In collaboration with
Accenture

Quantum for Society:
Meeting the Ambition of the SDGs

INSIGHT REPORT

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Foreword

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Quantum technologies promise to accelerate the achievement of the United Nations' 17 Sustainable Development Goals (SDGs), paving the way for a more liveable and equitable world for current and future generations. With the 2030 SDG agenda far from completion, quantum technology could be the breakthrough innovation needed to make significant strides in the remaining six years before the 2030 deadline.

The World Economic Forum's Quantum Economy Network[1] has been working with the global quantum ecosystem to advance the responsible innovation and commercialization of quantum technology, having set the goal of "developing a sustainable future with and for quantum computing technology" in the world's first set of governance principles[2] for the technology. Extending these principles into practice, the Quantum Economy Blueprint[3] was released earlier this year, outlining multiple approaches to including sustainability building blocks in national and regional strategies.

Aligned with our goals of building this ecosystem further, this report, *Quantum for Society: Meeting the Ambition of the SDGs*, offers evidence of quantum technologies as a catalyst for sustainability. While it is not an exhaustive exploration of all possible futures, it provides a thorough analysis, real-world examples and guidance for global leaders using quantum advances to tackle planetary-scale challenges.

The report aims to raise awareness about the transformative potential of quantum solutions for society. By focusing on quantum computing, quantum sensing and quantum communication, it highlights how these technologies can deliver early value ahead of the 2030 United Nations deadline.

Assessing quantum solutions that could significantly boost global development and positively affect billions of lives, this report underscores the urgent need to cultivate a "quantum for society" ecosystem. Such an ecosystem would not only support social entrepreneurs in accessing the necessary funding but also increase knowledge among stakeholders about grants and open challenge opportunities. As quantum investments will follow the money, and the return has a long time horizon, robust advocacy is essential for the ecosystem to thrive. Additionally, the report offers preliminary thoughts on quantum as a greener computing method, assessing its energy-saving potential.

The World Economic Forum, in collaboration with Accenture, is committed to advancing the quantum for society agenda. Realizing this vision requires coordinated efforts from all stakeholders, including business leaders, policy-makers, international organizations, innovators and social entrepreneurs. Global leaders must mobilize efforts worldwide to prioritize and accelerate the implementation of quantum for societal goals. National networks, meanwhile, should promote quantum for society agendas, learn from global experiences and provide inputs based on their discoveries and innovations.

Ensuring the equitable distribution of quantum technology benefits is a shared social responsibility. Preparing the global community for inclusive quantum technology use, ensuring broad access, disseminating knowledge and promoting multilateral cooperation will be crucial to advancing a societal agenda. Global leaders must prioritize investment in quantum applications that actively support the SDGs. The time to act is now, as people collaborate on promising early applications with the potential to affect the entire planet.

Executive summary

Quantum technologies hold immense potential to produce a healthier planet and a more equitable society.

Many quantum technologies are still in the early stages of development, but their future impact on the world is undeniable. Quantum innovations hold enormous potential to address some of the most complex global challenges, such as improving carbon capture efficiency, ensuring the transition to new energy sources and mitigating climate hazards.

This report explores the connection between quantum technologies and the 2030 Agenda for Sustainable Development, which United Nations Member States adopted to address these issues through 17 clearly defined Sustainable Development Goals (SDGs). Achieving these goals means moving towards a more equitable, prosperous and sustainable world by 2030. This report explores why organizations and leaders must act now to invest in and prepare for quantum, so that this game-changing technology can be effectively harnessed in the coming years. With the 2030 deadline approaching, all must work together swiftly to meet these sustainability goals and create a better world.

The goal of this report is to raise awareness of quantum technologies' potential for society. While the timeline for the availability of fault-tolerant quantum computers remains uncertain, other technologies such as quantum sensing and quantum communication may achieve commercial readiness sooner. R&D-intensive industries are the undisputed front-runners in the quantum field, having experimented with industry-driven use cases and built proofs-of-concept for several years. However, uncertainty regarding quantum readiness and lack of clear returns on investment (ROI) hinder the foundation of a robust quantum for society network.

Public–private partnerships (PPP) and government grants at the intersection of quantum and the SDGs can create incentives for innovators to push beyond current boundaries. Government discussions often focus on technology sovereignty concerns, risking the development of further geopolitical divides and neglecting planetary challenges and social well-being, thereby limiting the potential for quantum dissemination.

To make faster and more effective progress in achieving the 17 SDGs by 2030, those involved must:

– **Assess the timelines:** Evaluate whether quantum technologies can be ready in time to accelerate the SDG agenda. Industry leaders and policy-makers must take swift, decisive action to address humankind's most complex and critical challenges. As quantum technologies evolve, all involved must closely examine which ones might realistically help achieve these goals by 2030.

– **Evaluate the impact:** Determine how quantum can have a meaningful, measurable impact on sustainability and social well-being. Identify and prioritize quantum use cases with the potential to benefit billions of lives.

– **Promote dialogue:** Encourage conversations between quantum scientists and sustainability experts. The current state of quantum technology development calls for strategic discussions on prioritizing sustainability challenges, ensuring the involvement of field experts in different disciplines.

– **Shape a "quantum for society" ecosystem:** Creating an ecosystem that uses quantum technologies to achieve societal goals requires a multistakeholder approach. Global leaders and decision-makers should promote a borderless, collaborative culture, encouraging cooperation and supporting systemic change.

Introduction

Imagine a world in which quantum technologies can accelerate the discovery of a new class of antibiotics or novel CO_2 capture solutions.

Transforming the world: The 2030 agenda for SDGs

In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development to make faster progress towards a more sustainable world. Central to this agenda are 17 Sustainable Development Goals (SDGs)[4] that promote a global framework for peace and prosperity and address a wide range of the world's most pressing issues.

Initially, efforts towards these goals seemed to yield favourable results, but recent years have seen a slowdown in progress. Factors such as the COVID-19 pandemic, the climate change crisis and geopolitical tensions have had a negative impact, leading to increased energy and food costs affecting billions of people. According to the United Nations' 2023 Sustainable Development Goals Report,[5] humanity has made only minimal progress on more than 50% of the SDG targets, and on 30% of the SDG goals progress has stalled or even reversed. The pressure to act urgently has never been greater. If stakeholders do not act, the 2030 Agenda could be "an epitaph for a world that might have been", as expressed by Haoliang Xu, UN Assistant Secretary-General and Director of the United Nations Development Programme (UNDP).

Governments and organizations need to search for innovative ways to tackle these complex, multifaceted challenges, and reignite the drive to develop transformative technologies for a sustainable future. They must prioritize sustainability and rapid progress on technological advances to reach the 2030 agenda. Here an opportunity lingers on the horizon. Could quantum technologies be the sustainability game-changer people have been waiting for? How might these technologies affect the quest to build better societies and a healthier planet?

FIGURE 1 **The 17 UN Sustainable Development Goals**

Source: United Nations, Department of Economics and Social Affairs. (2024). The 17 Goals

Quantum technologies – defined for the purpose of this report as the trio of quantum computing, quantum communication and quantum sensing – could very well be the best hope for a more sustainable future. Quantum computing, with its massive computational power, offers tremendous potential to address problems that cannot be solved or would take too long to solve with today's computers and those of the foreseeable future.

Although quantum computing is not quite ready today to address the world's most pressing challenges, some areas within quantum sensing are evolving at a much faster speed. For instance, the HYDRI consortium (HYDrogen sensoR for Industry project) led by BP, is exploring how quantum sensors can help detect hydrogen gas leaks. Accurate detection is key since hydrogen gas is invisible to the human eye and highly flammable when mixed with air.[6] Meanwhile, quantum-inspired technologies – such as classical computers that run algorithms inspired by quantum physics – are available and ready to be harnessed for good.

Although some of the benefits of quantum are already visible, it is crucial to adopt a responsible approach. Quantum computing, despite its tremendous potential, poses significant threats to cybersecurity protocols. Thankfully, three emerging technologies can help mitigate these quantum threats: post-quantum cryptography (PQC), quantum key distribution (QKD) and quantum random number generation (QRNG). These technologies will enable people to mitigate risk and stay focused on the multitude of benefits that quantum can bring.[7]

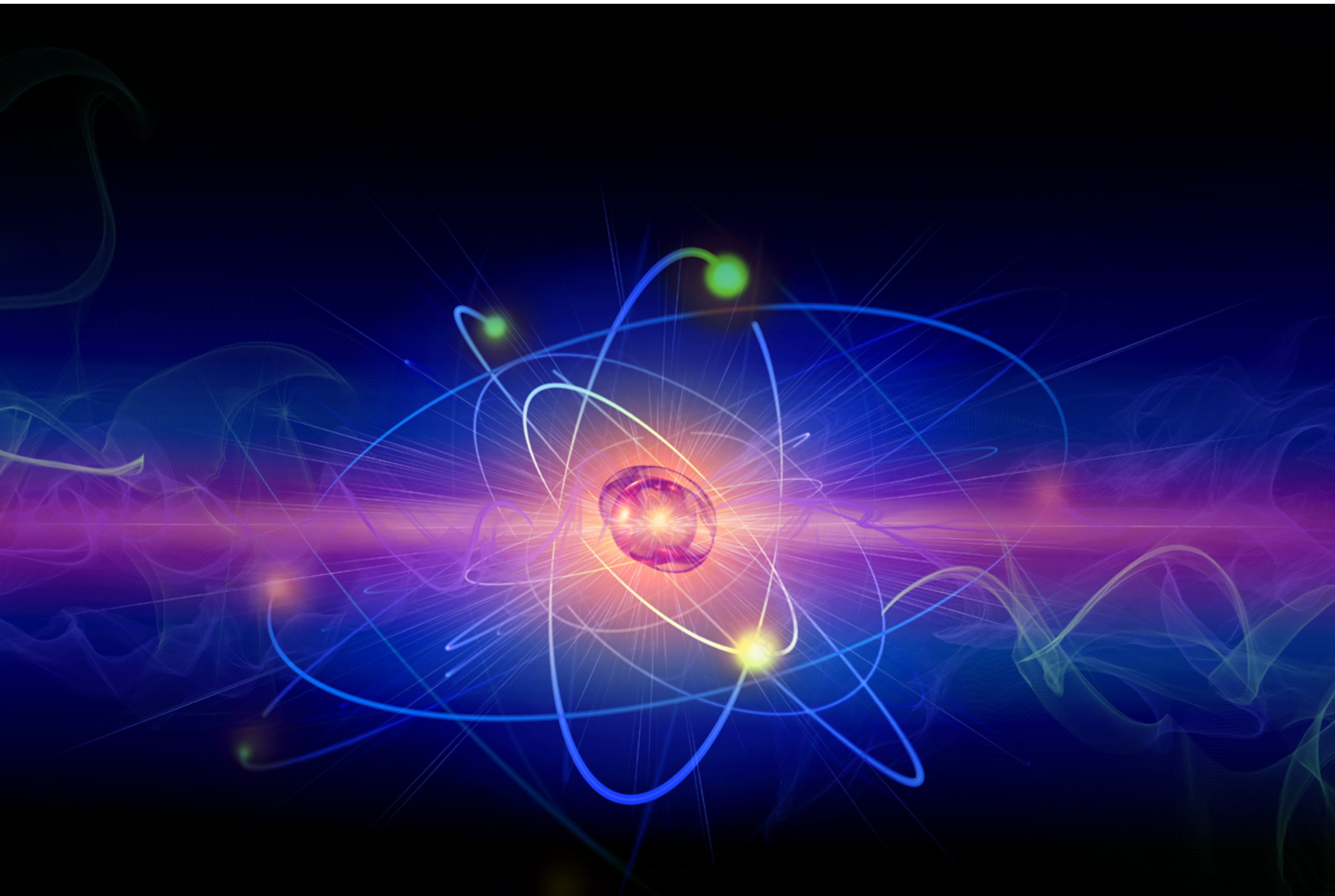
This report consists of four sections, exploring the potential impact of quantum technologies in addressing the SDG goals:

Section 1 **Seizing the quantum opportunity for a sustainable future** assesses the timelines for the 2030 SDG agenda and quantum's potential to create a meaningful global impact.

Section 2 **Reality check: Quantum investments will follow the money** discusses how industry-driven quantum solutions will generate tailwinds for quantum for society.

Section 3 **Shaping the roots of an ecosystem that prioritizes quantum for society** provides insights into how stakeholders can shape a quantum ecosystem for societal goals.

Section 4 **Quantum as a step towards sustainable computing** investigates quantum's carbon footprint, water consumption and its contribution to a clean energy transition.



1 Seizing the quantum opportunity for a sustainable future

Could quantum technologies be the sustainability game-changer people have been waiting for?

Harmful industrial practices coupled with uneven economic growth frequently result in environmental degradation (pollution, exploitation of natural resources, natural hazards and climate change) as well as growing inequality. To tackle these issues, the United Nations created a global framework to guide countries towards economic development, while at the same time balancing social and environmental sustainability.

The SDGs are an interconnected set of measurable goals designed to address interrelated social and environmental challenges and achieve global sustainable development as well as tracing the path towards the 2030 milestones. The route to achieving these milestones, however, is not simple; it requires continuous progress on multilateral dialogue and commitment from industry leaders and policy-makers to take coordinated action. In recent years, the deepening of the climate crisis has led to a growing awareness of the urgent need to advance the agenda at a faster pace. As former Secretary-General of the United Nations Ban Ki-moon expressed it, “there can be no Plan B because there is no planet B”.[8]

On top of global commitment from leaders to discuss and act on shared concerns, the power of science and technology to turbocharge efforts to advance the sustainability goals has been widely recognized, and quantum technologies could contribute to this effort. The excitement generated around quantum has led the United Nations to proclaim 2025 as the International Year of Quantum Science and Technology (IYQ).[9] This will propel coordinated events at the national, regional and local levels, raising awareness of the importance of this theme to broader audiences.

It is not yet clear when quantum will move past the research and development (R&D) stage into something that can be widely applied and used, so governments and industries must prepare now for a world in which quantum is a reality and explore ways to use it for social good. Acting today means that humanity is one day closer to reaching its sustainability goals – whether that is on a smaller scale, for individual businesses, or on a much larger one, working for example, to address global problems such as food insecurity and climate change.

And, ready or not, the clock is ticking; the 2030 SDG deadline is just six short years away. Time is running out to solve the world’s humanitarian and environmental challenges before it is too late. While it might feel daunting to attempt to move any of the SDG goals towards total fruition in such a short time frame, disruptive technologies such as quantum have a great deal of potential to accelerate the pace of progress.

1.1 **Assessing the timelines:** Can quantum technologies help accelerate the SDG agenda?

Quantum technologies are maturing at different speeds. Several quantum sensing and quantum communication solutions exist today, but quantum computers remain difficult to build and challenging to program, with full-scale machines expected in a decade or more. And developing quantum hardware is not the only challenge. Quantum algorithms are much more complex to design than classical algorithms, requiring highly skilled developers with a good understanding of the principles of quantum physics.

The list of quantum use cases to turbocharge SDGs is a long one, from weather modelling and forecasting to carbon capture and green fertilizers, to name just a few. The list of potential use cases could be much longer if concrete steps were taken to propel a continuous and coordinated dialogue between social and environmental experts and quantum experts, similar to the kind carried out for other emerging technologies. Today, most efforts naturally focus on quantum solutions with a promising return for industries. As described in Section 2, the lack of immediate ROI discourages quantum for society investments. In the next decade, however, quantum could well be *the technology* the world has been waiting for to solve the most pressing sustainability challenges.

