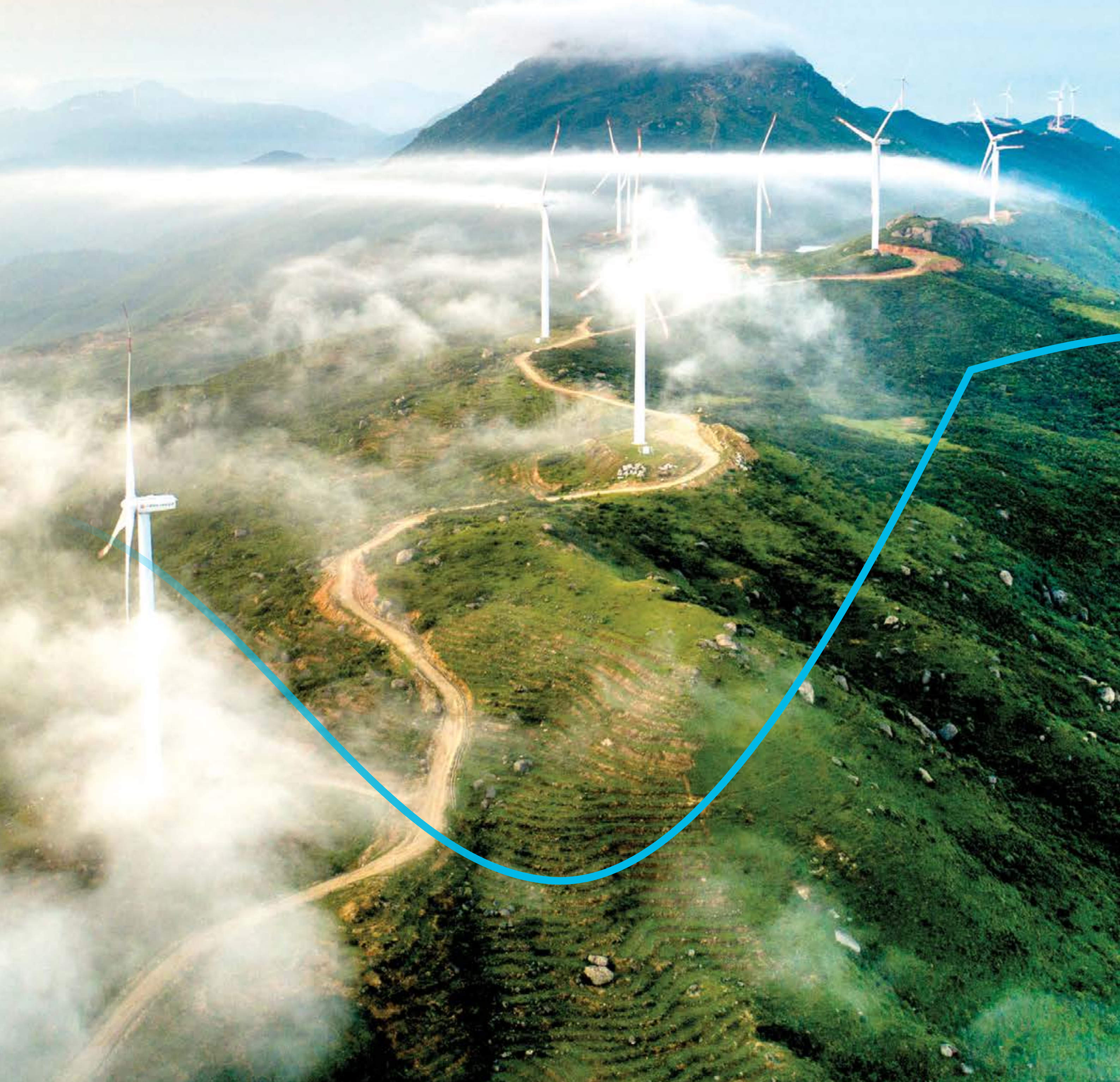
