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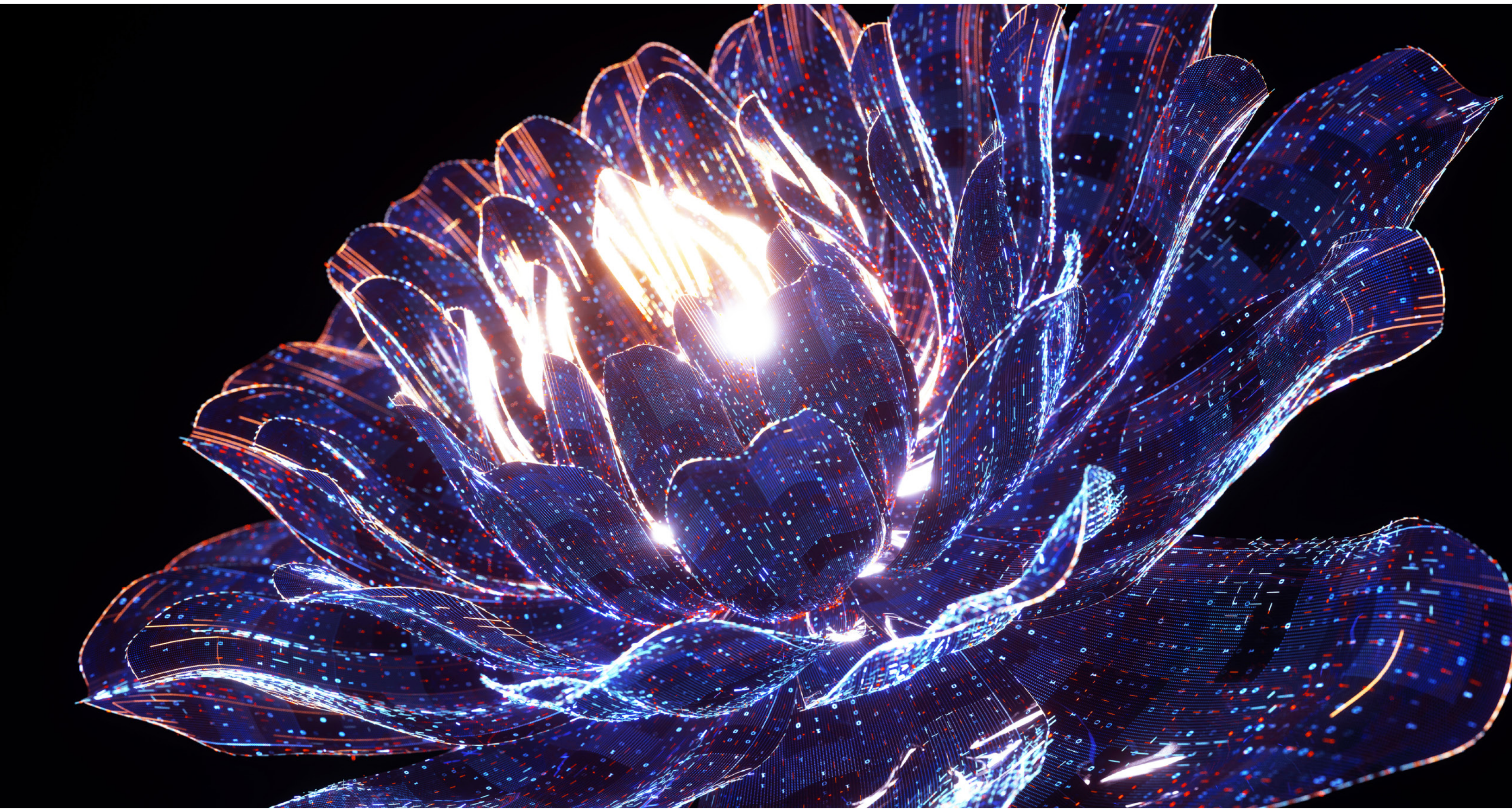
Quantum computing just might save the planet

Exponentially more powerful machines could make possible major reductions in emissions, putting the goal of limiting global warming within reach.

by Peter Cooper, Philipp Ernst, Dieter Kiewell, and Dickon Pinner



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May 2022

The emerging technology of quantum computing[1] could revolutionize the fight against climate change, transforming the economics of decarbonization and becoming a major factor in limiting global warming to the target temperature of 1.5°C (see sidebar "What is quantum computing?").

Even though the technology is in the early stages of development—experts estimate the first generation of fault-tolerant quantum computing[2] will arrive in the second half of this decade—breakthroughs are accelerating, investment dollars are pouring in, and start-ups are proliferating.[3] Major tech companies have already developed small, so-called noisy intermediate-scale quantum (NISQ) machines, though these aren't capable of performing the type of calculations that fully capable quantum computers are expected to perform.

Countries and corporates set ambitious new targets for reducing emissions at the 2021 United Nations Climate Change Conference (COP26). Those goals, if fully met, would represent an extraordinary annual investment of $4 trillion by 2030, the largest reallocation of capital in human history. But the measures would only reduce warming to between 1.7°C and 1.8°C by 2050, far short of the 1.5°C level believed necessary to avoid catastrophic, runaway climate change.