FIGURE 2 | **The quantum technology subfields**

Source: World Economic Forum

Quantum computing: Avoiding the hype while seeking early value

Since quantum computing is a way of leveraging nature's operating system, quantum scientists have long anticipated that it would be easier to compute elements that actually happen in nature. This revolutionary idea triggered enthusiasm throughout the scientific community and the hope that quantum computing – when readily available – would play a pivotal role in solving the most pressing sustainability challenges.

It is important to note that quantum computing is expected to work best in three specific domains, with significant environmental and societal opportunities associated with them:

- Molecular simulation and discovery in materials science and biology
- Optimization and risk management in complex systems
- Artificial intelligence and machine learning

Despite the hype, quantum computers available today barely exceed a thousand qubits,[10] where a qubit or "quantum bit" is the building block for a quantum computer. For context, classical supercomputers have trillions of classical bits. Scaling current machines to perform useful tasks, such as discovering new CO_2 catalysts, would require millions of qubits. For instance, a quantum computer would require millions of physical qubits[11] to find a new catalyst for ammonia.

BOX 1 | **Improving fertilizers to enhance crop productivity**

Ammonia is employed in the production of fertilizers – which are crucial for increasing agricultural productivity and contributing to zero hunger (SDG 2). The current Haber-Bosch process of artificial nitrogen fixation used to produce ammonia is a century old but finding an alternative has been impossible because simulating the key catalysts would take more than 800,000 years on a classical computer. Moreover, the current process consumes about 3–5% of the world's natural gas, contributing to CO_2 release into the atmosphere and worsening the climate crisis (SDG 13).

For the moment, humanity is still transiting the "noisy intermediate-scale quantum" (NISQ)[12] era in which quantum machines can do certain computations in a limited fashion and subject to certain constraints and noise but with no commercial value. Without full quantum error correction (QEC), NISQ has limited utility.[13]

While a vast number of quantum architectures are actively in development (e.g. superconducting, trapped ion, neutral atoms, photonics, etc.) and more still are being researched, the plausibility of transitioning to the "full-tolerant quantum computing" (FTQC) era – with machines that can perform calculations with low error rates – is at least a decade away.[14] Stakeholders do not know when quantum will deliver on its promise, but they do know for certain that Amara's Law[15] – market hype leads typically to overestimating the short-term impact of emerging technologies while the long-term effects might be largely underestimated – applies to quantum as well.[16]

While FTQC remains on the horizon, hybrid classical-quantum and quantum-inspired approaches play a pivotal role in finding solutions to intricate problems in diverse fields. To further reduce the adverse environmental impact on urban areas and act upon sustainable cities (SDG 11), the automotive company Ford Motors experimented with quantum-inspired methods to help reduce Seattle's traffic congestion. The trial delivered balanced routing suggestions that resulted in a 73% improvement in total congestion when compared to "selfish" routing.[17]

Even if full-scale quantum computing readiness before 2030 remains uncertain, the present document intends to create awareness of how this new paradigm could become a game changer to advance the SDG goals and encourage investments that interlock quantum and the sustainability agenda, since early experimentation and talent formation are critical now and will lay the foundation for future solutions. Moreover, 2030 is simply the closest deadline in the sustainability calendar. To keep global warming to no more than 1.5°C above pre-industrial levels, emissions need to reach net zero by 2050[18] and the expectation is that FTQC will be real by that time.

Moreover, the combination of quantum plus AI is rapidly evolving and even if it is too early to imagine what might happen before 2030, quantum-powered AI could translate into breakthrough solutions for complex sustainability problems.

BOX 2 Quantum plus AI: unlocking value for the SDGs

The transformative effect of a combination of emerging technologies has always been more profound than what a single technology could provide — such is the power of "synergistic effects". Today, humanity is at the tip of the iceberg of a new duo: quantum plus AI. The intersection of these technologies will create a symbiotic relationship in which each will propel the other forward. Moreover, the revolution caused by generative AI (GenAI) will only add to the equation.

AI can advance quantum by accelerating quantum code programming and potentially algorithm development, optimizing system design and accelerating translation. The consequences of this could be significant. Any simplification in quantum algorithms will have a massive impact on the timeline of quantum advantage, allowing a real-world problem to be processed faster on a quantum than on a classical machine. Simultaneously, quantum can advance AI by overcoming the computational limitations of classical computing for training AI models and inspiring new types of machine learning (QML) algorithms rooted in quantum mechanics. Moreover, quantum may reduce the sustainability impact of existing AI models such as large language models (LLMs).

The power of these technologies combined could lead to breakthroughs for multiple industries and also unlock value for the SDGs. Early use cases with potential to meet the world's most pressing challenges are already emerging, particularly for health (SDG 3) and sustainable cities (SDG 11). Biotech companies are pioneers in this combined field. Moderna,[19] for instance, is exploring quantum computing and GenAI to advance and expedite its messenger RNA (mRNA) research to develop vaccines faster. Thanks to the synergistic effects of GenAI and quantum computing, scientists could create synthetic genetic data that closely resembles real-world data. In the future, this could then feed quantum algorithms to develop more accurate molecular models, thus speeding up the entire drug discovery process.

Sustainable cities also have a great deal to gain from quantum plus AI. Urban planners could combine these emerging technologies and create synthetic traffic data that simulates real-world traffic patterns. This data could then be used to train quantum algorithms to develop more accurate traffic projections, congestion management and route optimization models, leading to more sustainable cities with efficient transport systems, reduced travel times and improved air quality.[20]

Once these synergistic effects within a specific industry demonstrate significant impact, momentum within that entire sector will likely surge. While applications in the AI field can tackle real-world problems now, quantum offers more potential for future promise. Combined, they herald a new era of innovation that could accelerate the SDGs and unlock new value.

> **The role of business is essential in finding innovative solutions to help advance the SDG agenda. By significantly boosting the efficiency of information processing, quantum computing shows great potential in solving planetary challenges and moving towards a more sustainable future.**
>
> Tahmid Quddus Islam, Quantum Technologies Lead, Citi Global Insights

Quantum sensing: From promise to reality

Quantum sensors represent one of the most promising near-term opportunities for SDGs. Compared to quantum computing, quantum sensing is a more mature technology, with applications such as magnetic resonance imaging (MRI) in medical diagnostics having already been deployed for several years.

In contrast to other quantum technologies, quantum sensors generally compete against a wide range of devices already in use. As such, their ultimate impact will be determined by the degree to which they can enable new capabilities or drastically improve existing options in terms of sensitivity, accuracy or cost-efficiency.

Quantum sensors have a huge potential to make a real impact on people's lives. The next generation of quantum magnetometers and quantum gravimeters, which measure the strength of magnetic and gravitational fields respectively, are promising technologies and the closest ones to commercialization. For instance, the quantum sensors on a magnetocardiography (MCG) device[21] may help physicians capture a better picture of the heart's electrical activity, which could help to spot unusual patterns or signs of potential health issues. The social impact is not minor considering that coronary heart disease kills millions of people each year. Also, this advance has the potential to greatly increase the use of fetal MCG and enable routine assessment of the cardiac electrophysiology of the fetus, particularly during the first three months, which is when most complications arise.[22]

CASE STUDY 1

Using AI and quantum technologies for heart diagnostics

Cardiovascular disease (CVD) is the leading cause of death globally, causing approximately 17.9 million deaths each year. The cost of heart disease each year is more than $230 billion annually in the United States and €282 billion annually in the European Union,[23] including both direct costs for healthcare services and medicines and indirect costs for productivity loss and relatives' informal care of patients.

Addressing this issue requires a proactive approach centred on preventive diagnostics for early detection and management of heart conditions. Conventional diagnostic tools, such as the electrocardiogram (ECG), are limited, however. The ECG's reliance on the skin's electrical signals to monitor heart activity renders it susceptible to distortions as these signals traverse bodily tissues, which can lead to inaccuracies that impede medical professionals' diagnostic accuracy and lead to misdiagnosis.

Jeffrey Bander, Chief of Cardiology at Mount Sinai West, said: "The current methods for heart attack diagnosis include EKG [ECG], which is a 150-year old technology and misses many cardiac conditions. Blood tests are costly, take time to process and give false negatives and positives. SandboxAQ's approach to revolutionize cardiac diagnoses with contactless, high-performance sensors and sophisticated AI will benefit patients, save lives and impact cardiac care globally with on-demand, real-time analysis."

In response to these challenges, SandboxAQ has pioneered the development of a groundbreaking solution: magnetocardiography (MCG). This device studies the heart by measuring the magnetic fields rather than electrical impulses and mapping the magnetic activity to detect anomalies. Unlike electric signals, magnetic fields are not distorted by bone and tissue. MCG is also contactless.

SandboxAQ's MCG system uses both advanced sensors and AI: quantum sensors to detect even the slightest deviations in magnetic fields and AI to both remove interferences (such as those from other hospital devices) and assist doctors in interpreting the results and generating new insights and predictions. Thus, AI and quantum-enabled MCG have significant potential to improve the confidence and speed of diagnosing CVDs. This may offer a more reliable alternative to ECGs, and is a more affordable option compared with MRI and computed tomography (CT) scans, potentially improving the health and well-being of those with CVD (SDG 3).

> **The combination of AI and advanced sensing has the potential to profoundly impact medical imaging and improve the quality of life for millions.**
>
> Kit Yee Au-Yeung, General Manager of AQMed, SandboxAQ

Quantum magnetometers may have a new purpose in neurology as well. Next-generation quantum sensors can revolutionize brain imaging as real-time neuron-tracking can be extremely beneficial for neurologists to check if a patient's brain activity is slowing down as they age. Next-generation magnetoencephalography (MEG) devices to diagnose neurological conditions such as epilepsy, Alzheimer's disease and Parkinson's disease could also move the needle for health (SDG 3) targets. More than 55 million people have dementia worldwide, over 60% of whom live in low- and middle-income countries. And every year, there are nearly 10 million new cases, according to the World Health Organization.[24]

Quantum gravimeters, on the other hand, might contribute to a more accurate assessment of climate change due to their ability to detect alterations in Earth's gravitational field. By monitoring changes in sea levels, climate scientists better understand the mechanisms driving these shifts, resulting in more accurate predictions of melting ice and flooding dynamics. Gravimeters can also be used to monitor seismic activity, allowing early warnings of earthquakes and volcanic eruptions. Exploiting quantum for climate action (SDG 13) is one of the main components of the European Space Agency's Accelerator: Space for a Green Future, which pushes for advanced technology for a sustainable life on Earth.[25]

Other sensors such as optical atomic clocks, Rydberg atom-based radio frequency (RF) sensors and inertial sensors have demonstrated significant promise for societal applications but have not yet achieved sufficient maturity.[26]

Quantum communication: Towards ultra-secure communications that connect metropolitan or regional-scale networks

Quantum communication is a game changer because it ensures the ultra-secure transmission of data in a way that modern communication systems cannot. It is expected that in the next 25 years,[27] quantum communications will make real the construction of a secure global quantum information network – the quantum internet. A crucial breakthrough for this to happen will be the use of satellites or terrestrial quantum repeaters that can securely amplify the signals to enable transmissions over 500 km (around 300 miles).

The EuroQCI[28] is working towards a secure quantum communication infrastructure spanning the whole of the EU including its overseas territories during the next decade, but greater research and testing on a large scale will be needed to push trials in more countries and ensure the benefits can be realized. Only China has already achieved long-distance transmissions, establishing a 4,600-km (2,900-mile) quantum communications network so far.[29]

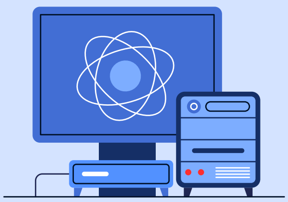
Quantum communication can help advance SDG milestones in two notable ways. First, quantum-safe communications can help to strengthen organizations against potential cybersecurity threats from criminal organizations, promoting peace, justice and strong institutions (SDG 16). For instance, the port of Rotterdam is testing a quantum communication infrastructure to ensure an untappable connection to improve the logistics chains of which the port is part. Malignant tapping of the communication systems can lead to significant financial losses for the port, disrupting critical business operations and even global supply chains. As a first step in the test, the central hub for the distribution of quantum keys will be hosted at the Port of Rotterdam Authority.[30]

Second, quantum communication will be core to every nation's infrastructure and key to advancing industry, innovation and infrastructure (SDG 9) goals. But the accent must be put on making quantum communication accessible for all, with no countries left behind. As the global quantum race intensifies, more developing countries are targeting the advancement of their quantum communication progress. For instance, in 2023 researchers at the Indian Institute of Technology Delhi achieved secure quantum communication for 380 km (236 miles)[31] in standard telecom fibre, a crucial step towards the commercial production of long-distance secure communications. In South America, the Brazilian organization EMBRAPII (Empresa Brasileira de Pesquisa e Inovação Industrial) invested 60 million Brazilian reais ($10.8 million) and selected SENAI CIMATEC to be a competence centre in quantum technologies including quantum communication[32] to advance research and quantum skills, thus positioning Brazil in a prominent position in international R&D related to quantum technologies.

Navigating the quantum S-curve: A roadmap to 2030 and beyond

In the past decade, quantum technologies have been evolving at a fast pace; however, every quantum field shows a different level of readiness. To define quantum readiness, it is essential to understand the nature of quantum technologies. This can help to estimate the potential impact and implications of these innovative areas in the short and long run, as well as identify areas in which further research and development is needed.

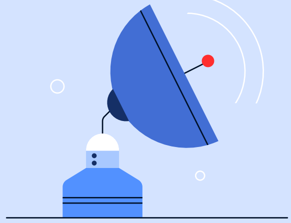
FIGURE 3 **Key challenges to quantum technology readiness**



Quantum computing (FTQC)