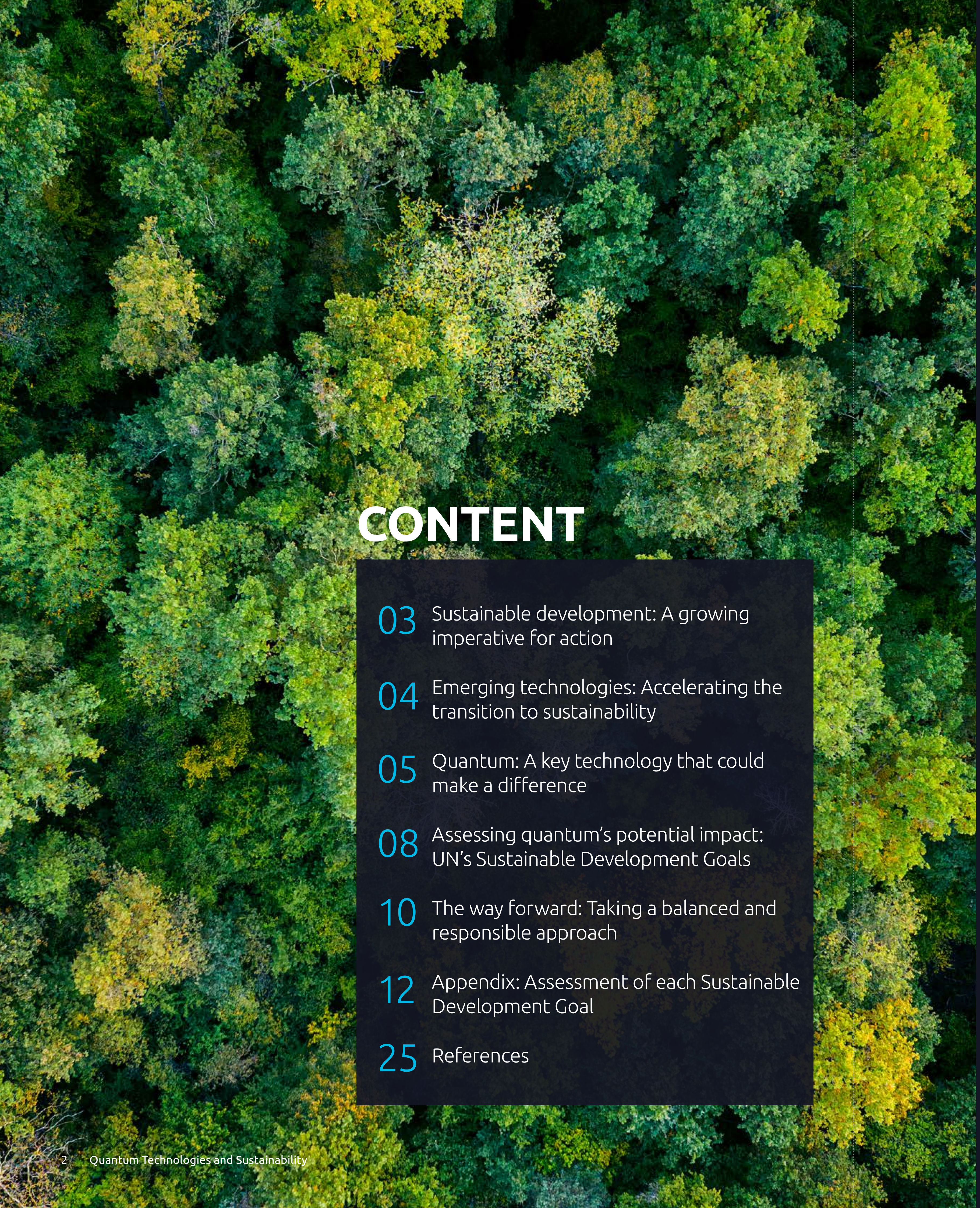
Capgemini