Meeting the goal of net-zero emissions that countries and some industries have committed to won't be possible without huge advances in climate technology that aren't achievable today. Even the most powerful supercomputers available now are not able to solve some of these problems. Quantum computing could be a game changer in those areas. In all, we think quantum computing could help develop climate technologies able to abate carbon on the order of 7 gigatons a year of additional CO_2 impact by 2035, with the potential to bring the world in line with the 1.5°C target.

What is quantum computing?

Quantum computing is a new technology that leverages the laws of quantum mechanics to produce exponentially higher performance for certain types of calculations, offering the possibility of major breakthroughs across several end markets.

The technology works by calculating with qubits, which can represent 0 and 1 at the same time. By contrast, classical computing calculates with transistors that represent either 0 or 1. In quantum computing, power increases exponentially in proportion to the number of qubits; with classical computing, power increases in a 1:1 relationship to the number of transistors.

While classical computers are better adapted to everyday, simple processing, the new machines are well suited for complex tasks such as quantum simulations in molecular chemistry, optimization, and prime factorization.

Quantum computing would be able to solve these specific problems much faster than even the most powerful supercomputer of today. In addition, the new technology could make it possible to solve certain problems that have long been considered insoluble. As an example, factoring a 2,048-bit prime number with today's supercomputer takes about one trillion years. With quantum, this calculation could take about one minute.

Recent innovation suggests that the first generation of fault-tolerant quantum computing could be operational by the end of this decade, with some quantum-computing companies suggesting it could be even sooner.

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[1] "Quantum computing use cases are getting real—what you need to know," McKinsey, December 14, 2021.

[2] Fault-tolerant quantum computing, in contrast to NISQ, enables sizable quantum computers to use error correction and perform billions more gate operations, which are necessary for most known valuable algorithms. NISQ-era quantum computers have 50 to several hundred qubits, which is not sufficient for error correction, restricting in the number of gate operations. Currently no valuable NISQ algorithms are known.

[3] *The quantum technology monitor*, McKinsey, September 2021.

Quantum computing could help reduce emissions in some of the most challenging or emissions-intensive areas, such as agriculture or direct-air capture, and could accelerate improvements in technologies required at great scale, such as solar panels or batteries. This article offers a look at some of the breakthroughs the technology could permit and attempts to quantify the impact of leveraging quantum-computer technology that are expected become available this decade.

Solving so far insoluble problems

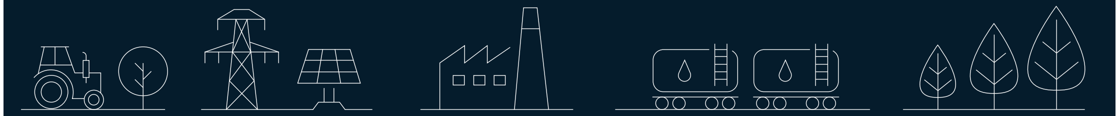
Quantum computing could bring about step changes throughout the economy that would have a huge impact on carbon abatement and carbon removal, including by helping to solve persistent sustainability problems such as curbing methane produced by agriculture, making the production of cement emissions-free, improving electric batteries for vehicles, developing significantly better renewable solar technology, finding a faster way to bring down the cost of hydrogen to make it a viable alternative to fossil fuels, and using green ammonia as a fuel and a fertilizer.

Addressing the five areas designated in the Climate Math Report[4] as key for decarbonization, we have identified quantum-computing use cases that can pave the way to a net-zero economy. We project that by 2035 the use cases listed below could make it possible to eliminate more than 7 gigatons of CO_2 equivalent (CO_2e) from the atmosphere a year, compared with the current trajectory, or in aggregate more than 150 gigatons over the next 30 years (Exhibit 1).

Exhibit 1

Quantum computing could bring about step changes throughout the economy that would have a huge impact on carbon abatement and carbon removal.

Visualizing postquantum climate action



Reform food and forestry

- Green fertilizers
- Methane-reducing vaccines for ruminants

Electrify our lives

- Higher-density electric batteries for heavy-goods electric vehicles
- Higher-density electric batteries for energy storage

Reshape industrial operations

- Zero-carbon cement clinkers
- New carbon-capture utilization and storage (CCUS) solvents

Decarbonize power and fuel

- CO_2 chemistry improvements for synfuels
- Better polymer electrolyte membrane and pulse electrolysis in H_2 generation
- More efficient perovskites for solar
- FeMo cofactor for green ammonia
- Green ammonia for shipping

Ramp up carbon markets

- New direct-air capture (DAC) adsorbents

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[4] "Climate math: What a 1.5-degree pathway would take," *McKinsey Quarterly*, April 30, 2020.

Shift 1: Electrifying our lives

Batteries

Batteries are a critical element of achieving zero-carbon electrification. They are required to reduce CO_2 emissions from transportation and to obtain grid-scale energy storage for intermittent energy sources such as solar cells or wind.

Improving the energy density of lithium-ion (Li-ion) batteries enables applications in electric vehicles and energy storage at an affordable cost. Over the past ten years, however, innovation has stalled—battery energy density improved 50 percent between 2011 and 2016, but only 25 percent between 2016 and 2020, and is expected to improve by just 17 percent between 2020 and 2025.