— Achieving fault tolerance, error correction and scalability

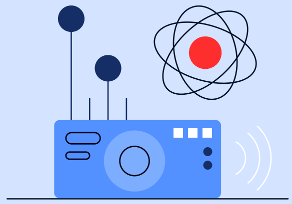
— Hardware cost



Quantum communication

— Bandwidth and distance, integration with standard communication systems

— Infrastructure cost

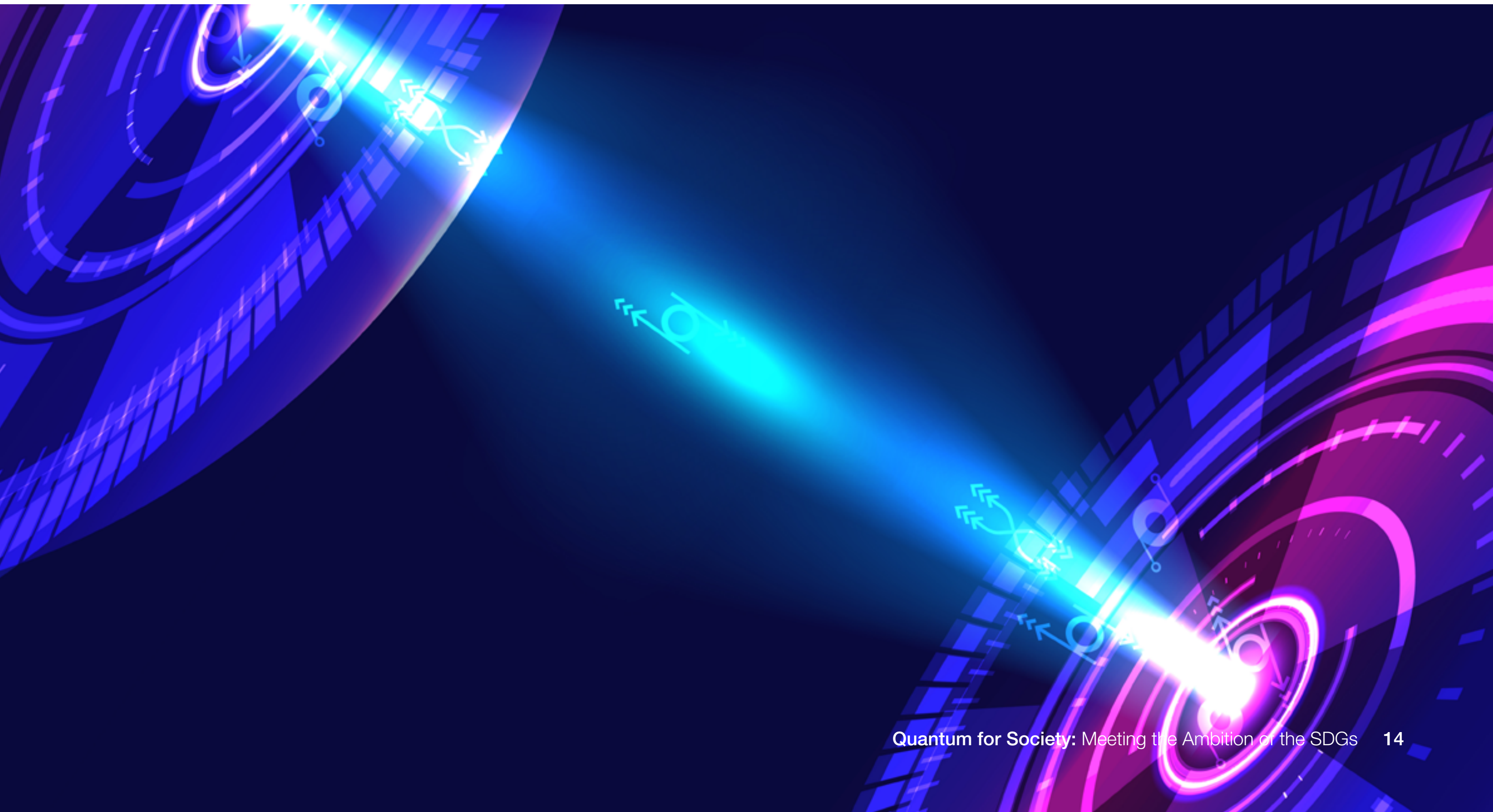


Quantum sensing

— Size, weight, power and cost (SWaP-C)

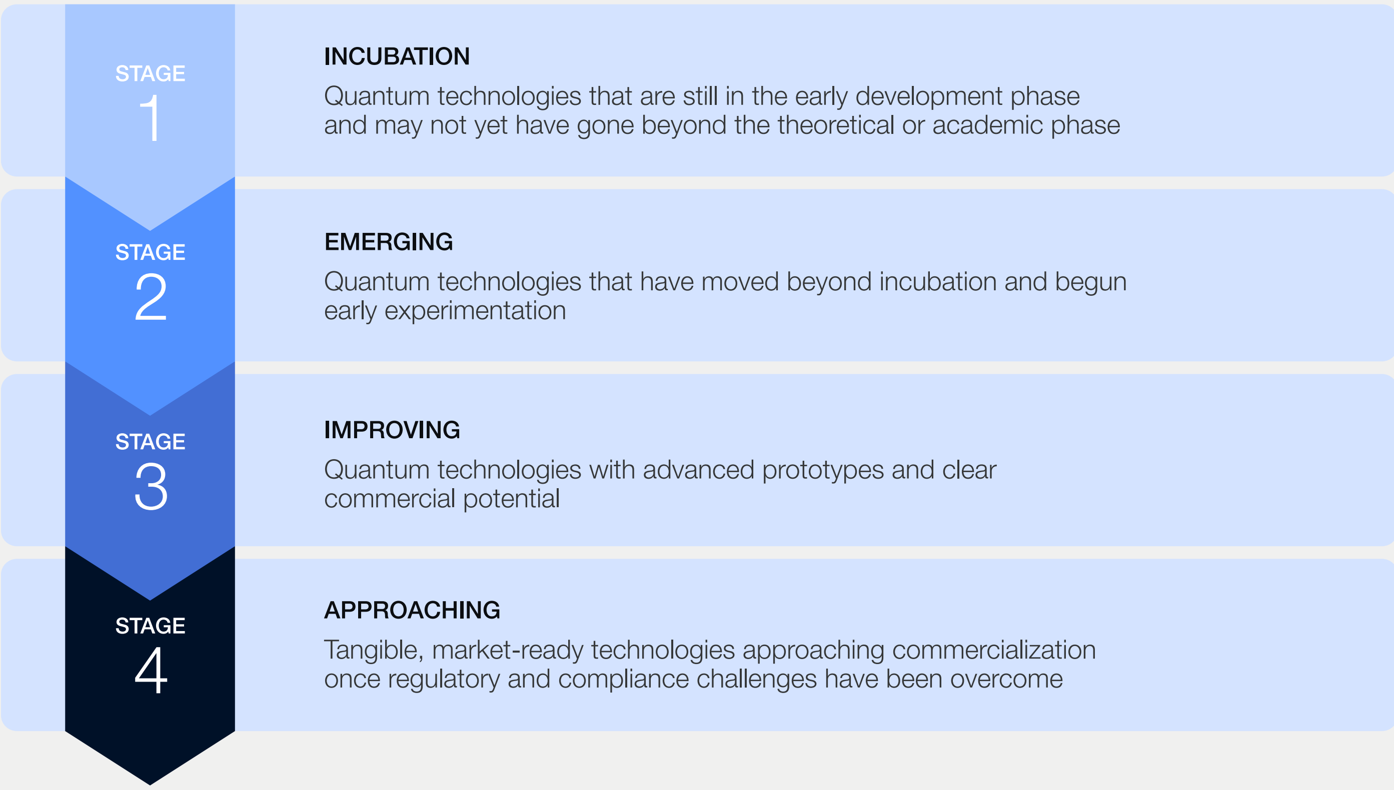
— Relative cost compared to existing sensor technology

Source: World Economic Forum



An S-curve is a useful conceptual framework for analysing the different development stages of innovation. The life cycle of new technologies has many implications for the management of innovations in businesses as well as for policy-makers supporting R&D investments. Before technology innovations achieve market readiness, government and industrial regulations need to be tackled. On the medical side, it is evident that a quantum solution will need deeper examination and more rigorous trials before it is ready for the public, while other industries might have fast-tracked procedures to comply with regulations before entering the commercial phase.

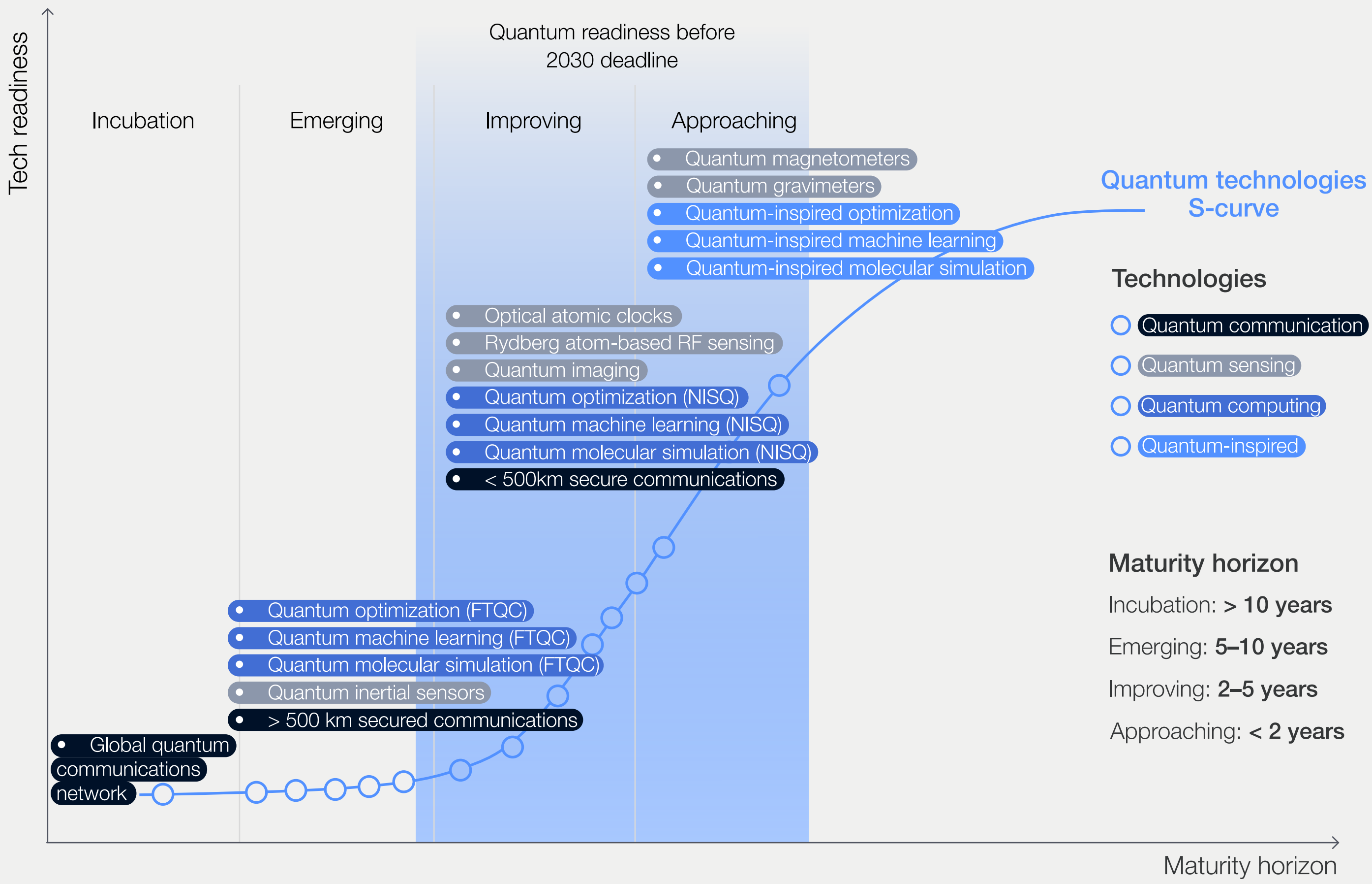
FIGURE 4 **The four stages of quantum technology readiness**



Source: World Economic Forum

Figure 5 shows the technology readiness stages of quantum computing, quantum sensing and quantum communication with an accent on 2030 timelines. The analysis displayed is directional and needs to be read with caution as quantum is a nascent field, and hence non-anticipated technological breakthroughs might change current quantum development roadmaps and drastically accelerate quantum readiness. On the contrary, investment fund movements towards other rapidly evolving emerging technologies might slow down quantum's pace of progress. Quantum plus AI is still embryonic, but if this opportunity becomes real, it might lead to an exponential change in the steepness of the S-curve. At this stage, predicting the future of quantum is an impossible task, and it should be emphasized that the ultimate goal of this conceptual framework is to equip global leaders with the tools to make assumptions and prepare strategic plans for what might be achievable given the 2030 constraints.

FIGURE 5 | **Quantum technologies with the potential to affect the SDG 2030 agenda**



Source: World Economic Forum conceptual framework based on QED-C Consortium and Citi Global Insights latest publications for quantum sensing; GESDA Radar and QURECA for quantum communication; US Department of Defense. (2023). *DoD Long View of Quantum Computing*; and publicly available quantum hardware roadmaps for quantum computing

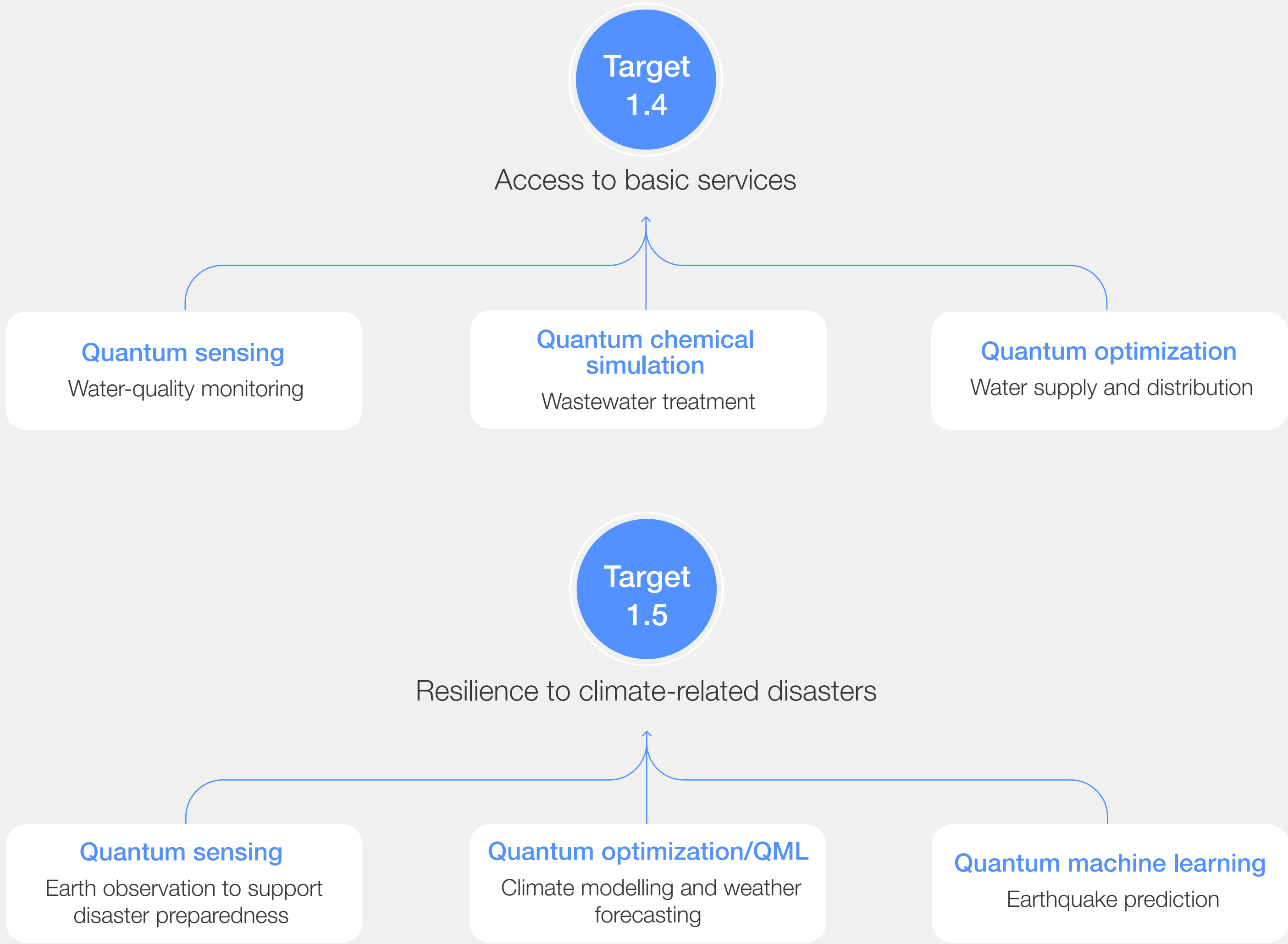
1.2 **Evaluating the impact:** How can quantum create meaningful results for society?

