund saw Phasecraft awarded a contract for a feasibility study to explore the application of quantum computing to optimisation problems within energy grids. Following the successful completion of Phase 1, Phase 2 of this project will see Phasecraft work with the Department for Energy Security and Net Zero to prioritise and attempt to address such optimisation problems with quantum solutions.

TRANSACTIONS ON SMART GRIDS VOL. X, NO. Y, JUNE 2023 1

Assessing Quantum Computing Performance for Energy Optimization in a Prosumer Community

Carlo Mastroianni, Francesco Plastina, Luigi Scarcello, Jacopo Settino, and Andrea Vinci

This paper focuses on the solution of the prosumer problem with a hybrid classical-quantum computing approach. We have outlined how this NP-hard problem can be transformed into the problem of finding the ground state of a Hamiltonian operator, which is the kind of problem that can be solved by the QAOA and Recursive QAOA algorithms. […] We have been able to inspect the scalability of the algorithms: we have checked that the quantum execution time does not depend on the number of binary variables and increases almost linearly with the requested accuracy. **This suggests that, as the problem size increases, a quantum approach is expected to be technologically favorable in the long term.**

Quantum Optimization for the Future Energy Grid: Summary and Quantum Utility Prospects

Jonas Blenninger[2], David Bucher[2], Giorgio Cortiana[1], Kumar Ghosh[1], Naeimeh Mohseni[1], Jonas Nüßlein[3], Corey O'Meara[1*], Daniel Porawski[2], Benedikt Wimmer[2]

[1*]E.ON Digital Technology GmbH, Hannover, Germany.
[2]Aqarios GmbH, Munich, Germany.
[3]Mobile and Distributed Systems Chair, Ludwig-Maximilians Universität, Munich, Germany.

March 2024

potential quantum advantage on use cases: decentralized energy generation and transmission, novel energy transportation and exchange methods such as Peer-2-Peer energy trading and microgrid formation

"We have demonstrated that quantum optimization approaches may provide some advantages over traditional classical optimization approaches in terms of application-specific benchmarks or hybrid algorithm solution quality, however further investigation is needed to explore any evidence of potential quantum utility in the energy sector"

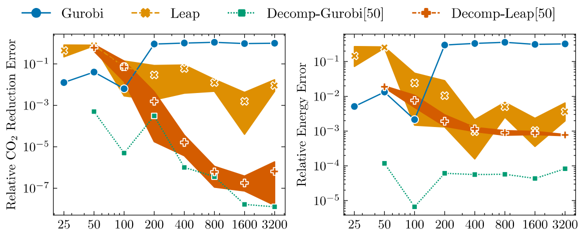


Fig. 4: The investigated metrics for different problem sizes and different solvers. The runtime of all solvers has been set to be equal for a certain problem size, but grows with N_c. The top row shows the global metrics, which tell the most about how the solver performed. The relative energy error is the central objective that we try to minimize, while the energy error gives an overview of the performance with regard to all optimization targets.

Investigating techniques to optimise the layout of turbines in a windfarm using a quantum computer

James Hancock, Matthew J. Craven, Craig McNeile, and Davide Vadacchino

Centre for Mathematical Sciences, University of Plymouth

February 2024

We study the optimal placement of wind turbines within a windfarm to maximize the power produced by mapping the system to a Quadratic Unconstrained Binary Optimisation (QUBO) problem. We investigate solving the resulting QUBO problem using the Variational Quantum Eigensolver (VQE) on a quantum computer simulator and compare the results to those from two classical optimisation methods: simulated annealing and the Gurobi solver. The maximum grid size we study is 4 × 4, which requires 16 qubits.

of the turbines in the windfarm will change the maximum amount of energy that the windfarm

7.5 Conclusions

The VQE-based solver of the WFLO problem finds good solutions when a sufficient number of measurements have been performed. The Gurobi optimizer always finds the optimal solution, and it outperforms the noisy VQE-based method.

logistics and transportation optimization

reduce delays and costs in transportation and logistics

VOLKSWAGEN

trafic optimization

with a simulation using 400 cabs in Beijing.

later implemented at the Lisbon Web Summit

source : D-Wave, Volkswagen

accenture

trucks routing

trucks routing optimization

source: Accenture, D-Wave

DENSO

fleet optimization

Denso and Toyota, presented at CES 2017 on Denso booth.