Recent research[5] has shown that quantum computing will be able to simulate the chemistry of batteries in ways that can't be achieved now. Quantum computing could allow breakthroughs by providing a better understanding of electrolyte complex formation, by helping to find a replacement material for cathode/anode with the same properties and/or by eliminating the battery separator.

As a result, we could create batteries with 50 percent higher energy density for use in heavy-goods electric vehicles, which could substantially bring forward their economic use. The carbon benefits to passenger EVs wouldn't be huge, as these vehicles are expected to reach cost parity in many countries before the first generation of quantum computers is online, but consumers might still enjoy cost savings.

In addition, higher-density energy batteries can serve as a grid-scale storage solution. The impact on the world's grids could be transformative. Halving the cost of grid-scale storage could enable a step change in the use of solar power, which is becoming economically competitive but is challenged by its generation profile. Our modeling suggests that halving the cost of solar panels could increase their use by 25 percent in Europe by 2050 but halving both solar and batteries might increase solar use by 60 percent (Exhibit 2). Geographies without such a high carbon price will see even greater impacts.

Through the combination of use cases described above, improved batteries could bring about an additional reduction in carbon dioxide emissions of 1.4 gigatons by 2035.

Shift 2: Adapting industrial operations

Cement

Many parts of the industry produce emissions that are either extremely expensive or logistically challenging to abate.

Cement is a case in point. During calcination in the kiln for the process of making clinker, a powder used to make cement, CO_2 is released from raw materials. This process accounts for approximately two-thirds of cement emissions.

Alternative cement-binding materials (or "clinkers") can eliminate these emissions, but there's currently no mature alternative clinker that can significantly reduce emissions at an affordable cost.

There are many possible permutations for such a product, but testing by trial and error is time-consuming and costly. Quantum computing can help to simulate theoretical material combinations to find one that overcomes today's challenges—durability, availability of raw materials and efflorescence (in the case of alkali-activated binders). This would have an estimated additional impact of 1 gigaton a year by 2035.

Shift 3: Decarbonizing power and fuel

Solar cells

Solar cells will be one of the key electricity-generation sources in a net-zero economy. But even though they are getting cheaper, they still are far from their theoretical maximum efficiency.

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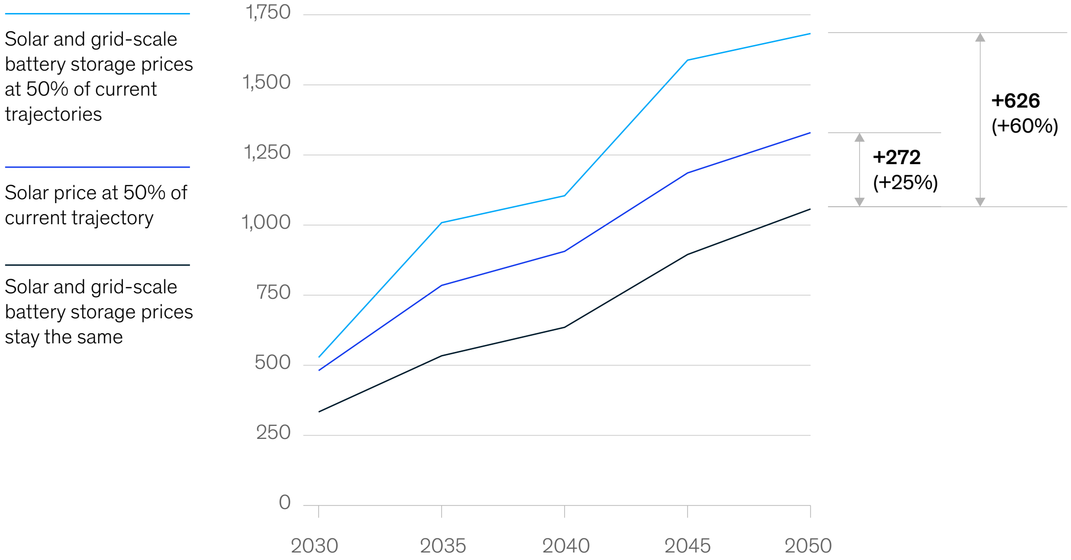
[5] Isaac H. Kim et al., "Fault-tolerant resource estimate for quantum chemical simulations: Case study on Li-ion battery electrolyte molecules," *Physical Review Research*, 2022, Volume 4, Number 2.

Exhibit 2

Quantum impacts can be synergistic.

Estimated solar power in the EU by quantum impact assumptions,[1] gigawatts



[1] The McKinsey Power Model focuses on building the lowest economic pathway to meet estimated power-demand profiles of European power grids. This combines expert estimates of cost of supply, plus a carbon price estimated at $100 by 2030 and $200 by 2050. The impacts of a quantum leap would be even more significant in countries without a carbon price.

Source: McKinsey Power Model

Today's solar cells rely on crystalline silicon and have an efficiency on the order of 20 percent. Solar cells based on perovskite crystal structures, which have a theoretical efficiency of up to 40 percent, could be a better alternative. They present challenges, however, because they lack long-term stability and could, in some varieties, be more toxic. Furthermore, the technology has not been mass produced yet.