Affecting billions of lives for the better

Quantum solutions with the potential to scale fast, affecting billions of lives and promising a better future for all, should be the ultimate goal of “quantum for society”. Eradicating poverty[33] (SDG 1) was recognized by the United Nations as the greatest global challenge and the one most deserving of leaders’ attention. The COVID-19 pandemic has left a legacy of rising poverty, with a total of 1.1 billion people identified as poor across multiple dimensions – monetary poverty, education and basic infrastructure services.[34]

The aim of the SDGs is to reduce the proportion of people living in poverty by half by 2030. Meeting this ambitious target will require much more than visionary policies and multistakeholder dialogue. One of the promises of quantum technologies is that they might help to advance some measurable targets corresponding to SDG 1: ensuring access to basic services (Target 1.4) and resilience to climate-related disasters (Target 1.5).

FIGURE 6 | **Quantum and the hope for poverty alleviation (SDG 1)**



Source: World Economic Forum

However, eradicating poverty is not the only goal affecting billions of people. The goals related to natural resources at risk due to climate change, demographic pressure and economic growth also have a bearing on the lives of billions: a total of 2.2 billion people around the world still lack safely managed drinking water, 800 million people lack electricity and an estimated 29.6% of the global population[35] – 2.2 billion people – are affected by moderate or severe food insecurity. It was in this context that UNESCO launched the "water–energy–food"[36] (WEF) nexus. This approach aims to advance access to food (SDG 2), water (SDG 6) and energy (SDG 7) simultaneously, creating synergistic effects across these interrelated goals. Core to advancing the WEF nexus is the need to reduce greenhouse gas (GHG) emissions that contribute to climate change (SDG 13). The 2030 agenda advocates for an integrated approach that can be facilitated by a nexus scheme. As stated by former European Commission International Partnerships department Director-General Stefano Manservisi, "The SDGs are obliging us to work in an integrated way and not in silos."

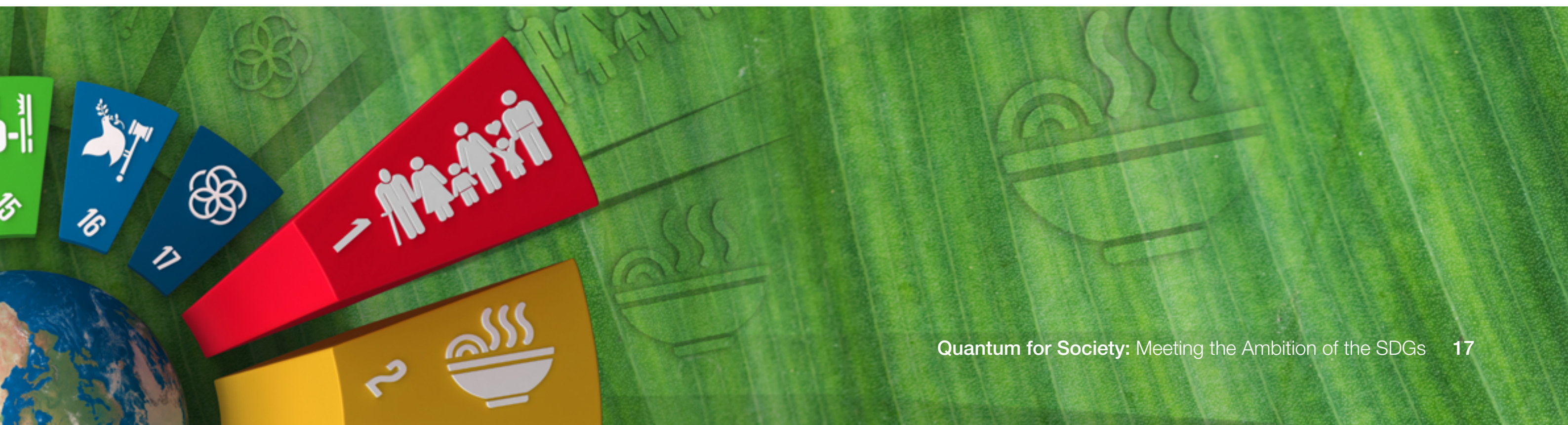
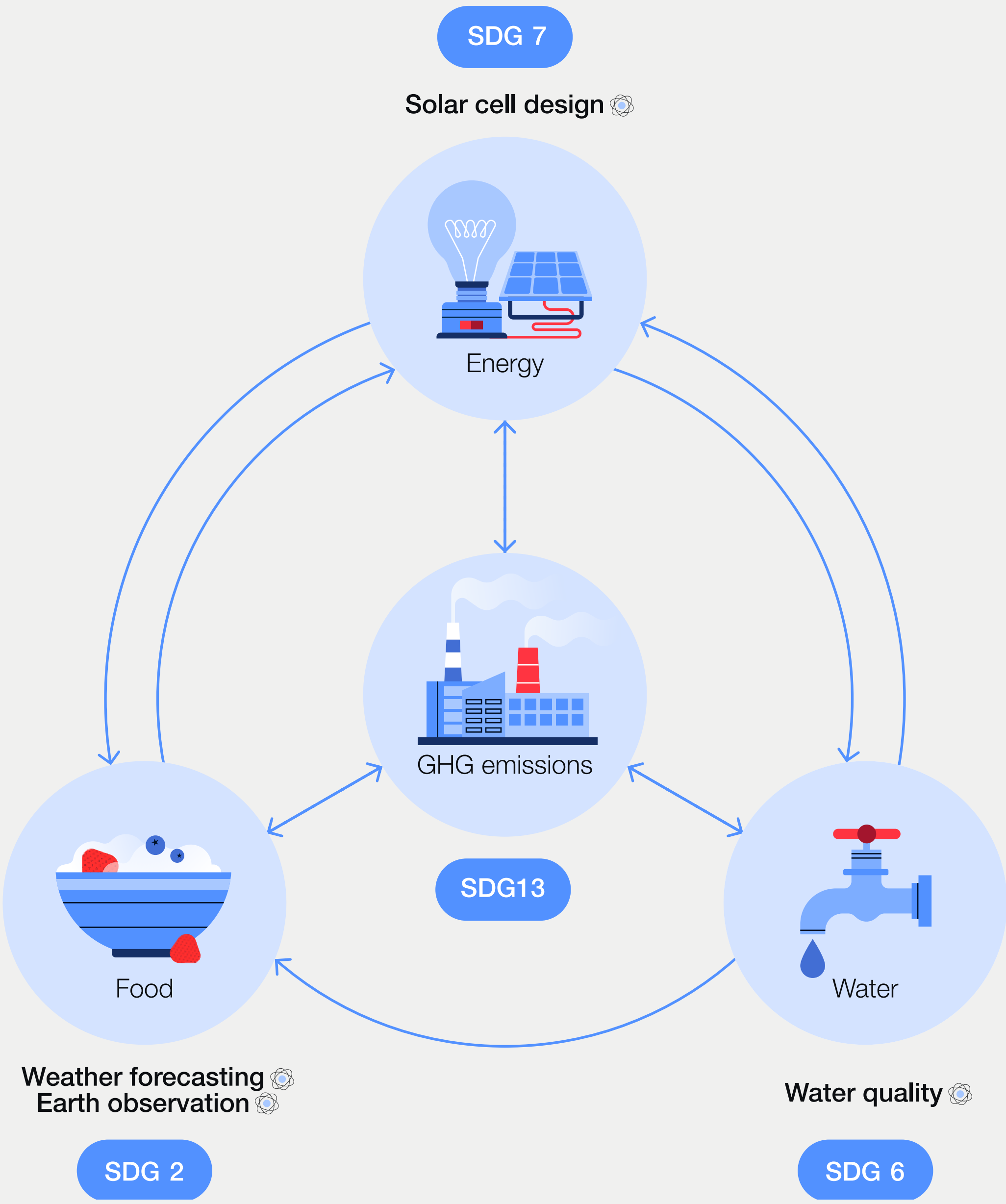


FIGURE 7 | **The water–energy–food nexus**



Source: World Economic Forum

In this regard, the World Economic Forum's analysis, covering almost 100 quantum use cases with the potential to achieve the SDGs, has identified a select group of cases that might have a multiplier effect across several SDGs. A single use case impact across several SDGs serves as an extra push for advancing the 2030 agenda at a faster pace and affecting the lives of billions of people.

Earth observation is one of the most promising use cases that can directly affect a group of SDGs.

The addition of quantum-enabled gravity and magnetic-field sensors to satellites can provide a new set of eyes to see the unseen, measuring changes that are currently invisible and gathering crucial information to understand and monitor climate change, hydro- and cryosphere evolution, groundwater, early warning of hydrological extremes and geohazards. To advance this use case, the European Space Agency (ESA) is currently working to develop technologies and components for a space quantum gravimeter or gradiometer.[37]

TABLE 1 | **Quantum use cases with a multiplier effect on the SDGs**

SDGs affected	Use case	Use case benefit	Quantum application
1 NO POVERTY; 11 SUSTAINABLE CITIES AND COMMUNITIES; 13 CLIMATE ACTION; 15 LIFE ON LAND	Earth observation	Satellites measuring many aspects of life on Earth have provided undeniable evidence of climate change for policy-making.	**Quantum sensing** can measure changes that are currently invisible and gather crucial information to understand and monitor climate change.
7 AFFORDABLE AN CLEAN ENERGY; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 13 CLIMATE ACTION	Solar cell design	Halving the cost of solar panels could increase exponentially the use of clean and affordable energy sources in developing countries.	**Quantum simulation** will help speed up the search for new solar cell materials that can process the photovoltaic effect more efficiently to convert more solar energy into electricity.
1 NO POVERTY; 6 CLEAN WATER AND SANITATION; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Water quality monitoring and purification	Understanding how water quality is changing through the network allows for the treatment process to be optimized in real time, reducing the number of incidents and associated environmental damage.	**Quantum sensing** can be used to detect pollutants in drinking water, allowing authorities to take timely action to protect public health. **Quantum simulation** can lead to the design of new chemicals for water purification.
7 AFFORDABLE AN CLEAN ENERGY; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 13 CLIMATE ACTION	Climate modelling and weather forecasting	The information provided is valuable for making adequate predictions, helping to advance scientists' understanding of climate change while mitigating its impact.	**Quantum simulation** can be used to produce weather models that leverage many variables such as atmospheric pressure, humidity, temperature and wind speed to provide accurate predictions about future weather patterns.

Source: World Economic Forum

CASE STUDY 2

Quantum for space: Artificial Brain optimizes satellites scheduling

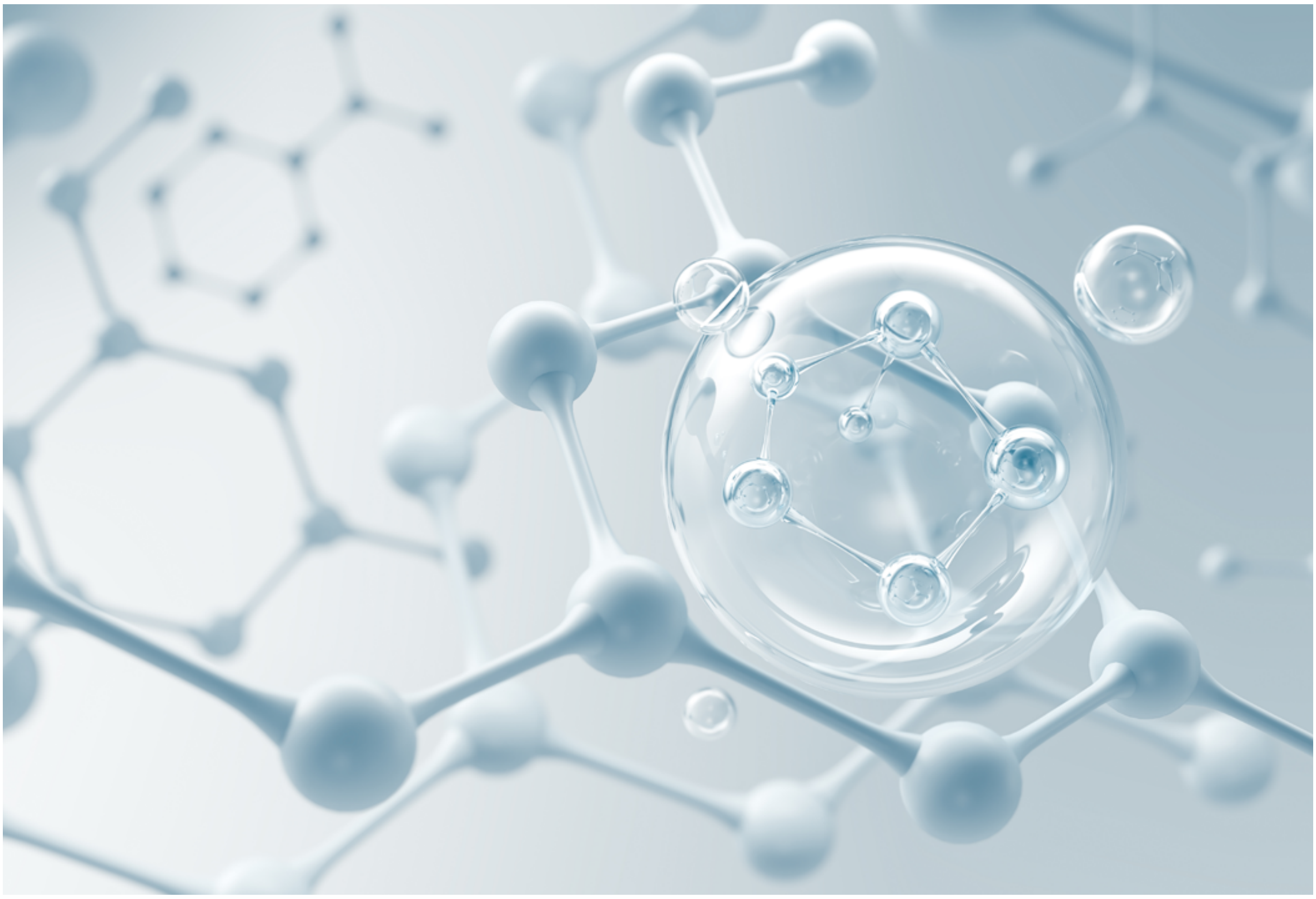
Earth observation satellites (EOS) collect essential data for decision-making in many fields, ranging from weather forecasting, disaster management and environmental monitoring to crop optimization or control and prospecting activities in mining or fishing.

To operate efficiently, EOS need to optimize their scheduling for target selection. However, this involves dealing with multiple restrictions such as satellites' storage and energy limits, weather conditions, other satellites' trajectories and orbits, and a large number of valuable targets from which to choose and prioritize. Given this complexity, classical computers' algorithms and methods are unable to come up with real-time solutions that maximize output, leading to suboptimal target selection that engenders losses in data collection and revenues.

Artificial Brain is a pioneer in quantum for space, having built quantum software to maximize the use of EOS capabilities that can potentially increase productivity and efficiency. The company is also using quantum computing to label the vast amounts of data collected from satellites, overcoming the limitations of manual data labelling. The data can then be used for machine learning.

The EOS data optimization solution has a significant impact on multiple SDGs. Improving the efficiency of satellite scheduling and data use enhances sustainable ocean management (SDG 14) by providing more accurate and timely data on ocean conditions. Additionally, the solution contributes to space sustainability by reducing pollution in outer space and optimizing the use of supranational and commercial weather satellites. Enhanced data sharing and optimization support better climate action (SDG 13) through improved weather forecasting and environmental monitoring. With potential customers such as the National Aeronautics and Space Administration (NASA) and ongoing discussions with the governments of the Netherlands and Canada, this technology promises to advance global efforts toward sustainable development.

> **Viewing space activities as a possible source of pollution to Earth is a topic which is commonly ignored and not contemplated by SDG goals.**
>
> Dana Linnet, Senior Executive for Quantum Market Engagement, Artificial Brain



CASE STUDY 3

Fighting "forever chemicals" that pollute the environment

Known colloquially as "forever chemicals", PFAS (per- and polyfluoroalkyl substances) are a group of more than 4,000 human-made chemicals, highly toxic and environmentally detrimental, that enter the human ecosystem through waterproof coatings, non-stick surfaces in cookware and food packaging.