SUSTAINABLE DEVELOPMENT

How Quantum Technologies Can Help Drive the UN's Sustainable Development Goals





CONTENT

SUSTAINABLE DEVELOPMENT

A GROWING IMPERATIVE FOR ACTION

As we are at the beginning of the United Nations Decade on Ecosystem Restoration, it is surely a positive indicator that many industry leaders are now recognizing the need to take steps to address the most critical global challenges facing us all. Many governments and organizations have made bold commitments to global sustainability goals and have also demonstrated actions that could significantly reduce the damage to the environment.

This increased awareness of the need for environmental sustainability across governments, industries, and consumers has intensified several key trends that are on the rise around the globe, such as:

- Ambition for decarbonization and the race to net zero: An increasing number of organizations, public and private, are setting themselves the goal to achieve net-zero emissions by 2050, or before, as part of a more extensive decarbonization process involving energy efficiency across operations and renewable energy sourcing.
- Growing consumer demand for sustainable products and services: A new generation of consumers is aware of the impact of climate change and the need for sustainability. What is more, they are willing to contribute positively and proactively push companies to produce products and deliver services sustainably. Positive consumer demand is also leading to the adoption of a circular economy across industries.
- Increasing the proportion of renewable energy: As industries strive towards decarbonization goals, the first action is replacing the current high ratio of energy from traditional fossil fuel sources (oil, coal, and gas) with energy from local/regional renewable sources like solar, wind, and others. In addition, due to advancements in technology, the cost of renewable energy is being brought down progressively and the lower prices are helping to drive the willingness of consumers to switch to green energy procurement. The challenge is that the volume produced is low.
- Rise in environmental, social, and governance (ESG) investment: There has been increased momentum around responsible – or impact – investing (based on ESG principles), intensified in recent years by a change of thinking as a result of the pandemic. According to a Bloomberg analysis, global ESG assets are on track to exceed $50 trillion by 2025, representing more than a third of the $140.5 trillion in projected total assets under management. This has resulted in companies actively reporting their strategies, plans, and performance on ESG parameters.

As a result, companies are looking to employ key technologies and approaches to achieve their committed sustainability goals. For example, Capgemini has set the dual ambition to be an active member of the environmental transition. While Capgemini has focused on reducing its own footprint, it also aims to deliver higher impact through the solutions and services it offers to its customers. For its internal objectives, Capgemini has developed a 10-point net zero plan to address all areas needed to achieve net zero through a range of measures across the organization. For the external client-facing objective, Capgemini is committed to help its clients to save 10 million tCO2e by 2030. To achieve this objective, Capgemini has set up a dedicated offering framework to empower and support its clients in turning climate challenges into opportunities. The framework enables organizations to accelerate their net-zero transformation from commitment to sustainable achievements relying on three strata:

- Commit: Help organizations to define their net-zero strategy, build the underlying organization, embark all relevant stakeholders internally and externally, while adjusting their business models accordingly,
- Act: Help clients to operationalize their strategy by designing more sustainable products and services, refining their operations and supply chains to reduce their environmental footprints, and switching their legacy IT capabilities to sustainable IT, and
- Monitor and Report: Precisely model, track and anticipate the evolution of any organization's greenhouse gas (GHG) emissions through sustainability data hubs and leveraging innovative technologies.

As we have seen over the past decades, technology often offers a way of accelerating the pace of change, in particular using new disruptive technologies; but while the appeal of shortcuts is obvious, their use is not without its detractors.

EMERGING TECHNOLOGIES

ACCELERATING THE TRANSITION TO SUSTAINABILITY

Technology has increasingly become an indispensable part of our lives and its use has significant implications on our society and environment. New breakthrough technologies are emerging on a regular basis, which offer us a chance to accelerate changes in an unprecedented way, and to enhance human productivity and life experience. Adopting such technologies can also help us to positively impact sustainability with the potential for example to lower emissions and waste with increased efficiency.

Emerging technologies, including 5G, creative AI, blockchain, the metaverse, and permacomputing, have the potential to help meet some sustainability goals across industries; however, it should also be noted that some indeed include trade-offs that could also be detrimental. Nevertheless, industries and governments across the globe have started exploring the practicality of numerous use cases and applications of these technologies for environmental sustainability and are weighing up their degree of success and assessing both positive and negative impacts.

The focus of this paper is another key technology, quantum, which offers a wealth of opportunities for the future of technology enabled sustainability. Quantum technologies are based on quantum physics, which is more than a century old. Yes, this is the same theory of physics regarding which one of the most outstanding scientists, Einstein, once said, "If [quantum theory] is correct, it signifies the end of physics as a science." Since then, the human quest for understanding the physics of nature has progressed significantly.

Quantum technology is based on the principles of quantum mechanics – the physics of sub/atomic particles that use properties such as the spin of an electron or orientation of a photon, and the theories of superposition and entanglement.

The three broad quantum technologies (see below) are at different levels of development maturity, but nevertheless we have now reached a point where their potential is starting to move out of the scientific research environment, and being viewed purely as theoretical, and is now seen as having real-world application. By leveraging the quantum principles, it will, in the years to come, be possible to build quantum machines of unprecedented computational powers, to develop more highly sensitive devices using quantum sensors, and develop the most secure communication systems, using post-quantum encryption and Quantum Key Distribution methods.

QUANTUM

A KEY TECHNOLOGY THAT COULD MAKE A DIFFERENCE

In this paper we look at three broad quantum technologies: Quantum computing, quantum communication and security, and quantum sensing. As indicated, these quantum technologies are still in their infancy; some industry and research-driven projects have reached the proof-of-concept stage, but so far tangible, real-world advantages over existing technologies remain some way off. However, looking ahead, quantum's impact is predicted to be substantial and transformative, and the use cases abound across many industries, - ranging from optimization to machine learning, simulation, precision sensing, and security.