Quantum computing could help tackle these challenges by allowing for precise simulation of perovskite structures in all combinations using different base atoms and doping, thereby identifying higher efficiency, higher durability, and nontoxic solutions. If the theoretical efficiency increase can be reached, the levelized cost of electricity (LCOE) would decrease by 50 percent.

By simulating the impact of cheaper and more efficient quantum-enabled solar panels, we see a significant increase in use in areas with lower carbon prices (China, for example). This is also true of countries in Europe with high irradiance (Spain, Greece) or poor conditions for wind energy (Hungary). The impact is magnified when combined with cheap battery storage, as discussed above.

This technology could abate an additional 0.4 gigatons of CO_2 emissions by 2035.

Hydrogen

Hydrogen is widely considered to be a viable replacement for fossil fuels in many parts of the economy, especially in industry where high temperature is needed and electrification isn't possible or sufficient, or where hydrogen is needed as a feedstock, such as steelmaking or ethylene production.

Before the 2022 gas price spikes, green hydrogen was about 60 percent more expensive than natural gas. But improving electrolysis could significantly decrease the cost of hydrogen.

Polymer electrolyte membrane (PEM) electrolyzers split water and are one way to make green hydrogen. They have improved in recent times but still face two major challenges.

1. They are not as efficient as they could be. We know that "pulsing" the electrical current rather than running it constantly improves efficiency in lab environments, but we don't understand this enough to get it to work at scale.

2. Electrolyzers have delicate membranes that allow the split hydrogen to pass from the anode to the cathode (but keeps the split oxygen out). In addition, they have catalysts that speed up the overall process. Catalysts and membranes do not yet interact well. The more efficient we make the catalyst, the more it wears down the membrane. This doesn't have to be the case, but we don't understand the interactions well enough to design better membranes and catalysts.

Quantum computing can help model the energy state of pulse electrolysis to optimize catalyst usage, which would increase efficiency. Quantum computing could also model the chemical composition of catalysts and membranes to ensure the most efficient interactions. And it could push the efficiency of the electrolysis process up to 100 percent and reduce the cost of hydrogen by 35 percent. If combined with cheaper solar cells discovered by quantum computing (discussed above), the cost of hydrogen could be reduced by 60 percent (Exhibit 3).

Increased hydrogen use as a result of these improvements could reduce CO_2 emissions by an additional 1.1 gigatons by 2035.

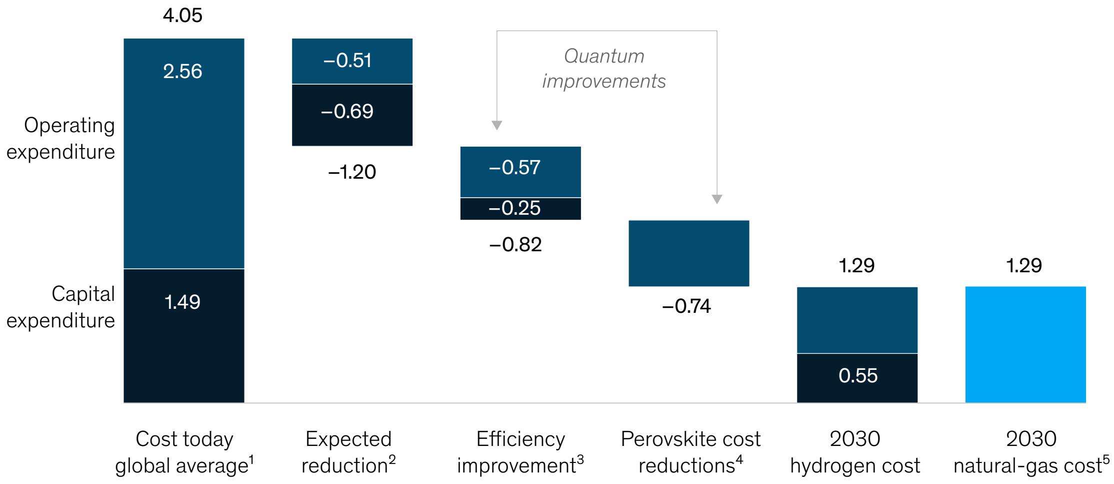
Ammonia

Ammonia is best known as a fertilizer, but could also be used as fuel, potentially making it one of the best decarbonization solutions for the world's ships. Today, it represents 2 percent of total global final energy consumption.

Exhibit 3

A combination of quantum-computing innovations could put hydrogen's carbon price on par with that of natural gas by 2030.