source: D-Wave, Denso

FERROVIE DELLO STATO ITALIANE

trains station optimization

to reduce passengers connecting time

source: D-Wave

DLR

aircraft gate allocation in airports

to minimize passagers transit time

source: DLR, D-Wave

ExxonMobil

containers shipment optimization

using VQE, MIP, QUBO

source: IBM, ExxonMobil

modeling climate and weather

PASQAL Quantum Enabled Business Industry Solutions Learn Company Contact us

Back

BASF Collaborates with PASQAL to Predict Weather Patterns

Published by Henrique Silvério , July 20, 2022

rigetti

Rigetti Enhances Predictive Weather Modeling with Quantum Machine Learning

December 01, 2021 09:00 ET| Source: Rigetti Computing Follow

with 32 qubits!

arXiv > quant-ph > arXiv:2210.17460

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Quantum Physics

[Submitted on 31 Oct 2022]

Quantum Computers for Weather and Climate Prediction: The Good, the Bad and the Noisy

Felix Tennie, Tim Palmer

Over the past few years, quantum computers and quantum algorithms have attracted considerable interest and attention from numerous scientific disciplines. In this article, we aim to provide a non-technical, yet informative introduction to key aspects of quantum computing. We discuss whether quantum computers one day might become useful tools for numerical weather and climate prediction. Using a recently developed quantum algorithm for solving non-linear differential equations, we integrate a simple non-linear model. In addition to considering the advantages that quantum computers have to offer, we shall also discuss the challenges one faces when trying to use quantum computers for real-world problems involving "big data", such as weather prediction.

what is being practically done

classical computers

quantum inspired

- financial services solutions improvements.
- machine learning improvements.

ALPHARAIL

quantum emulators

- code learning.
- code debugging.
- designing new algorithms.
- simulating qubit physics.
- simulating error correction codes.

analog quantum computers

quantum annealing computers / analog quantum simulators

- solving optimization problems at mid-sized scale, in transportation (Volkswagen, Denso), retail (Ocado, Pattison), job shop scheduling and financial services (Mastercard, CACIB).
- physics simulations (statistical physics, spin glass, ferromagnetism, topological matter, …).
- potential energetic advantage.

e.on — EDF

digital quantum computers

gate-based

NISQ (Noisy Intermediate Scale Quantum)

- low-level physics simulations ("IBM quantum utility" with 127 qubits and kicked Ising model).
- creating and testing algorithms at small scale (QML, optimizations, chemical simulations).

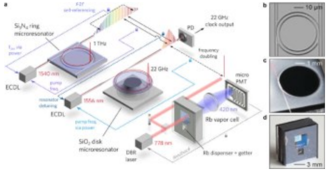
EDF — TOTAL — PHASECRAFT

FTQC (Fault-Tolerant Quantum Computing)

- large algorithms and resource estimations.
- creating and testing error correction codes (Google, Quantinuum, QuEra, PsiQuantum, …).

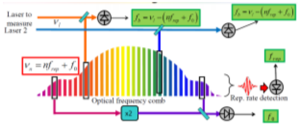
HYUNDAI — Mercedes-Benz — VOLKSWAGEN — MITSUBISHI CHEMICAL