PFAS can be toxic, causing serious health conditions including cancer. Due to their ability to move easily through some ground surfaces, these substances can reach groundwater used for public water supplies, causing the contamination of drinking water, bioaccumulation in wildlife (particularly in fish) and subsequent transportation back into the human food chain.

As finding a way to remediate PFAS is crucial, it is therefore widely studied from the computational point of view. Currently, computational models are used with classical high-performance computing (HPC) for simulation and analysis of molecular structures and their chemical properties. However, such classical HPC models are computationally expensive and not particularly scalable, which limits their accuracy, as well as the size and number of compounds subject to study.

The Irish Centre for High-End Computing (ICHEC) in collaboration with Accenture and IonQ created a scalable software platform for chemistry simulation on quantum computers to calculate the energy needed to break chemical bonds in molecules such as PFAS.[38] The experiments allowed the mapping of molecular and electronic properties, which are inherently quantum.

> **Chemistry simulation on quantum computers helps with finding mechanisms to destroy PFAS, which are human-made carcinogenic 'forever chemicals' that pollute the environment.**
>
> Venkatesh Kannan, Associate Director, Irish Centre for High-End Computing (ICHEC)

2

Reality check: Quantum investments will follow the money

Quantum for society is not regulated by the laws of supply and demand. Financial incentives are needed to propel activities that can create social change.

With total investment reaching $4–5 billion[39] yearly (if conservatively spreading government funding commitments over 10 years), the public and private sectors are joining forces to explore how quantum might affect industries and society at large. These funds have enabled exciting advances in quantum technologies, but only a tiny fraction has been allocated to solutions for social good. It seems likely that quantum solutions to solve complex industry problems in, for example, renewable energies, sustainable agriculture and health and life sciences will develop and evolve faster than other solutions such as water quality and treatment. Innovation in water-related technologies, however, requires urgent attention and funding. As water becomes scarcer and its supply more stretched, this will negatively affect progress on several of the SDGs, particularly poverty, hunger, sustainability and the environment.

CASE STUDY 4

TotalEnergies quantum-driven research for carbon capture

TotalEnergies' transition strategy aims to contribute to the development of a new decarbonized energy system based on electricity and renewables. The company is currently devoting 65% of its 2024 R&D budget to low-carbon energy (renewables, biomass, batteries, etc.) and to reducing its environmental footprint through carbon capture, utilization and storage (CCUS), and sustainable development programmes. Aimed at achieving its net zero ambition in 2050 together with society, TotalEnergies R&D's carbon capture and storage (CCS) strategy gives priority to decarbonizing the activities of the company to reduce Scope 1+2 emissions from its assets.

To be a pioneer in the exploration of new oil and gas fields, TotalEnergies has developed a long-standing expertise in scientific computing. Quantum computing is part of TotalEnergies' ambition in computation and is identified as a potential game changer for complex computations in some domains such as molecular simulations. Despite the nascent stage of quantum computing technology, TotalEnergies believes in its disruption potential, especially within the realm of CCS.

CCS stands as a pivotal technology in the global fight against climate change, offering a viable pathway to mitigate carbon dioxide (CO_2) emissions from industrial processes and the atmosphere. The efficiency of CCS hinges upon the adsorption capacity of materials used to capture CO_2 molecules. Metal-organic frameworks (MOFs), for instance, have emerged as a promising material for carbon capture.

Numerical modelling of interactions between CO_2 and MOF molecules could help to identify the right material pool before undertaking physical experiments, and quantum computing could improve the computing process. However, the current generation of noisy intermediate-scale quantum (NISQ) machines remains constrained by limitations in qubit count and error rates.

Amid the urgent imperative to accelerate CO_2 removal efforts, TotalEnergies envisions a crucial role for quantum computing in enhancing the efficiency of carbon capture processes. The world must accelerate the removal of CO_2 from the atmosphere, achieving between 3.5 billion and 6 billion tons a year by 2050.[40] A mere 1% improvement in capture efficiency, facilitated by quantum technologies, holds the potential to yield substantial cost savings, amounting to billions of dollars, thus facilitating the expansion of the technology. Such advancements underscore the critical intersection of quantum computing and environmental sustainability in driving transformative outcomes on a global scale.

> **We are confident in the vibrant quantum ecosystem of research and innovation to enhance the number of logical qubits and reduce the noise level to perform full-scale computations. In TotalEnergies, we actively enhance our understanding of quantum calculation through a key use case of CO_2 capture, recognizing that even after achieving readiness, additional efforts will be necessary to transition from material development to full-scale industrial production, likely extending beyond 2030.**
>
> Victor Martin, Head of R&D Digital Hub Paris-Saclay, TotalEnergies

Quantum for society looks set to be a two-speed investment case. Quantum applications that could propel industries to improve their bottom line or position governments to stay ahead of the curve in technology sovereignty matters are being addressed by existing R&D agendas, whether on basic or applied science. Pharmaceutical companies are investing heavily in quantum to radically shorten drug discovery timelines, and energy distribution companies are experimenting with quantum to optimize their grids. Many of these solutions will have an impact on the planet and social well-being, too. But this is not all good news; quantum use cases with a loose link to industries might now be falling behind since the ROI is less tangible, and the boundaries and responsibilities are even less clear. After all, who owns the oceans? Who is responsible for the rise in ocean temperatures?

FIGURE 8 | **The dual-speed approach of quantum for society**

Strong link to industrial use cases

Use cases

- Green fertilizers
- Molecular modelling
- Protein folding
- Route optimization
- Carbon capture
- Solar cell design
- Power grid optimization
- Battery design

Loose link to industrial use cases

Use cases

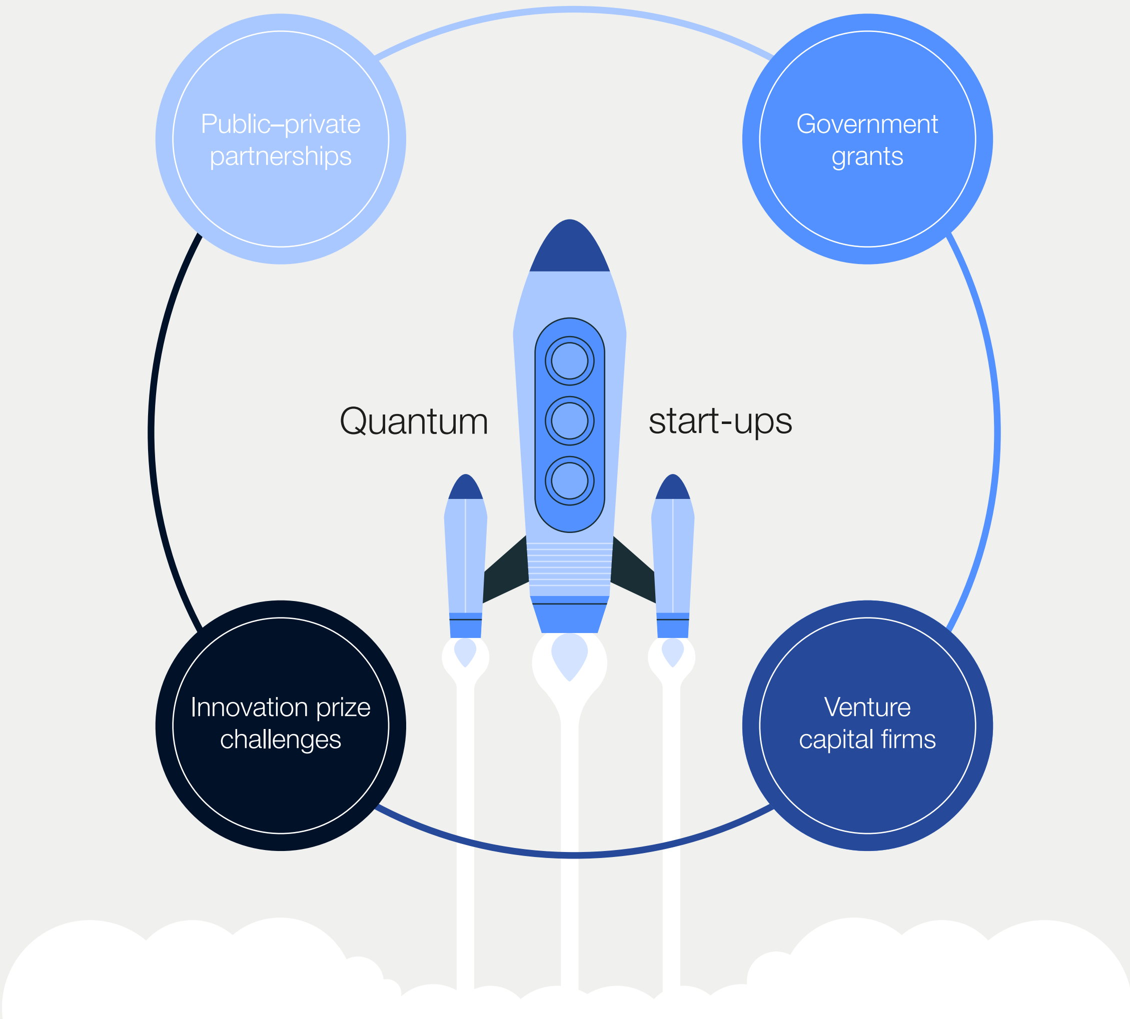
- Ocean acidification (pH) monitoring
- Biodiversity conservation planning
- Groundwater storage monitoring
- Water stress forecasting
- Air-quality monitoring
- Earth observation to support disaster preparedness
- Climate modelling

Source: World Economic Forum

This dual-speed approach might cause an unacceptable delay in solutions that are critical to ensuring the planet remains a liveable place. Innovators need access to new financial schemes that incentivize and prioritize social well-being and a sustainable planet because the SDGs are not regulated by the laws of supply and demand.

Specific funding schemes at the intersection between quantum and social impact would be an incentive for innovators to step outside of their current boundaries. Quantum needs a long time from research to commercialization, and this long-term view requires initial funds and the support of a robust environment that helps innovators prosper and thrive.

FIGURE 9 | **Ecosystem for funding quantum social innovators**



Source: World Economic Forum

Government grants

The US federal government currently provides seed funding for many scientific research projects through various agencies, including the National Science Foundation (NSF), the National Institutes of Health (NIH) and the Department of Energy (DOE). In Canada, the government released a call for projects called Quantum Computing for Climate,[41] which asked small and medium-sized enterprises (SMEs) and start-ups to demonstrate a potential application of their technology to combating climate change by reducing emissions.

Similarly, in Europe the EU-funded European Research Council (ERC) grants funding in the quantum field. The European Space Agency (ESA) and the Quality Assurance Framework for Earth Observation (QA4EO), two research projects from Europe, aim to identify Earth observation practical use cases that can be solved using quantum computers. In the UK, the Quantum Catalyst is aimed at helping innovators find quantum solutions in several areas of interest for the government, including net zero, health and many others.[42]

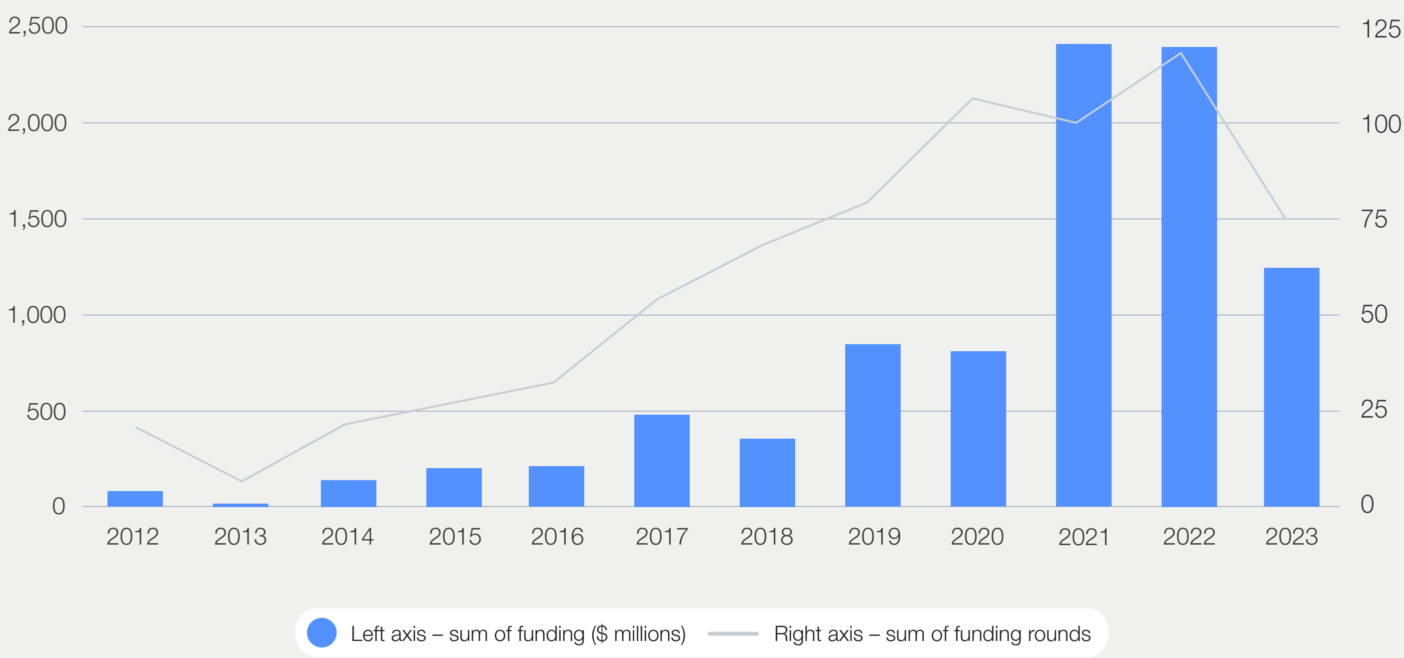
The Australian government has recently announced grants to help capture the power and potential of quantum technologies to address nationally significant challenges such as the transition to net zero, medical imaging to support diagnosis, treatment of disease and monitoring activities inside the human body, and resource exploration and extraction, among many others.[43]

These examples demonstrate that a targeted strategy at the intersection of quantum and social impact requires more attention and funding.

Venture capital firms

Quantum technology remains a niche sector, accounting for less than 1% of total venture capitalism (VC) funding. In recent years, the sector has witnessed a remarkable surge in venture investments, reaching a zenith in 2022 with $2.2 billion.[44] Most VC funds go to quantum hardware organizations that hope to one day demonstrate real-world applications. The data reveals that less than 5%[45] of funds correspond to quantum software. It is evident that while software start-ups are unable to demonstrate that their solutions can achieve a tangible benefit or advantage, the VC interest and investment in quantum solutions have a ceiling. Therefore, social innovators in this space seem to be even further away, unless they can demonstrate a clear ROI.

FIGURE 10 **Venture capital investment in quantum technologies** ($ millions, rounds)



Source: The Quantum Insider, January 2024

Private investments may be affected by other factors as well. As shown in Figure 10, following the 2022 zenith, investment in quantum start-ups declined by nearly 50%[46] in 2023. This drop was primarily driven by 2022 being a significant year for quantum technologies. Meanwhile, investments in generative AI increased by 153%,[47] following advances that allow for clear materialization of its commercial potential.