Cost reduction levers for green hydrogen,[1] $ per kilogram of hydrogen



[1] Hydrogen Council hydrogen cost projection assumptions—global "average" location. [2] Without quantum computing, the costs of electrolysers are expected to decrease by far from the requirements to be cost competitive with natural gas (International Energy Agency [IEA]). [3] Either from membrane/catalyst improvements or pulse electrolysis. [4] Assuming electrolysis is powered via improved solar. [5] Equivalent value to H_2 energy content—CO_2 price is $75/t$CO_2$ (IEA current trajectory); underlying gas price of $8/MMBtu, global average from late 2021.
Source: Hydrogen Council; International Energy Agency; McKinsey analysis

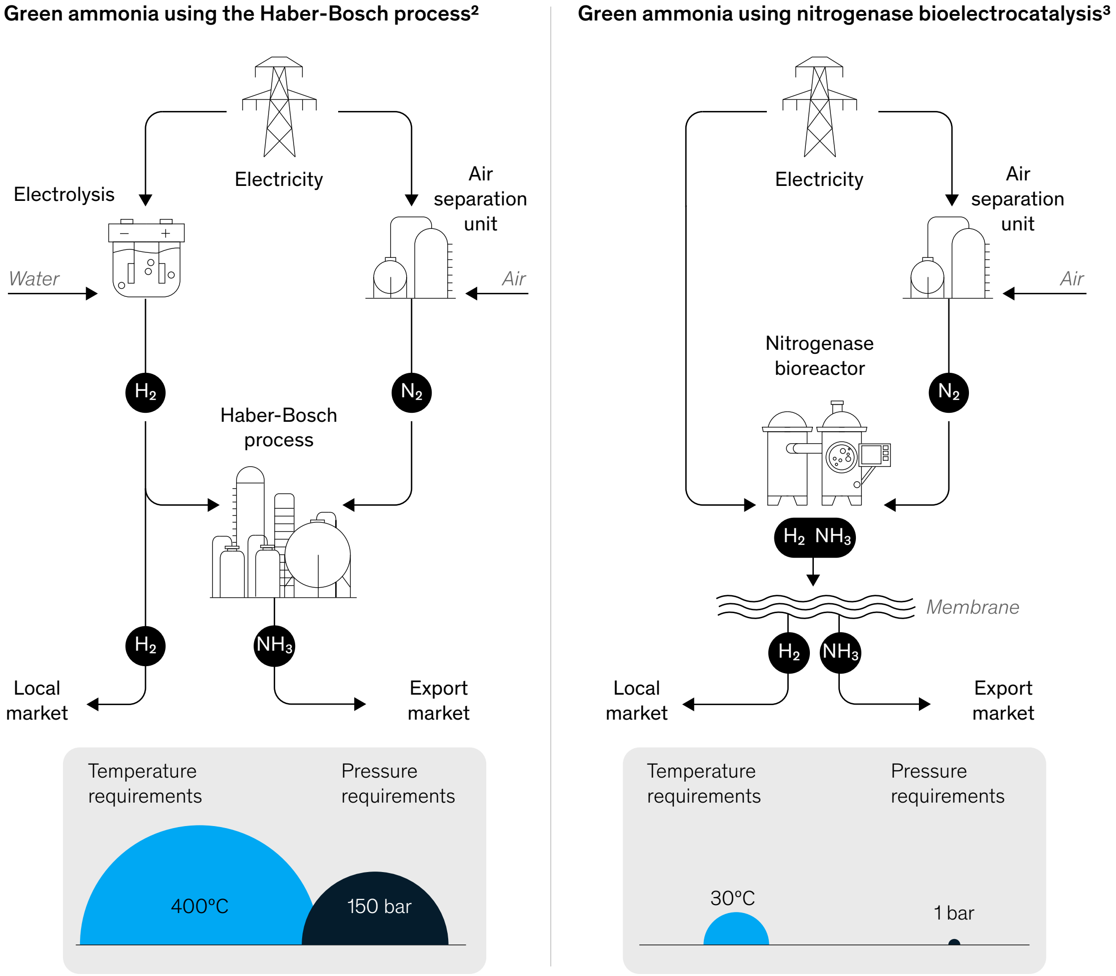
For the moment, ammonia is made through the energy-intensive Haber-Bosch process using natural gas. There are several options for creating green ammonia, but they rely on similar processes. For example, green hydrogen can be used as a feedstock, or the carbon dioxide emissions that are caused by the process can be captured and stored.

However, there are other potential approaches, such as nitrogenase bioelectrocatalysis, which is how nitrogen fixation works naturally when plants take nitrogen gas directly from the air and nitrogenase enzymes catalyze its conversion into ammonia. This method is attractive because it can be done at room temperature and at 1 bar pressure, compared with 500°C at high pressure using Haber-Bosch, which consumes large amounts of energy (in the form of natural gas) (Exhibit 4).

Exhibit 4

Nitrogen fixation using nitrogenase is a less energy-intensive way of producing ammonia.

Green ammonia production by nitrogenase needs less time and energy[1]



Green ammonia using the Haber-Bosch process[2]

Green ammonia using nitrogenase bioelectrocatalysis[3]

[1] Outline of the proposed route for exporting renewable hydrogen as ammonia and how nitrogenase can shorten this multistep process. [2] The current model for the production of NH_3 using H_2 produced through water electrolysis, via the Haber-Bosch process. [3] Outline of the process using nitrogenase enzymes. The purified N_2 feedstock is converted to ammonia and hydrogen via a solar-powered nitrogenase bioreactor. The NH_3 and H_2 are separated using a vanadium-based membrane for either export or local use, respectively.

Source: Trevor D. Rapson et al., "Insights into nitrogenase bioelectrocatalysis for green ammonia production," *ChemSusChem*, 2020, Volume 13, Number 18

Innovation has reached a stage where it might be possible to replicate nitrogen fixation artificially, but only if we can overcome challenges such as enzyme stability, oxygen sensitivity, and low rates of ammonia production by nitrogenase. The concept works in the lab but not at scale.