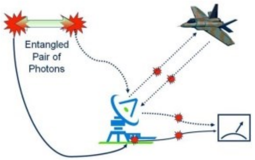
quantum sensing



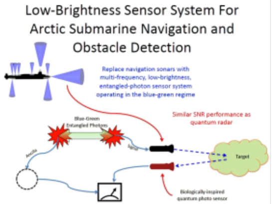
clocks
spectrographs
ultra-sound mikes

lasers and
frequency combs





radars
LiDARs



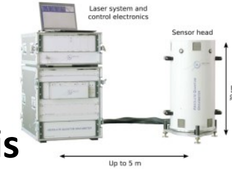
ultra-sensitive
imaging

entangled photons

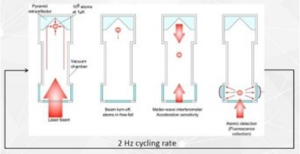
gyroscopes
sonars

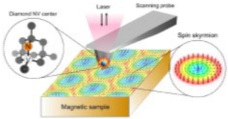
gravimeters

RF
analysis



cold atoms





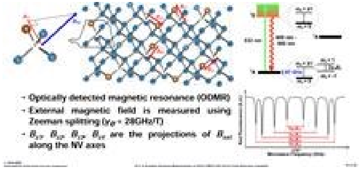
microscopy, medical imaging

magnetometers

SQUIDs

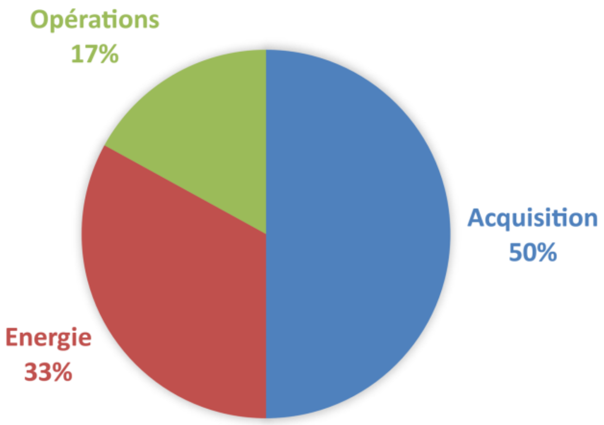
thermometers

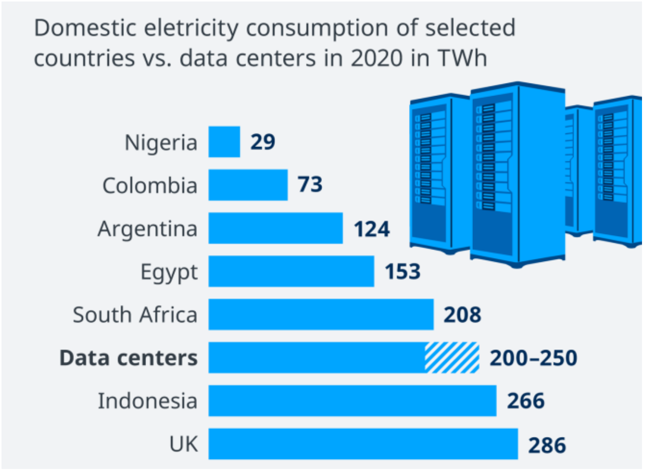
NV centers



sensor type			qubit nature	type I	type II	type III	rotation	acceleration	force	pressure	displacement	time	frequency	refractive index	magnetic field	electric field	voltage	temperature	mass
neutral atoms		atomic vapor	atomic spin		X	X	X					X	X		X				
neutral atoms		cold atom clouds	atomic spin		X	X		X				X	X		X				
Rydberg atoms			Rydberg states		X	X										X			
trapped ions			electronic state		X	X	X			X		X	X						
trapped ions			vibrational mode		X				X							X			
solid state	spin ensembles	NMR	nuclear spins		X										X				
solid state	spin ensembles	NV/SiC center ensembles	electron spins		X		X			X					X	X		X	
solid state	single spins	P donor in Si	electron spins		X										X				
solid state	single spins	quantum dot	electron spins	X	X										X	X			
solid state	single spins	single NV center	electron spins		X		X			X					X	X		X	
superconducting circuits		SQUIDs	supercurrent	X	X										X				
superconducting circuits		flux qubits	circulating current		X										X				
superconducting circuits		charge qubits	charge eigenstates		X											X			
single electron transistor			charge eigenstates	X												X			
optomechanics			phonons	X				X	X						X		X		
interferometer			photons, atoms		X	X	X				X			X					

HPC and data center energy costs





up to 1/3 of total cost of operations of datacenters comes from energy consumption and half from hardware acquisition costs.

WW data centers spent >200 TWh in 2020. source: DW. The first WW HPC spends as much energy as a 40K habitants city in France.

EDF spends 7 GWh per year in energy in its data centers (199€/MWH as of 2023)

WW TOP500 HPC data centers have a total power of 341 MW.

how about QPU’s energy consumption?

RESEARCH-ARTICLE

Energy Cost of Quantum Circuit Optimisation: Predicting That Optimising Shor’s Algorithm Circuit Uses 1 GWh

Authors: Alexandru Paler, Robert Basmadjian Authors Info & Claims

ACM Transactions on Quantum Computing, Volume 3, Issu

1–14 • https://doi.org/10.1145/3490172

energy hogs?

or advantage?

Optimizing resource efficiencies for scalable full-stack quantum computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3] Yvain Thonnart,[4] Hui Khoon Ng,[5,3,6,†] Robert S. Whitney,[7,‡] and Alexia Auffèves[2,6,§]

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[5]Yale-NUS College, Singapore
[6]MajuLab, International Joint Research Unit UMI 3654, CNRS, Université Côte d’Azur, Sorbonne Université, National University of Singapore, Nanyang Technological University, Singapore
[7]Université Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France.