In this context, social innovators in the quantum field will struggle to create interest for private investors. Therefore, the need for prize challenges, hackathons and public–private partnerships with a clear focus on social impact is clear. It is reasonable to assume that when the first quantum machines approach the time for evidencing real-world applications, VC flows will redirect to them (as happened with generative AI), creating new funds for quantum for society as well.

As with generative AI, VC will certainly have a major role to play in the development of this whole set of technologies. As a matter of fact, current VC funding volume for quantum technologies is comparable in size to that for AI a decade ago.

Innovation prize challenges

Several prize challenges have emerged in the past few years inviting start-ups, universities and large organizations to present quantum solutions to tackle global challenges. Still, a great deal more could be done to create incentives for social innovators in the quantum space, reach global audiences and be more visible to potential participants with a deep knowledge of the main SDG issues in developing countries. Table 2 presents a non-exhaustive list of challenges addressing SDGs.

In addition, the World Economic Forum announced in April 2024 that it will embark on a partnership with its Centre for the Fourth Industrial Revolution in Saudi Arabia to bring the power of quantum computing to bear on sustainability challenges, including climate action and economic development. The collaboration will seek to identify and elevate the most scalable quantum technologies that can accelerate progress towards meeting the SDGs in Saudi Arabia.[48]

> **C4IR Saudi Arabia's collaboration with the World Economic Forum holds the potential to unlock innovative solutions that address sustainability challenges through the power of quantum technologies, while also creating a more inclusive, collaborative, innovative and impactful innovation ecosystem in Saudi Arabia and beyond.**
>
> Basma AlBuhairan, Head of Centre for the Fourth Industrial Revolution, Saudi Arabia

BOX 3

The [re]Generative Quantum Challenge: Seeking to address SDG challenges while lowering the energy footprint with quantum computers

In 2023, French start-up Pasqal, in close collaboration with Blaise Pascal Advisors, launched the Blaise Pascal [Re]generative Quantum Challenge. This inaugural hackathon attracted more than 750 participants from 25 countries across the globe and resulted in three winning teams providing novel solutions on renewable energy forecasting, windmill farm optimization and molecular docking (drug discovery).

Participants were given six sustainability challenges, related to 10 SDGs.

- Drug discovery (SDG 3)
- Smart grids, affordable and clean energy (SDG 7)
- Environment, climate and biodiversity (SDGs 13, 14 and 15)
- Sustainable agriculture (SDG 2)
- Sustainable transport and industry, circular economy (SDGs 9 and 12)
- Smart cities (SDGs 6 and 11)

What was different compared to other quantum for SDGs challenges? Participants were evaluated not only on the sustainability value and technical quality of the use case but also on the carbon footprint advantage resulting from energy savings as compared to an existing classical HPC solution. The teams were asked to demonstrate the feasibility of the proposed solution on Pasqal's neutral atoms computers. As a result of the success of this hackathon, the company expects to launch a "Sustainable Quantum AI" hackathon by the end of 2024.

> **We are not just advancing technology for its own sake, our goal is to anchor quantum computing in solving the world's most pressing challenges.**
>
> Georges-Olivier Reymond, Chief Executive Officer and Co-Founder, Pasqal

TABLE 2 | Innovation challenges contributing to SDG progress

Initiative	Host country	Organizer	Year	SDGs addressed	Purpose of the challenge
Commercialising quantum technologies challenge	UK	UK National Quantum Technologies Programme (NQTP)	2018–2025	3. Good health and well-being 7. Affordable and clean energy 9. Industry, innovation and infrastructure 11. Sustainable cities and communities 13. Climate action 14. Life below water 15. Life on land	Drive innovation across sectors (e.g. healthcare, communications)
NYUAD Hackathon for Social Good in the Arab World	United Arab Emirates	New York University Abu Dhabi (NYUAD)	2024	Social impact in a broad sense (SDG not specified)	Use quantum computing for social good
OQI Use Case Ideas Submission	Switzerland	European Organization for Nuclear Research (CERN)	2024	Social impact in a broad sense (SDG not specified)	Rebalancing the focus of quantum computing applications towards impact for the benefit of humanity
Quantum City Challenge	Canada	University of Calgary	2024	7. Affordable and clean energy	Solve energy problems with quantum technologies
Deloitte's Quantum Climate Challenge	UK	Deloitte	Annually since 2022	13. Climate action	Enhance flood forecasting
Quantum for Bio (Q4Bio)	USA	Wellcome Leap	2023	3. Good health and well-being	Demonstrate biology and healthcare applications benefitting from quantum computers
Quantum for Environment Design Challenge	Canada	University of Waterloo	2023	6. Clean water and sanitation 7. Affordable and clean energy 11. Sustainable cities and communities 13. Climate action 14. Life below water 15. Life on land	Create a design document leading to innovation for the environment
Quantum for Health Design Challenge	Canada	University of Waterloo	2022	3. Good health and well-being	Search opportunities for quantum technology to advance health
Quantum Simulator Challenge	Japan	Fujitsu	2023	3. Good health and well-being 7. Affordable and clean energy 11. Sustainable cities and communities"	Demonstrate quantum algorithms to improve Alzheimer's disease diagnosis, improve drug discovery and optimize distributed energy resources
The Blaise Pascal [re]Generative Quantum Challenge	France	Pasqal, Blaise Pascal Advisors	2023	2. Zero hunger 3. Good health and well-being 6. Clean water and sanitation 7. Affordable and clean energy 9. Industry, innovation and infrastructure 11. Sustainable cities and communities 12. Responsible consumption and production 13. Climate action 14. Life below water 15. Life on land	Address SDG challenges while lowering the energy footprint with quantum computers
XPRIZE Quantum Applications	USA	Google Quantum AI and GESDA	2024	3. Good health and well-being 7. Affordable and clean energy 9. Industry, innovation and infrastructure 13. Climate action"	Enhance drug discovery, improve electrical grid loads efficiency and reduce carbon emissions

Source: World Economic Forum

Public–private partnerships (PPPs)

The most effective way to identify a set of potential quantum for society applications is through a discovery process that involves cooperation among all stakeholders, from quantum scientists and domain subject matter experts to end users. Accordingly, governments should consider establishing PPPs or using an existing PPP that helps pinpoint quantum solutions that are nearly ready for widespread use. To do this, they should facilitate collaboration and interaction among quantum experts and user communities and garner their thoughts and opinions on the development of quantum technologies. Examples are provided in Table 3.

An integrated approach that considers how all elements interact is needed. This approach is one in which public and private stakeholders at a global and domestic level work together to bridge the SDG financing gap, achieving more than they could on their own.

TABLE 3 | Public–private partnerships addressing the SDGs

Initiative	Host country	Public sector	Private sector	Academy	SDGs addressed
European Quantum Industry Consortium (QuIC)	EU, UK		Airbus, Classiq, BASF, BBVA, Pasqal, SAP, Accenture, others	CERN, Delft University, University of Cambridge and others	3. Good health and well-being 9. Industry, innovation and infrastructure 13. Climate action 14. Life below water 15. Life on land
Open Quantum Institute (OQI)	Switzerland	Geneva Science and Diplomacy Anticipator (GESDA), CERN, Swiss Federal Department of Foreign Affairs	UBS	ETH Zurich, EPFL and others	2. Zero hunger 3. Good health and well-being 6. Clean water and sanitation 7. Affordable and clean energy 13. Climate action
QuantumCT	USA	State government and municipalities from the state of Connecticut	IBM, Microsoft, RTX, Quantinuum, Boehringer Ingelheim	Yale University, University of Connecticut, five others	3. Good health and well-being 7. Affordable and clean energy
Quantum Delta NL (QDNL)	Netherlands		Each Innovation hub contains research institutes, universities, companies and start-ups – QDNL Delft, QDNL Amsterdam, QDNL Leiden, QDNL Eindhoven, and QDNL Twente		Social impact in a broad sense (SDG not specified)
Quantum Economic Development Consortium (QED-C)	USA	44 public agencies, departments and other institutions, including the Defense Advanced Research Project Agency (DARPA), NASA, NSF, DoE and the Federal Bureau of Investigation (FBI)	165 companies including IBM, Google, Microsoft, Intel, SRI and Accenture	35 universities and research institutes including Harvard and Stanford	7. Affordable and clean energy 9. Industry, innovation and infrastructure 11. Sustainable cities and communities 13. Climate action
Quantum STrategic industry Alliance for Revolution (Q-STAR)	Japan	Japan Science and Technology Agency (JST), National Institutes for Quantum Science and Technology (QST) and others	Toshiba, Toyota, Hitachi, Fujitsu, Mitsubishi, Suzuji, SoftBank and others	Kyushu University, Tohoku University, Yokohama National University, Central Research Institute of Electric Power Industry and others	Social impact in a broad sense (SDG not specified)
UK National Quantum Technologies Programme (NQTP)	UK	Department for Business, Innovation and Skills (BIS), Ministry of Defence, Government Communications Headquarters (GCHQ)	Airbus, GlaxoSmithKline, Johnson Matthey, Rolls-Royce, others	University of Oxford: Quantum Computing and Simulation Hub University of Birmingham: UK Quantum Technology Sensors and Timing Hub University of York: Quantum Communications Hub University of Glasgow: Quantum Technology Hub in Quantum Enhanced Imaging (QuantIC)	3. Good health and well-being 7. Affordable and clean energy 13. Climate action

Source: World Economic Forum

CASE STUDY 5

Cleveland's quantum partnership propels advanced medical research

Cleveland Clinic is committed to pioneering medical research aimed at enhancing patient outcomes and propelling medical innovation. Through its robust research programmes, the enterprise spearheads groundbreaking studies and clinical trials spanning a diverse array of medical disciplines, inspiring transformative advances in healthcare.

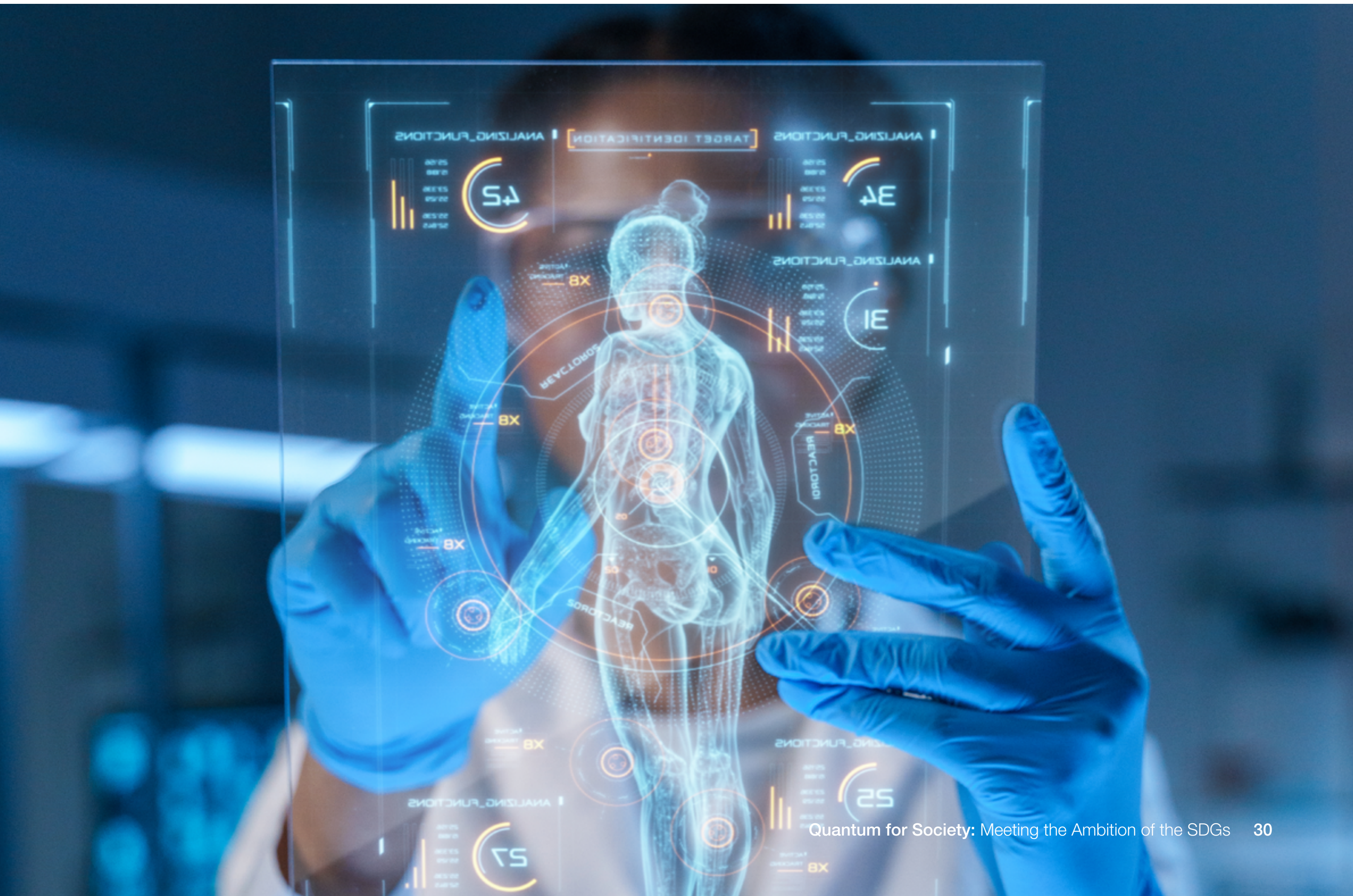
Notably, Cleveland Clinic is in the vanguard of quantum healthcare research through its 10-year Discovery Accelerator partnership with IBM. The goal of the partnership is to advance the pace of discovery in healthcare and life sciences through advanced computing. An important aspect of the partnership is the world's first quantum computer dedicated to healthcare research, housed at Cleveland Clinic's main campus. This initiative is also part of the Cleveland Innovation District and supported in part by an investment of more than $500 million over a decade from the State of Ohio, JobsOhio and Cleveland Clinic, aimed at accelerating biomedical discoveries. This strategic investment significantly increases the medical centre's research personnel and physical research space, equipping it with enhanced computing capabilities to drive efficiency and innovation.

At the core of the Discovery Accelerator's quantum research endeavours is the development of a framework for identifying problems with the potential for quantum advantage. More than a dozen quantum research projects have been initiated under this initiative. Cleveland Clinic has been selected by Wellcome Leap to lead a quantum computing research project, while also playing a significant role in another led by Algorithmiq – both in collaboration with IBM Quantum.

One project harnesses quantum simulation to predict protein structures and elucidate their behaviour and interactions with other molecules, thereby shedding light on the underlying mechanisms of diseases crucial for the development of targeted therapies. Meanwhile, another project explores how quantum computing can facilitate the development of photon-activated drugs for cancer prevention and treatment. These endeavours are at the forefront of showcasing the potential of quantum computing to advance global health and well-being (SDG 3) but also underscore the impact of collaborative efforts in healthcare research and innovation.

Quantum is still a nascent technology, but it is our future – if we don't prepare for it now, we'll be late.

Lara Jehi, Chief Research Information Officer, Cleveland Clinic



3

Shaping the roots of an ecosystem that prioritizes quantum for society

The cornerstone of a quantum for society ecosystem is the creation of a collaborative culture, with cooperation among key stakeholders supporting systemic change.

Quantum's tremendous power opens the door to solutions unimaginable today to the challenges faced by humanity. It could help to decarbonize the world at scale, design new solar cells for globally expanding the use of clean energies or even monitor groundwater reserves, an issue critical to the survival of all species on Earth. Complex problems require quantum solutions that can scale globally, creating meaningful and measurable impact for society and the planet, all of which cannot happen without a strong collaborative network of key stakeholders.