Our paper now looks at these quantum technologies to assess how they can be leveraged to help contribute to achieving a range of sustainability goals.

Quantum computing: Unrivalled compute processing of complex calculations at scale

This application of quantum principles – quantum computing – is certainly generating a lot of hype, thanks in part to the high levels of inbound investment from hardware companies and venture capitalist investors. The building block of quantum computing, the qubit, is fundamentally different from classical hardware bits. Unlike a classical bit, which can be in the state of binary "0" or "1", a qubit can be in a quantum state of "0" or "1" or in a superposition of states "0" and "1" – i.e., at the same time. Quantum computing, in some cases, has the potential to provide an exponential speed-up in computing power, particularly in processing complex data, when compared to classical computers.

Use cases for quantum computing focus on this synchronous process ability to tackle previously intractable problems that classical computers cannot process in a realistic timeframe. Some examples are gene therapy, drug simulation, aerodynamic modeling, supply chain optimization, financial modeling, and many more. We envisage a range of problems, predominantly incredibly complex ones, that could be confronted and potentially resolved, in addition to many where we could achieve a quantum advantage of performance, better than classical computing approaches. The benefits of timesaving and accuracy would be uppermost in importance.

Application areas where quantum computers are expected to deliver value can be grouped at a high level in three areas: Optimization, simulation, and machine learning. We explore each one below.

- **Optimization:** Many complex problems in industries relate in one way or another to optimization. The examples where improvements are sought are many and varied, including improving the overall efficiency of a business or manufacturing process, enhancing product performance, reducing overall costs of production or delivery, increasing returns on investment, efficient routing of goods, and other logistics or supply chain issues. These are mostly based on a combination of several variables and solutions and the task is to find the best possible solution given the known variables. Solving such problems with classical methods can be very time consuming and resource-heavy, whereas quantum computers promise to be highly effective in dealing with such complex optimization problems in terms of time taken to process and flex the multi-factorial variables and high levels of accuracy.

- **Simulation:** Another anticipated application is the efficient simulation of materials and their properties and interactions. This calculation is currently intractable for classical computers; even using supercomputers, we cannot accurately simulate or calculate the properties. For example, in developing new drugs or chemicals, pharma and chemical companies need to evaluate the exact nature of the particular molecules to understand how they react with other molecules. Simulating chemistry is a challenging task using classical methods, but quantum computers are predicted to have the potential to simulate complex molecules and their interactions accurately and more quickly.
- **Machine Learning:** There has been significant progress in the use of machine learning in business and industrial applications in recent years and an appreciation of the value it can add. And now, with the increasing development of quantum computers, exploring the interplay of quantum computing with machine learning is another focus area that is expected to deliver enhanced value. The standard application scenario is quantum-enhanced machine learning, which refers to machine learning algorithms used to analyze classical data on a quantum computer. This can also involve a hybrid scenario with classical data and quantum/natural data processed in combination with classical and quantum computers, with suitable algorithms leveraging the best of both.

The ongoing development of quantum computers paints a promising picture of a future with unprecedented computing capabilities, but we need to inject a note of caution and pragmatism. While there's been significant progress in recent years, the current state of the technology is far from its eventual promise, so it is important not to infer that these changes are near term. The quality and stability of qubits, and the operations we can perform on those qubits, are prone to error in the current generation of quantum computers, called NISQ (noisy intermediate-scale quantum) devices. (The future generation, projected to deliver the full promise, are referred to as large-scale fault-tolerant (LSFT) computers.)

The nascent state of quantum computers will undoubtedly limit the level of adoption by industry to solve real use cases in the near term. Still, as the technology matures, the role of quantum versus classical computers will become clear, based on performance, energy efficiency and environmental impact.

We would encourage organizations to explore those use cases that are critical to their business, so that as the technology matures and accessing the hardware becomes easier, they have already made progress towards implementation and stay ahead of competition. The potential of quantum will, we believe, materialize in the longer term.

Quantum communication: Unbreakable encryption and networked quantum computing

Quantum communication describes the generation and use of quantum states, systems, and components for communication protocols. It leverages the properties of quantum mechanics to protect the data and provide a new mechanism for communication that cannot be realized using classical communication methods. The significant aspect of this communication is the security of information transfer that it will provide.