Quantum computing can help simulate the process of enhancing the stability of the enzyme, protecting it from oxygen and improving the rate of ammonia production by nitrogenase. That would result in a 67 percent cost reduction over today's green ammonia produced through electrolysis, which would make green ammonia even cheaper than traditionally produced ammonia. Such a cost reduction could not only lessen the CO_2 impacts of the production of ammonia for agricultural use but could also bring forward the breakeven for ammonia in shipping—where it is expected to be a major decarbonization option—forward by ten years.

Using quantum computing to facilitate cheaper green ammonia as a shipping fuel could abate an additional CO_2 by 0.4 gigatons by 2035.

Shift 4: Ramping up carbon capture and carbon sequestration activity

Carbon capture is required to achieve net zero. Both types of carbon capture—point source and direct—could be aided by quantum computing.

Point-source capture

Point-source carbon capture allows CO_2 to be captured directly from industrial sources such as a cement or steel blast furnace. But the vast majority of CO_2 capture is too expensive to be viable for now, mainly because it is energy intense.

One possible solution: novel solvents, such as water-lean and multiphase solvents, which could offer lower-energy requirements, but it is difficult to predict the properties of the potential material at a molecular level.

Quantum computing promises to enable more accurate modeling of molecular structure to design new, effective solvents for a range of CO_2 sources, which could reduce the cost of the process by 30 to 50 percent.

We believe this has significant potential to decarbonize industrial processes, which could lead to additional decarbonization of up to 1.5 gigatons a year, including cement. If the cement clinker approach described above is successful, this would still have an effect of 0.5 gigatons a year, due to fuel emissions. In addition, alternative clinkers may not be available in some regions.

Direct-air capture

Direct-air capture, which involves sucking CO_2 from the air, is a way to address carbon removals. While the Intergovernmental Panel on Climate Change says this approach is required to achieve net zero, it is very expensive (ranging from $250 to $600 per ton a day today) and even more energy intensive than point-source capture.

Adsorbents are best suited for effective direct-air capture and novel approaches, such as metal organic frameworks, or MOFs, have the potential to greatly reduce the energy requirements and the capital cost of the infrastructure. MOFs act like a giant sponge—as little as a gram can have a surface area larger than a football field—and can absorb and release CO_2 at far lower temperature changes than conventional technology.

Quantum computing can help advance research on novel adsorbents such as MOFs and resolve challenges[6] arising from sensitivity to oxidation, water, and degradation caused by CO_2.

Novel adsorbents that have a higher adsorption rate could reduce the cost of technology to $100 per ton of CO_2e captured. This could be a critical threshold for uptake, given that corporate climate leaders such as Microsoft[7] have publicly announced

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[6] Gabriel Greene-Diniz et al., *Modelling carbon capture on metal-organic frameworks with quantum computing*, March 2022.

[7] Jesse Klein, "3 things learned from Microsoft's carbon removal report," GreenBiz, April 1, 2022.

an expectation to pay $100 a ton long term for the highest-quality carbon removals. This would lead to an additional CO_2 reduction of 0.7 gigatons a year by 2035.

Shift 5: Reforming food and forestry

Twenty percent of annual greenhouse-gas emissions come from agriculture[8]—and methane emitted by cattle and dairy is the primary contributor (7.9 gigatons of CO_2e, based on 20-year global-warming potential).

Research has established that low-methane feed additives could effectively stop up to 90 percent of methane emissions. Yet applying those additives for free-range livestock is particularly difficult.

An alternative solution is an antimethane vaccine that produces methanogen-targeting antibodies. This method has had some success in lab conditions, but in a cow's gut—churning with gastric juices and food—the antibodies struggle to latch on to the right microbes. Quantum computing could accelerate the research to find the right antibodies by precise molecule simulation instead of a costly and long trial-and-error method. With estimated uptake determined according to data from the US Environmental Protection Agency, we arrive at carbon reduction of up to an additional 1 gigaton a year by 2035.

Another prominent use case in agriculture is green ammonia discussed as a fuel above, where today's Haber-Bosch process uses large amounts of natural gas. Using such an alternative process could have an additional impact of up to 0.25 gigatons a year by 2035, replacing current conventionally produced fertilizers.

Additional use cases

There are many more ways that quantum computing could be applied to the fight against climate change. Future possibilities include identification of new thermal-storage materials, high-temperature superconductors as a future base for lower losses in grids, or simulations to support nuclear fusion. Use cases aren't limited to climate mitigation, but can also apply to adaptation, for example, improvements in weather prediction to give greater warning of major climatic events. But progress on those innovations will have to wait because first-generation machines will not be powerful enough for such breakthroughs (see sidebar "Methodology").

Opportunity for corporates

The leap in CO_2 abatement could be a major opportunity for corporates. With $3 to $5 trillion in value at stake in sustainability, according to McKinsey research,[9] climate investment is an imperative for big companies. The use cases presented above represent major shifts and potential disruptions in these areas, and they are associated with huge value for players who take the lead. This opportunity is recognized by industry leaders who are already developing capabilities and talent.