This network of stakeholders must contribute to the development and adoption of quantum for societal goals by ensuring a fluid exchange of technical and domain expertise to facilitate the foundation and growth of the ecosystem. The Q4Climate initiative[49] is a good example of how research and industry communities can collaborate across national borders to develop new insights into using quantum technologies to reduce the pace and impact of climate change.

However, international collaboration for quantum in today's fragmented global landscape is not a given. Government discussions are often driven by concerns about the sovereignty of technology, creating the risk of further geopolitical divides, with little emphasis on sustainability and social impact, thus limiting the potential for quantum for society.

Building a quantum for society ecosystem is a 'glocal' effort

Building a quantum for society ecosystem might require a glocal approach, combining global and local considerations. From a global perspective, the most effective way to identify and prioritize a set of practical solutions might be through a discovery process that involves cooperation and dialogue among global leaders, from quantum scientists to sustainability domain experts, international organizations, industry and academia. Thematic working groups could be organized covering social and sustainability issues, such as for access to water (SDG 6) or climate action (SDG 13). This global effort could potentially affect billions of people and would help to bring closer the date at which real-world progress can be made on the SDGs.

The identified application areas can help policy-makers push forward public investments in quantum, customizing the global findings to their own national agendas and most pressing sustainability challenges. For instance, less than half the population in all sub-Saharan African countries had access to safely managed drinking water in 2022.[50] Developing countries have the highest need for applications to advance the SDGs: they know what specific needs they have (e.g. eradicating poverty, access to water, etc.) but may lack access to the quantum infrastructure and algorithms to make it happen.

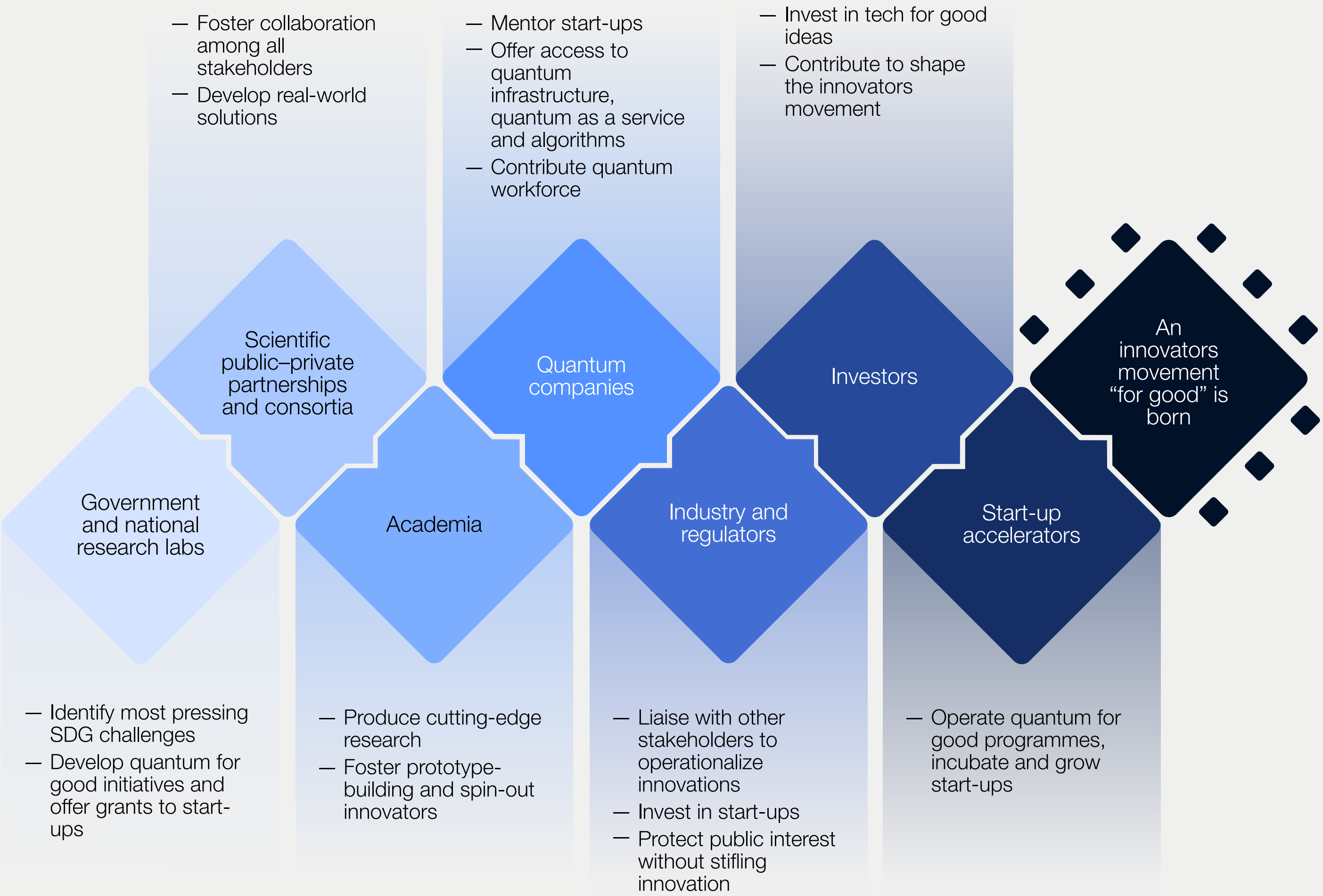
FIGURE 11 | **Global commitment to accelerate quantum for society solutions**

Source: World Economic Forum

National governments have pressing challenges of their own. Knowledge exchange must move in both directions: from global to local, and vice versa. Federal agencies might need to accelerate the introduction of grants and funded initiatives as well as endorse PPPs that promote the creation of a vibrant ecosystem. Cooperation among all actors involved – for example, from academia to start-up accelerators, research laboratories and quantum vendors – will fuel an embryonic entrepreneurs' movement that works for the well-being of the community and the planet.

Innovators in the quantum field face many challenges that go well beyond the need for funding. Focusing on solutions for society will require an extra push, offering them more targeted aid. Quantum innovators are typically spin-offs of university-based research centres, and count on academic backing while often lacking global support to expand their reach and scale their solutions. Moreover, to accelerate real-world applications, they need easier access and exposure to quantum infrastructure.

FIGURE 12 | It takes a village to build an innovators movement for sustainability and social good



Source: World Economic Forum

Building an inclusive quantum ecosystem

Scaling the ecosystem to achieve its full potential requires full commitment from all stakeholders. However, the goal of building and nurturing this network might be too difficult for the least developed countries to achieve.

Building upon the concept of "quantum for all", in autumn 2024 the World Economic Forum will launch the Quantum Applications Hub: a one-of-a-kind experiential platform showcasing success stories of quantum technologies from around the world and aiming to shape a scalable and inclusive quantum ecosystem. As well as providing open access to these stories, it will offer demos of applications across all quantum technologies, with the aim of increasing awareness and adoption of both industrial and societal goals.

By focusing on the SDGs, the Forum expects also to open the benefits of quantum to all humankind.

> **The development of quantum technologies requires large investments, specialized training and a highly and mature technological environment which is only achievable in a few developed countries. Governments, private companies and public institutions must find innovative ways to ensure an inclusive, equitable and global development of these technologies to meet the SDGs and face our collective global challenges.**
>
> Karen Hallberg, Professor of Physics and Principal Researcher, Bariloche Atomic Centre and Balseiro Institute (CNEA and UNCu) and CONICET, Argentina

BOX 4 The Open Quantum Institute: Developing applications for the benefit of humanity

The Open Quantum Institute (OQI)[51] was established in January 2023, creating a neutral platform around which a large and committed global community of stakeholders has united, with the goal of shaping technology for the benefit of society. As a novel science diplomacy instrument, OQI brings together stakeholders from research, diplomacy, industry and philanthropy to promote global and inclusive access to quantum computing and develop applications for the benefit of humanity. It was created at the Geneva Science and Diplomacy Anticipator (GESDA), is hosted at the European Organization for Nuclear Research (CERN) and supported by UBS.

OQI has an active and supportive advisory committee, comprising 35 members from all corners of the world, representing all of the stakeholders above and working together to provide strategic input and contribute to the achievement of the organization's goals. Moreover, the large OQI community of more than 300 participants is an integral component of the initiative, and one that is continuing to grow formally, with 13 partners, 16 members and 49 friends of OQI to date. With strong collaboration between public and private stakeholders, OQI is uniquely positioned to rebalance the focus and resources of quantum towards applications beneficial to meeting the SDGs, rather than simply being used for commercial or geostrategic advantage.

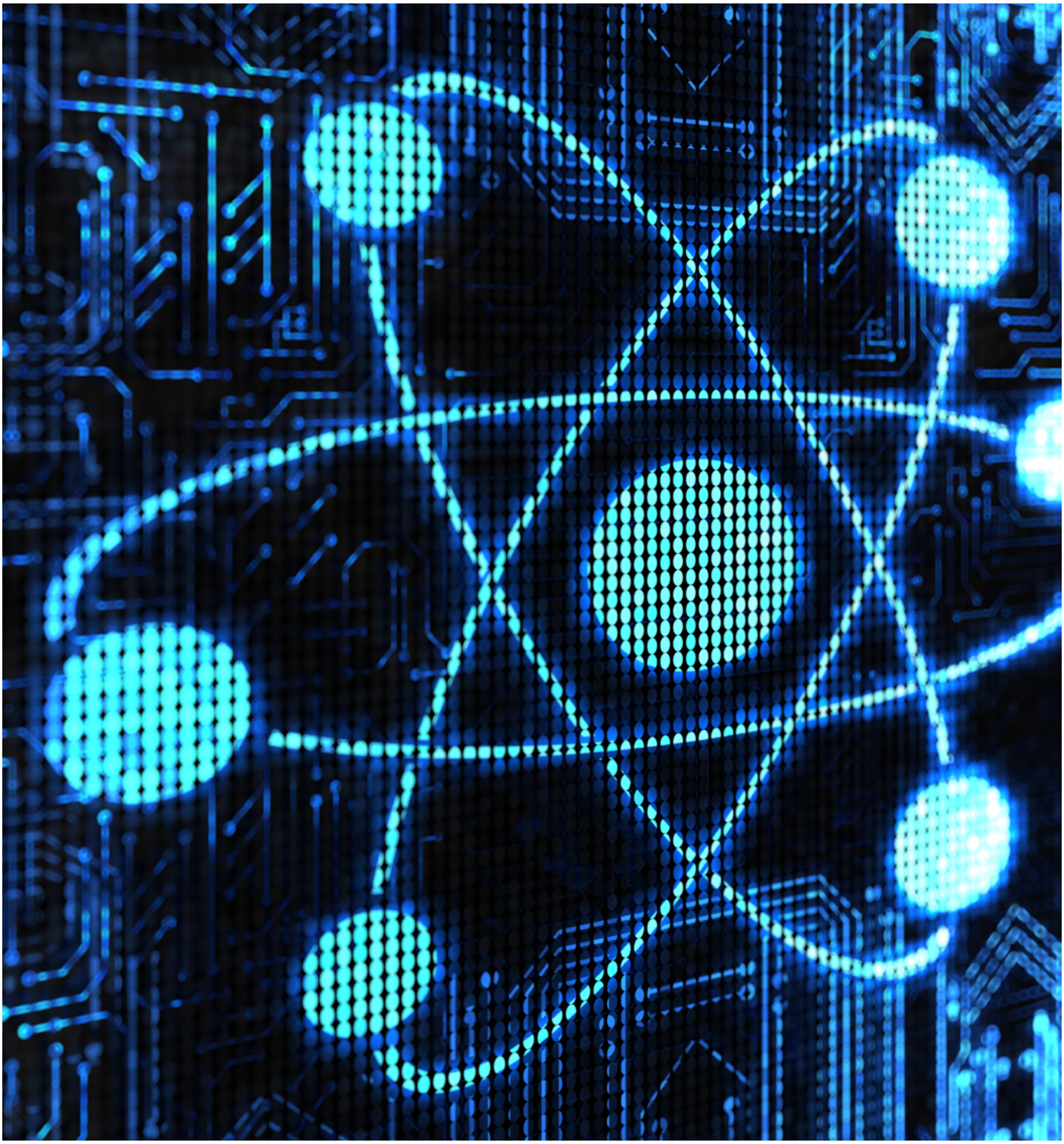
In the past year and a half, teams from the OQI Community have worked collaboratively to explore use cases related to food (SDG 2), health (SDG 3) and climate change (SDG 13). During its pilot phase (2024–2026), OQI is aiming to build a large repository of quantum computing use cases for the SDGs, with the objective of inspiring greater participation in this ambitious endeavour to affect humanity. OQI strongly promotes a responsible approach throughout its use case development pipeline, from initial ideation to implementation on quantum computing devices. This encompasses the assessment of both societal and environmental effects (including energy/carbon footprint). In doing so, OQI collaborates with experts to assess such impacts, anticipate negative externalities and prioritize use cases.

To ensure the broadest and most inclusive capture of ideas, OQI is using a multipronged approach to feed its use case development pipeline – from calls for submission of use case ideas through to focused approaches via workshops with UN organizations and activation of like-minded initiatives, to fast-tracked use cases from OQI's incubation phase. With tens of use case ideas that have already passed the impact/quality criteria, the aim is to refine many of the outlines, with the goal of developing some use cases as proof of concepts to be implemented on quantum simulators, contributed by private-sector partners, by 2025.

> **OQI aims to reverse the common technology development cycle by ensuring that the world's most pressing issues guide the shaping of appropriate future technology.**
>
> Enrica Porcari, Head of IT Department, CERN

4 Quantum as a step towards sustainable computing

The search is on for a new computing paradigm that may rein in energy usage.