#QEI

the quantum energy initiative

quantum-energy-initiative.org

>400 participants, >50 countries

IEEE

IEEE Quantum Energy Initiative standardization working group

+

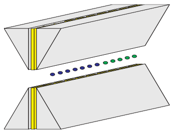
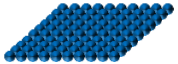
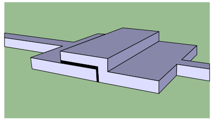
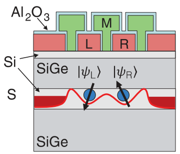
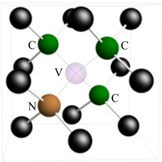
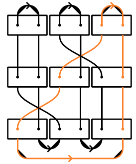
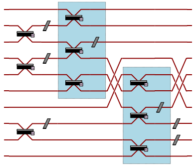
METRIQS/BACQ project.

questions

- is there a **quantum energy advantage** vs classical computing as quantum processors scale up?
- how to avoid **energetic dead-ends** on the road to LSQ?

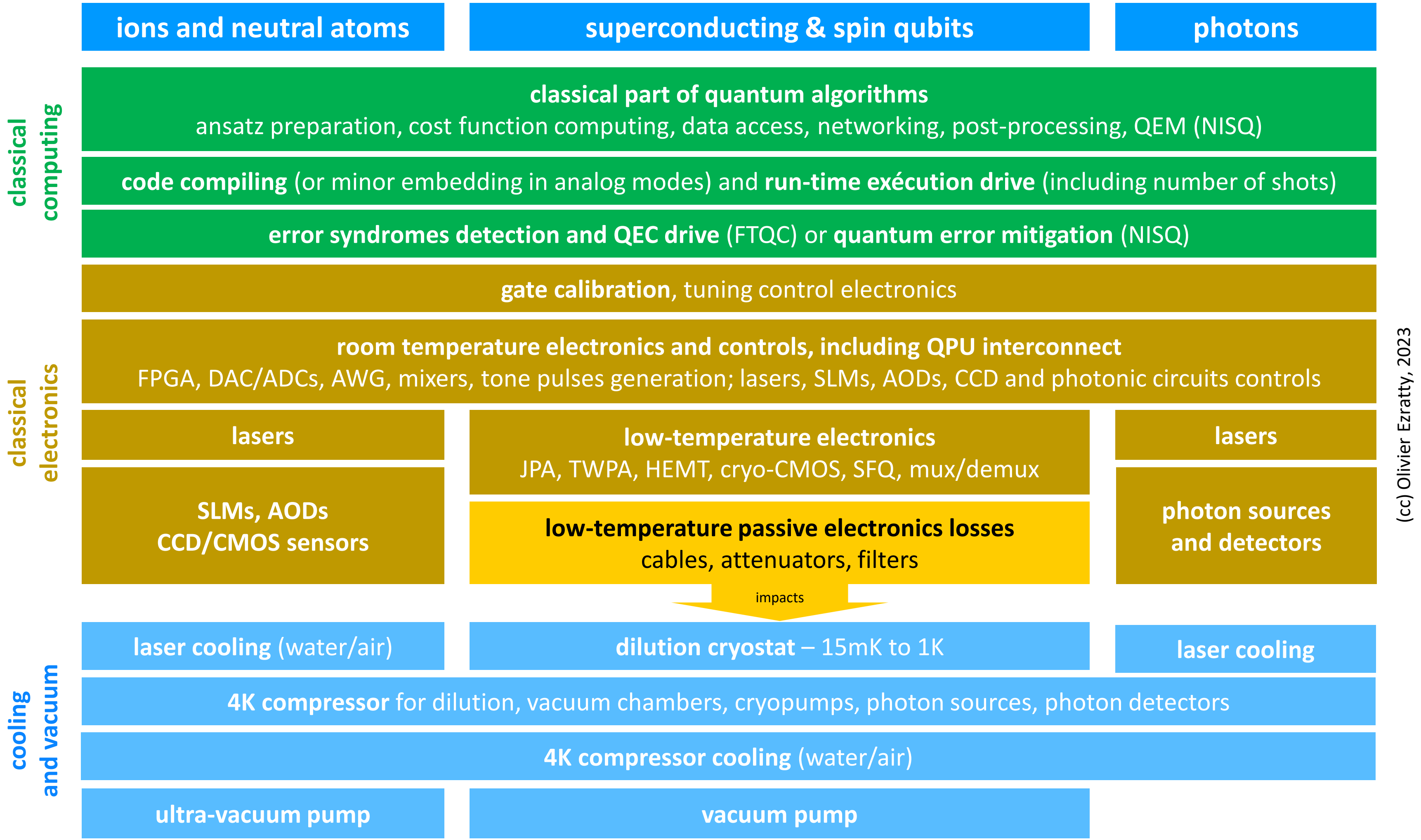
mission + goals

- create a new **transversal line of research** and collaborative projects.
- create a worldwide **community** working on this matter associating research and industry.
- create **optimization methodologies, frameworks** and **benchmarks** for quantum technologies, enabling technologies and software engineering,

	atoms		electron superconducting loops & controlled spin				photons
							
qubit type	**trapped ions**	**cold atoms**	**supercond.**	**silicon**	**NV centers**	**Majorana**	**photons**
cryogeny	300 W-6 kW	7-10 kW (2)	16-105 kW	12 kW	< 1 kW	16 kW	3 kW
vacuum pumps[1]	ultra-vacuum	ultra-vacuum	vacuum	vacuum	vacuum	vacuum	vacuum
qubits gate controls	<1.4 kW ions heating, lasers, micro-aves generation, CMOS readout electronics	1.8 kW atoms heater, lasers, control (SLM, AOD), readout sensor + electronics	from 20 mW to 100 W / qubit depending on architectures with micro-wave generation outside or inside the cryostat		N/A	<25 mW / qubit	300 W for photons sources and detectors, qubit gates controls
computing	300 W	300 W	<1 kW	<1 kW	<1 kW	<1 kW	700 W
# qubits used	24	100/256 (1) - 300-1000 (2)	53-433	12	<10	N/A	20
total	**2 KW** (5)	**3** (1)-**20 KW** (2)	**25-140 KW** (3)	**21 KW**	**N/A**	**N/A**	**4 KW** (4)

[1] : fixed energetic cost, for preping stage