As quantum communication technology matures, it is expected to enable secure communication. It will become the backbone of future communication networks, improving data security and reducing fraudulent theft of sensitive information. It has tremendous implications for how we do business in the future.

Currently, there are two promising options to replace the public-private key cryptography that underpins current communications systems. Quantum key distribution (QKD) is a key cryptographic distribution protocol (using both Discrete Variable QKD and Continuous Variable QKD) to generate "quantum" keys that can be used for secure information exchange over a classical channel with classical cryptography techniques. The keys are distributed using rules of quantum mechanics, where any act of listening in leaves a detectable sign of interference. Heisenberg's Uncertainty Principle states that if the quantum states are observed, the state will change, and the interception can be detected, resulting in secure communication.

Post-quantum cryptography (PQC) alters current encryption standards on classical networks to make them quantum-safe. It describes cryptographic algorithms that are thought to be secure against quantum computer attacks and include lattice-based, hash-based, and multivariate cryptography.

Quantum sensing: Unparalleled sensitivity, accuracy, and accessibility using atoms and photons

The third type of quantum technology is quantum sensing, which we predict will be the first to generate real commercial success in the quantum field. These are a class of sensors that offer an exceptionally high level of sensitivity to measure physical properties based on certain quantum phenomena, such as quantum decoherence and quantum entanglement. These quantum sensors hold the potential to deliver a step-change in performance; they are more sensitive, accurate, and in some cases more stable than current technologies.

Because of the advances already made, market analysts predict significant traction in the adoption of quantum sensors in various measuring devices in the automotive, consumer electronics, healthcare, industrial, and aerospace & defense industries. In addition, the proliferation of Industry 4.0 with IoT technologies, along with the shrinking size of sensors, will accelerate their adoption.

The quantum sensing industry is currently developing an impressive list of devices, including atomic clocks, single-photon detectors, PAR sensors, quantum LiDAR and quantum radar, gravity sensors, atomic interferometers, magnetometers, quantum imaging devices, spin-qubit-based sensors, and quantum rotation sensors. We believe the potential for this area of quantum is significant for both business and society.

In the following section, we explore how quantum technologies could potentially help in addressing sustainability issues. We have taken the 17 Sustainable Development Goals (SDGs), defined by the United Nations as a framework to assess the potential value that could be achieved by using these disruptive technologies in the future.

This is not to assert that quantum technologies alone can resolve these major and, some might argue, intractable problems facing the world, but that they should be considered as additional potential future solutions, when so much has been tried and failed. For this assessment, we have focused on the value brought by quantum computing and quantum sensing. We have not specifically considered the impact of quantum communication, as we see it as a horizontal or transversal technology, providing secured communication across most of the sustainability areas.

ASSESSING QUANTUM'S POTENTIAL IMPACT

UN'S SUSTAINABLE DEVELOPMENT GOALS

In 2015, United Nations, with all its member states, defined a collection of 17 global goals designed to be a "blueprint for achieving a better and more sustainable future for all." These Sustainable Development Goals (SDGs) are intended to address global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

These goals are quite broad and interdependent with specific targets and indicators identified for each goal. Some of these targets have timelines to achieve by 2030 and some do not have any such specific target dates. The current quantum computers are still in their early stages of development and need to go through significant enhancements before they deliver on their promise. Though there is rapid progress happening in multiple directions, including hardware, software and algorithms accelerating the time to a quantum advantage, it is difficult to predict timelines. Hence for our study/analysis we have considered the SDGs and related use cases where quantum could potentially have an impact per se, but implementation timelines are not part of this analysis.

As indicated, we used these goals as a framework to assess how well quantum could be used to effect real and sustainable change. Our approach for evaluating the potential impact of quantum technologies on these goals started by a review of each of the 17 SDGs and their associated targets and indicators. For each goal, we identified the relevant industries and related use cases that could potentially impact the goals through primary (subject-matter-expert discussions) and secondary research (public domain publications).

We then mapped the use cases across the quantum computing application areas – optimization, simulation, machine learning – and to quantum sensing. Taking the volume of applicable use cases as a proxy for benefits accrued, we rated the potential level of impact of quantum technologies on SDGs as follows: No direct impact, low impact, medium impact, high impact, and large impact. Based on these consolidated evaluations, we developed the table below.

Table 1: Summary of the level of potential impact that quantum computing (optimization, simulation, and machine learning) and quantum sensing could have across the 17 SDGs.