Nevertheless, quantum technology is in the early stage and comes with the risks linked to leading-edge technology development, as well as tremendous cost. We have highlighted the stage of the industry in the Quantum Technology Monitor.[10] The risk to investors can be mitigated somewhat through steps such as onboarding technical experts to run in-depth diligence, forming joint investments with public entities or consortia, and investing in companies that bundle various ventures under one roof and provide the necessary experience to set up and scale these ventures.

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[8] "Climate math," 2020.

[9] "The economic transformation: What would change in the net-zero transition," McKinsey, January 25, 2022.

[10] *The quantum technology monitor*, McKinsey, September 2021.

Methodology

We selected the use cases in this article from a list of more than 150 that present stubborn technical challenges for quantum applicability. We filtered them into two stages: the first for climate impact and the second for the ability of quantum computing to find solutions for the challenges, based on likely stakeholder behavior.

As a result, we have prioritized seven use cases in five areas. Using a conservative estimate, these use cases represent 7 gigatons of additional CO_2 reduction a year in 2035, equivalent to at least 0.2°C of warming avoided by 2050. These estimates only consider use cases we have prioritized so far.

We arrived at our long list through a wide-ranging collection of ideas, expert interviews, reviews of research, and input from industry contacts, including McKinsey's Technology Council, where we assemble leading quantum technology firms regularly. We approached this process from several angles. For example, we examined both climate technologies that have major cost or implementation barriers as well as theoretical quantum innovations that may have a climatic use.

We then conducted impact analysis on our short list in three steps:

1. *Translate quantum impact to changing stakeholder behavior.* We first worked out the new cost of a technology after a quantum leap, using academic reports, expert interviews, or first principles of theoretical limits. Then, to determine stakeholder reactions, we used a "breakeven" logic in simple situations. For example, people switch to a new fuel when it is cheaper. For situations with more complex interactions, we used advanced modeling. One example: solar in grids, where generation/consumption patterns matter.
2. *Investigate the implementation ramp-up for new tech.* The delay between the time when a quantum leap is found to improve a technology and the time when a solution can be implemented needs to be factored in. For example, the time for a computer to go live; the time to build additional infrastructure such as solar; and the time to switch out assets such as zero-carbon ships). This interval varies between use cases, with the fastest expected to have impact in 2028 and the slowest starting in 2035.
3. *Subtract carbon impact that would have happened anyway.* We create counterfactual scenarios and subtract their benefit. In general, we use a 1.7°C to 1.8°C scenario based on the "stated ambitions" policy from the International Energy Agency after COP26.

For the sake of this work, we assume that the first-working fault-tolerant quantum computer will be deployed in 2026. Though consensus expert estimates are closer to 2030,[1] some quantum-computing companies have announced plans to roll them out sooner. It will then take one to two years to discover new technologies. We further assume there will be a ramp-up period ranging from two to seven years, depending on the innovation, to allow technologies to reach full scale because some applications will require large infrastructure (direct-air capture) or will need more time to switch in zero-carbon technologies (ammonia for shipping or vehicles).

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[1] "Quantum computing use cases are getting real—what you need to know," McKinsey, December 14, 2021.

In addition, governments have an important role to play by creating programs at universities to develop quantum talent and by providing incentives for quantum innovation for climate, particularly for use cases that today do not have natural corporate partners, such as disaster prediction, or that aren't economical, such as direct-air capture. Governments could start more research programs like the partnership between IBM and the United Kingdom,[11] the collaboration between IBM and Fraunhofer-Gesellschaft,[12] the public–private partnership Quantum Delta[13] in the Netherlands, and the collaboration between the United States and the United Kingdom.[14] By tapping into quantum

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[11] Damon Poeter, "IBM partners with U.K. on $300M quantum computing research initiative," *VentureBeat*, June 4, 2021.
[12] Katia Moskvitch, "Fraunhofer goes quantum: IBM's Quantum System One comes to Europe," IBM, June 15, 2021.
[13] Quantum Delta NL, accessed May 2022.
[14] "The United States and United Kingdom issue joint statement to enhance cooperation on quantum information science and technology," White House, November 4, 2021.

computing for sustainability, countries will accelerate the green transition, achieve national commitments, and get a head start in export markets. But even with those measures, the risk and expense remain high (Exhibit 5).

Here are some questions corporates and investors need to ask before taking a leap into quantum computing.