typical configurations for Pasqal and QuEra (1), neutral atoms with 4K pump/chamber cooling (2), Google Sycamore with 53 qubits, and guestimate for IBM System 2 with its KIDE cryostat(3), Quandela/QuiX (4), AQT (5) rough estimates for others



ions and neutral atoms
superconducting & spin qubits
photons
classical computing
classical part of quantum algorithms
ansatz preparation, cost function computing, data access, networking, post-processing, QEM (NISQ)
code compiling (or minor embedding in analog modes) and run-time exécution drive (including number of shots)
error syndromes detection and QEC drive (FTQC) or quantum error mitigation (NISQ)
classical electronics
gate calibration, tuning control electronics
room temperature electronics and controls, including QPU interconnect
FPGA, DAC/ADCs, AWG, mixers, tone pulses generation; lasers, SLMs, AODs, CCD and photonic circuits controls
lasers
low-temperature electronics
JPA, TWPA, HEMT, cryo-CMOS, SFQ, mux/demux
lasers
SLMs, AODs
CCD/CMOS sensors
low-temperature passive electronics losses
cables, attenuators, filters
photon sources
and detectors
impacts
cooling and vacuum
laser cooling (water/air)
dilution cryostat – 15mK to 1K
laser cooling
4K compressor for dilution, vacuum chambers, cryopumps, photon sources, photon detectors
4K compressor cooling (water/air)
ultra-vacuum pump
vacuum pump
(cc) Olivier Ezratty, 2023

some good news on QPU energetics

cryogeny is not that a big problem

qLDPC QEC can reduce the physical qubit # per logical qubit

FPGA ⋙ ASIC energy savings potential in control electronics

SFQ superconducting electronics

innovation with various qubit modalities

elements used in quantum technologies

alkali metals: used in trapped ions qubits, mostly strontium and calcium

transition metals: titanium and niobium, used in superconducting cables, niobium used in superconducting qubits

iron, cobalt, nickel, chrome: used in cryostats

group IIB metals: sometimes used in trapped ions qubits, zinc, cadmium, mercury

carbon: used in nanotubes for silicium qubits

nitrogen: used in some cryostats, mostly for quantum sensing

helium: used in cryostats at lower than 10K, and helium 3 to reach <3K temperature