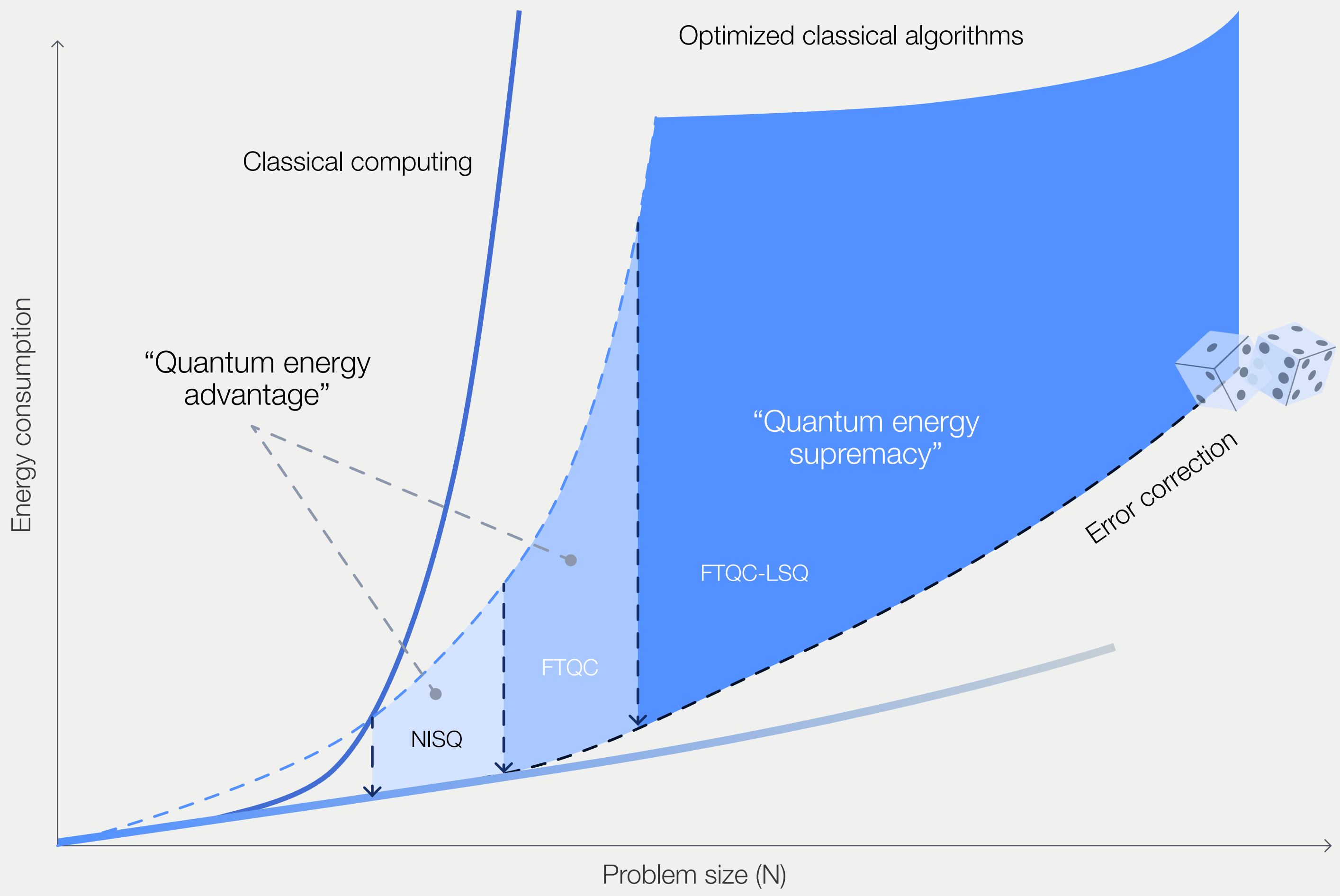
The use of compute-intensive systems comes at a high cost. Today, data centres account for 1–1.5% of global electricity usage,[52] which plays against energy efficiency targets for 2030 (SDG 7). But a much less well-known fact is that large data centres are also heavy water users, requiring between 1–5 million gallons a day on average,[53] putting at risk future generations' access to water (SDG 6). There is no doubt that compute-intensive systems can help humanity solve complex planetary problems, but a more rigorous debate about the implications for sustainability targets must be prioritized. What if quantum technologies could provide an advantage in terms of water and energy efficiency?

Energy efficiency: Can quantum deliver on its promise of a greener future?

It is expected that quantum computers will ultimately be able to solve problems that would take conventional systems thousands of years to work out. But what would be the value if quantum machines can merely match but not outperform classical computers? From a sustainability standpoint, the answer is clear: quantum might offer the promise of a more sustainable computing paradigm. And this could be the real power of quantum computing – to go well beyond qubits and algorithms and put the accent on a greener future.

While achieving quantum advantage is the holy grail for organizations, seeking "quantum energy advantage"[54] could be an attainable and sustainable goal. To further explore this concept, the Quantum Energy Initiative (QEI) was launched in 2022 to ensure that quantum computers were built with a consideration of the environmental impact from the design phase. A 2023 analysis by QEI indicates that some energy advantage for quantum computers may be found, as shown in Figure 13.

FIGURE 13 **Reducing digital footprint with quantum computers**



Source: Auffèves, A., & Ezratty, O. (2022). Quantum Energy Initiative

Proclaiming energy savings is much more than a simple calculation. A supercomputer might require a month to solve a specific problem that a quantum computer could solve within a few minutes, but the relationship between energy consumption and computation time in a quantum computer is not linear. According to Alexia Auffèves, Director of MajuLab, a French-Singaporean international research laboratory, “there is no proportionality between time and energy”.[55] Due to quantum’s challenge to preserve information, these machines use disproportionately more energy as the problem size grows to involve more consecutive operations.

There is a long list of factors to consider when measuring energy efficiency, from the specific problem to be solved to the hardware architecture and cooling system used. In addition, the overall infrastructure required to support quantum computing may reduce energy savings as quantum computers become larger and more powerful.

Past experiments have already shown promising results. In their 2019 quantum supremacy study, Google researchers found that a quantum computer offered energy savings over a state-of-the-art supercomputer.[56] In a more recent experiment using ARCHER2, the UK’s most powerful supercomputer, a group of researchers has been able to simulate 44-qubit Quantum Fourier Transform (QFT) 40% faster, achieving 35% energy savings.[57] Despite these and several other revealing experiments, it is too early to give a verdict. A more rigorous framework for evaluating energy efficiency is required.[58]

It should also be emphasized that replacing supercomputers with quantum machines is not the solution. It is not classical versus quantum, but classical plus quantum that will help humanity reduce its carbon footprint and get closer to achieving the SDGs.

Water: The hidden computing cost

The use of AI and compute-intensive systems is bad news for humanity’s water footprint. Data centres’ demand for water is constantly increasing. As stated in SDG 6 (Clean water and sanitation), water scarcity has become one of the most pressing global challenges in the face of a rapidly growing population, depleting water resources and ageing water infrastructure, especially in drought-prone areas.

Quantum computing might come to the rescue to reduce the water footprint of compute-intensive systems. First, quantum computers may be capable of solving complex problems related to the optimization of heat management in data centres. This would reduce the reliance on water-cooled air conditioning, saving significant amounts of water.

Also, quantum should be able to speed up data analysis, meaning that complex data-processing tasks might be completed more quickly, in a matter of hours instead of years, thus reducing the run time for time servers and consequently their demand for energy and cooling. Considering the exponentially growing current demand for AI, this point is critical.

The rise of generative AI has amplified this problem. However, innovative ways to maximize the use of recycled water and the advent of quantum computing offer cause for hope. While these are still in the early days, a more rigorous analysis and benchmark figures are much needed in this regard.

Renewables: The link from quantum to grid

As clearly stated in SDG 7 (Affordable and clean energy), moving to renewable energy sources will be critical to achieving net zero by 2050. In moving towards this goal, the integration of more solar, wind and other renewable sources into the grid will be required to replace higher-carbon sources, so that it is possible to provide affordable and sustainable electricity for all.

With the huge number of ways in which energy can now be generated and supplied, it is critical to handle many inputs and outputs, but classical computing is not designed to handle an exponential scale-up in input parameters. Dynamic resource management could be an area to further explore for sustainable quantum computing, so that systems demand can be flexibly matched to variable renewable generation.

In this regard, some initiatives are already under way. The National Renewable Energy Laboratory (NREL) and Atom Computing[59] are building a quantum smart grid control testbed, linking a quantum computer in-the-loop with a real-time digital grid simulator. E.ON and IBM[60] are also collaborating on quantum computing for several applications , including vehicle-to-grid optimization, while the start-up Phasecraft is conducting a feasibility study with the UK Department for Energy Security and Net Zero[61] on quantum computing for power system planning.

Quantum computing is still in its very early stages, and its value for power systems remains unproven. More experiments will be available as policy-makers support R&D and invest in widely accessible national quantum computing infrastructure.

Conclusion

Future generations deserve bold solutions to address the SDGs – it is therefore time to prioritize investment in quantum technologies.

The impact of quantum technologies is already evident in several R&D-intensive industries that are conducting early experiments or developing prototypes. In the future, this initial activity can accelerate societal objectives if stakeholders focus on practical solutions aimed at improving life on Earth. To positively affect billions of lives, cooperation and focus on the milestones established by the UN SDGs must be increased. Quantum technology could be the breakthrough needed to address complex planetary emergencies that cannot be solved with the systems available today.

Among the various quantum technology subfields, quantum sensors might be the most promising near-term opportunity. However, it is too early to determine which technology will achieve market readiness before the 2030 deadline. This report presents a shared vision of the technological developments that might provide early value before 2030, while acknowledging that quantum roadmaps are a moving target and unexpected technical breakthroughs might change the equation on what is feasible in the next six years. Nevertheless, climate and sustainability discussions must start now because 2030 is not the only finish line. Governments have agreed that emissions need to be reduced by 45% by 2030 and reach net zero by 2050, necessitating radical new ways to capture CO_2 from the atmosphere, for instance.

Later this year, the World Economic Forum will unveil a Quantum Applications Hub containing practical quantum solutions, including those advancing work towards meeting the SDGs, thereby contributing to levelling the playing field by providing a broad access platform for all. To shape and scale a social innovators' movement in the quantum space, the Forum will also embark on a partnership with its Centre for the Fourth Industrial Revolution in Saudi Arabia to leverage quantum computing for sustainability challenges, including climate action and economic development.

The Forum stated in a 2022 report that the governance of quantum computing should be directed to "the benefit of humanity".[62] The authors hope that this report encourages global leaders and decision-makers to take a holistic approach and assess these technologies, either alone or in tandem, to see how they can be used to create a deep, measurable global impact.

It is time to prioritize social well-being and actively work to preserve the environment for present and future generations. The opportunity to harness quantum technologies for social good must be seized now.

Appendices

A.1 Use cases

TABLE 4 An inventory of potential quantum for society use cases

SDGs	SDG target	Quantum computing	Quantum sensing	Quantum communication
1 NO POVERTY	1.4	Wastewater treatment	Water-quality monitoring	Secure data communication and cyberthreat prevention
	1.4	Water supply and distribution		
	1.5	Climate modelling and weather forecasting	Earth observation to support disaster preparedness	
	1.5	Earthquake prediction		
2 ZERO HUNGER	2.4	Green ammonia (fertilizers)	Soil moisture monitoring	
	2.4	Plant DNA sequencing		
	2.4	Climate modelling and weather forecasting		
	2.4	Smart vertical farming		
3 GOOD HEALTH AND WELL-BEING	3.3	Molecular modelling and simulation		
	3.4	Protein folding		
	3.4	Human DNA sequencing		
	3.4	Medical/drug supply chain		
	3.4	Vehicle routing		
	3.4	Disease outbreak prediction	Magnetocardiography (MCG)	
	3.6	Patient treatment scheduling	Magnetoencephalography (MEG)	
	3.8	Healthcare staff scheduling	Medical screening	
	3.8	Radiotherapy		
	3.b	Organ transplant pairing		
	3.b	Medical imaging/accelerated diagnosis		
	3.c	Disease analysis		
	3.d	Medical inventory management		
4 QUALITY EDUCATION	4.3	Effective resource allocation		
5 GENDER EQUALITY	5.2	Crime prevention		
	5.2	Patrol scheduling		
6 CLEAN WATER AND SANITATION	6.3	Wastewater treatment		
	6.4	Water stress forecasting	Water-quality monitoring	
	6.4	Water supply and distribution	Groundwater storage monitoring	
		Water purification		
7 AFFORDABLE AND CLEAN ENERGY	7.1	Electricity trading		
	7.1	Battery design (energy density)		
	7.1	Predictive maintenance		
	7.2	Solar cell design		
	7.3	Power grid optimization	Power grid monitoring	
	7.3	Gasoline (petrol) blending		
8 DECENT WORK AND ECONOMIC GROWTH	8.1	Credit risk analysis		
	8.a	Supply chain optimization		

SDGs	SDG target	Quantum computing	Quantum sensing	Quantum communication
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	9.1	Supply chain optimization	Quantum navigation	Secure data communication and cyberthreat prevention
	9.1	Vehicle routing		
	9.2	Robot movement optimization		
	9.2	Predictive maintenance		
	9.2	Workforce scheduling		
	9.4	Green hydrogen for steel manufacturing		
	9.4	Zero-carbon cement clinkers		
	9.c	5G radio cell planning		
10 REDUCED INEQUALITIES	10.5	Fraud detection		
11 SUSTAINABLE CITIES AND COMMUNITIES	11.1		Air-quality monitoring	
	11.2	Public transport scheduling		
	11.5		Earth observation to support disaster preparedness	
	11.6	Waste collection route optimization	Underground infrastructure	
	11.c	Green hydrogen for steel manufacturing		
	11.c	Zero-carbon cement clinkers		
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	12.2		Water-quality monitoring	
	12.2		Groundwater storage monitoring	
	12.a	Power grid optimization		
	12.a	Solar cell design		
13 CLIMATE ACTION	13.2	Energy shipping	Greenhouse gas emissions	
	13.2	Battery design (energy density)	Earth observation to support disaster preparedness	
	13.2	Point-source CO_2 capture	Air-quality monitoring	
	13.2	Direct-air CO_2 capture		
	13.2	Solar cell design		
	13.2	Waste collection route optimization		
	13.2	Wind/solar farm layout		
	13.2	Climate modelling and weather forecasting		
	13.2	Wind turbine design		
14 LIFE BELOW WATER	14.3		Ocean acidification (pH) monitoring	
	14.4	Fish stock prediction		
15 LIFE ON LAND	15.3		Earth observation to support disaster preparedness	
	15.5		Wildlife preservation	
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	16.1	Crime prevention		
	16.1	Patrol scheduling		
	16.4	Fraud detection		

A.2 Glossary

The table below provides definitions of the most-used terms throughout this document for reference.

TABLE 5 **Glossary of terms**

Classical computing	Approach to computing that employs a stream of electrical impulses in a binary manner (1 and 0) to encode information in bits
Fault-tolerant quantum computer (FTQC)	An advanced quantum computer able to perform calculations with arbitrarily low logical error rates
Hybrid quantum-classical computing	Exploiting the ability of quantum computers while alleviating the downsides of being limited, small and unreliable with classical computing
Noisy Intermediate-scale quantum (NISQ) computer	A quantum computer prone to errors that contains quantum processors with up to a few hundred qubits, not advanced enough yet for fault-tolerance
Quantum advantage	Demonstration of a quantum computer that can perform a computation with a super-polynomial speed-up compared with the best supercomputer
Quantum bit (qubit)	Physical structure that stores information, like a classical computer bit, but using the phenomena of superposition and entanglement
Quantum communication	Generation and use of quantum states for communication protocols
Quantum computing	Approach to computing that uses subatomic particles, such as electrons or photons, where quantum bits allow these particles to exist in more than one state (1 and 0) at the same time
Quantum computing modality: neutral atom	Modality that uses lasers to trap single atoms into a geometric, optical lattice
Quantum computing modality: photonics	Modality that uses light particles (photons) to encode and manipulate quantum information
Quantum computing modality: superconducting	Modality that uses superconducting electronic circuits that behave like artificial atoms with discrete energy levels
Quantum computing modality: trapped ion	Modality that uses elemental vapour inside ultra-high vacuum cells and lasers to strip the atoms of an electron to create an ion
Quantum energy advantage	Demonstration of a quantum computer that can solve a problem using less energy than the best supercomputer
Quantum error correction (QEC)	Computing technique for dealing with errors in quantum computers that exploits encoding across extra (large) number of qubits to reduce error rates
Quantum gravimeter	A powerful method for ultra-sensitive measurements of gravitational fields and their gradient
Quantum-inspired	Classical computers that emulate quantum behaviour
Quantum internet	A network of quantum computers able to send, compute and receive information encoded in quantum states.
Quantum magnetometer	A quantum resource to measure magnetic fields with precision and accuracy
Quantum noise	Unwanted disturbances in the computation process caused by undesirable external and internal factors that might lead to errors in the computation
Quantum plus AI	Synergistic approach that combines quantum computing with AI to create new algorithms, machine learning techniques, search procedure and data-processing techniques impossible to achieve with classical computers
Quantum repeater	Creation of entangled states between remote nodes by combining a series of elementary entanglements on individual links
Quantum sensing	Advanced sensor technology that leverages quantum mechanics properties to detect tiny changes in the physical world that would otherwise be undetectable
Quantum supremacy	Demonstration of a quantum computer able to solve problems that classical computers practically cannot in any feasible amount of time

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Endnotes

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