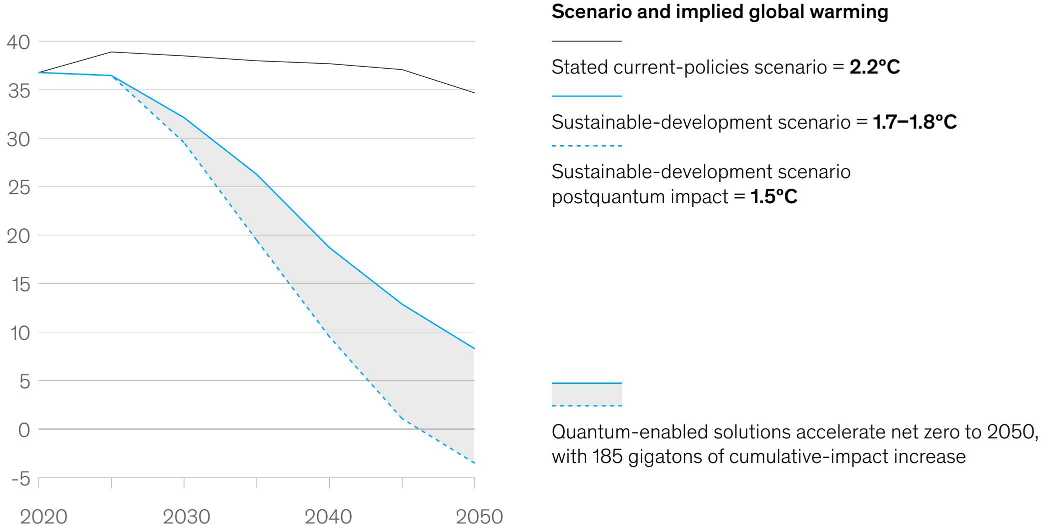
1. Is quantum computing relevant for you?

   Determine whether there are use cases that can potentially disrupt your industry or your investments and address the decarbonization challenges of your organization. This article has highlighted anecdotal use cases across several categories to showcase the potential impact of quantum computing, but we've identified more than 100 sustainability-relevant use cases

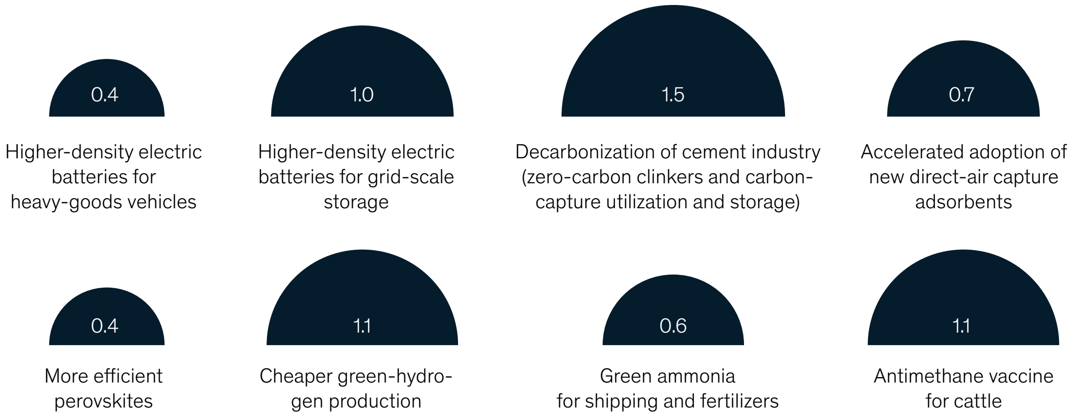
Exhibit 5

Quantum-enabled technologies could put the world back on track to becoming net-zero before 2050.

CO_2 emissions forecast,[1] gigatons



Annual additional CO_2 quantum impact abatement potential, gigatons



Source: International Energy Agency; McKinsey analysis where quantum computing could play a major role. Quickly identifying use cases that are applicable to you and deciding how to address them can be highly valuable, as talent and capacity will be scarce in this decade.

2. How do I approach quantum computing now, if it is relevant?

   Once you have engaged on quantum computing, building the right kind of approach, mitigating risk and securing access to talent and capacity are key.

   Because of the high cost of this research, corporates can maximize their impact by forming partnerships with other players from their value chains and pooling expense and talent. For example, major consumers of hydrogen might join up with electrolyzer manufacturers to bring down the cost and share the value. These arrangements will require companies to figure out how to share innovation without losing competitive advantage. Collaborations such as joint ventures or precompetitive R&D could be an answer. We also foresee investors willing to support such endeavors to potentially remove some of the risk for corporates. And there are large amounts of dedicated climate finance available, judging by pledges[15] made at COP26 that aim to reach the target of $100 billion a year in spending.

3. Do I have to start now?

   While the first fault-tolerant quantum computer is several years away, it is important to start development work now. There is significant prework to be done to get to a maximal return on the significant investment that application of quantum computing will require.

   Determining the exact parameters of a given problem and finding the best possible application will mean collaboration between application experts and quantum-computing technicians well versed in algorithm development. We estimate algorithm development would take up to 18 months, depending on the complexity.

   It will also take time to set up the value chain, production, and go-to-market to ensure they are ready when quantum computing can be deployed and to fully benefit from the value created.

Quantum computing is a revolutionary technology that could allow for precise molecular-level simulation and a deeper understanding of nature's basic laws. As this article shows, its development over the next few years could help solve scientific problems that until recently were believed to be insoluble. Clearing away these roadblocks could make the difference between a sustainable future and climate catastrophe.

Making quantum computing a reality will require an exceptional mobilization of resources, expertise, and funds. Only close cooperation between governments, scientists, academics, and investors in developing this technology can make it possible to reach the target for limiting emissions that will keep global warming at 1.5°C and save the planet.

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[15] "Long-term climate finance," United Nations, accessed May 2, 2022.

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The authors wish to thank Ivo Langhans, Molly Tinker, and Mateusz Trzaska for their contributions.

Designed by McKinsey Global Publishing