rubidium : used in cold atom qubits and in quantum sensing

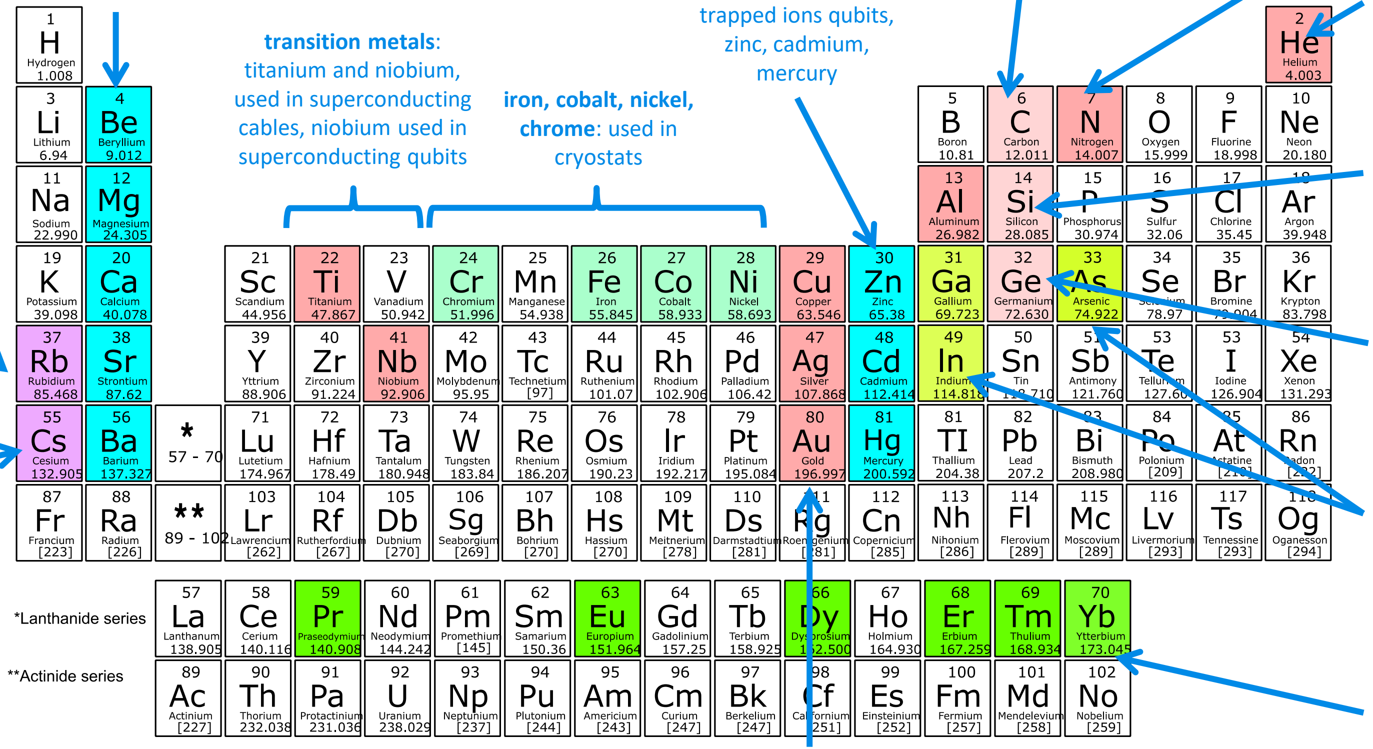
cesium : used in atomic clocks

silicon: used in wafers for electron spins qbits and photonics, Si_{28} for silicium qubits wafers.

germanium: used in some CMOS components and some electron spins qubits.

« III-V » elements: used for photonic semiconductors (arsenic, gallium, indium)

rare earths: ytterbium, europium, praseodyme and erbium used in trapped ions qubits, optical memories and some lasers.



copper, silver, gold: used in cryostats for cold plates and cabling

conclusion

1. there are many **quantum computing use cases** around energy production and distribution, and solving other environmental related problems.
2. they require a very **large number of logical and physical qubits** to process real-size real-life scenarios.
3. they are **rarely full-fledge solutions scenarios** (e.g. ground state estimations vs full chemical pathways).
4. need for **better integrated analysis** of use cases like for fertilizer production.
5. needs patience and to handle climate change with **classical solutions**.
6. some **quantum sensors** can bring interesting use cases although in a very fragmented and less visible market.
7. potential **energetic quantum advantage**, provided useful use cases are implemented.

discussion