SDG Goal	Optimization	Simulation	Quantum Machine Learning	Quantum Sensing
SDG 1: No Poverty	Low impact	Low impact	Low impact	No direct impact
SDG 2: Zero Hunger	High impact	Large impact	High impact	Medium impact
SDG 3: Good Health and Well-being	High impact	Large impact	Medium impact	Large impact
SDG 4: Quality Education	Low impact	No direct impact	Low impact	No direct impact
SDG 5: Gender Equality	Low impact	No direct impact	Low impact	No direct impact
SDG 6: Clean Water and Sanitation	Medium impact	Medium impact	Low impact	Low impact
SDG 7: Affordable and Clean Energy	Large impact	Large impact	Large impact	Large impact
SDG 8: Decent Work and Economic Growth	Low impact	Low impact	Low impact	No direct impact
SDG 9: Industry, Innovation and Infrastructure	Large impact	Large impact	Large impact	Medium impact
SDG 10: Reduced Inequalities	No direct impact	Low impact	Low impact	No direct impact
SDG 11: Sustainable Cities and Communities	Large impact	Medium impact	Large impact	Medium impact
SDG 12: Responsible Consumption and Production	Medium impact	Medium impact	Medium impact	Low impact
SDG 13: Climate Action	Low impact	Medium impact	Medium impact	High impact
SDG 14: Life Below Water	Low impact	Low impact	Medium impact	Low impact
SDG 15: Life on Land	Low impact	No direct impact	Medium impact	No direct impact
SDG 16: Peace, Justice and Strong Institutions	No direct impact	No direct impact	Medium impact	No direct impact
SDG 17: Partnerships for the Goals	No direct impact	Low impact	Low impact	No direct impact

Legend:
- No direct impact
- Low impact
- Medium impact
- High impact
- Large impact

According to our analysis, set out in the above table, we believe that quantum technologies could have significant potential to positively impact the Sustainable Development Goals, but to a clearly varying degree. While quantum will not be a panacea for all ills, in certain areas it offers a new platform for innovation with the potential to transform key activities in a number of industries and domains, and thus on these goals.

For instance, we believe that quantum technologies could have a high/large potential in areas such as Affordable and Clean Energy, Industry, Innovation, and Infrastructure, and Sustainable Cities and Communities. Other areas show medium impact including Zero Hunger, Good Health and Well-being, Clean Water and Sanitation, and Responsible Consumption and Production. However, the remaining goals, by contrast, are not impacted by quantum technologies to the same extent, at the moment.

It should also be acknowledged that the goals are not distinct and separate, so many of the use cases we have identified can be applied to more than one goal. In the Appendix, we explore in more detail each of the 17 goals, providing indication of use cases that could apply.

THE WAY FORWARD

TAKING A BALANCED AND RESPONSIBLE APPROACH

This review of the UN Sustainability Goals and how quantum technologies could play a positive role in meeting the goals is neither complete nor comprehensive and does not intend to be. The review does not capture all the aspects of the sustainability goals that need to be addressed and understanding and quantification of the quantum advantage, as applied to sustainable development, is still evolving.

However our paper does provide an insight into the opportunities that quantum technology – categorized in optimization, machine learning, simulation, and sensing – may bring and indeed, where governments and industry are already investing in use case research and proofs of concept on actual hardware, some quite advanced.

The fact that large scale optimization problems, such as enhancing supply chains, route and traffic management (as being explored by Volkswagen) or improving energy infrastructure, are omnipresent, suggests that a modest quantum speed-up could deliver a significant benefit in a wide range of SDGs such as Affordable and Clean Energy and Industry, Innovation, and Infrastructure.

Quantum simulation has perhaps the biggest potential impact on sustainable development goals. Well-known potential applications and research such as the FeMoco problem (simulating nitrogen fixation to improve industrial catalysts for fertilizer production) have a theoretically proven speed-up and could drastically reduce emissions. The development of new materials through quantum simulation might be another high-potential area. For example, the development of improved batteries (Daimler and IBM) could improve the availability of affordable and clean energy and more efficient electric vehicles.

Similarly to its classical counterpart, quantum machine learning (QML) has wide applicability across the SDGs. In the long run, quantum machine learning could speed up computation-intensive machine learning operations, resulting in larger and more accurate models. The advancements that this might bring in deep learning applications, such as natural language processing or computer vision, could impact a vast range of SDGs. In the near term, quantum machine learning has the potential to learn faster on less data in select applications; read more in our colleagues' paper Predict better with less training data using a QNN. There might be an opportunity in areas where large data volumes are scarce.

Furthermore, although quantum sensing is considered more niche than quantum computing, its impact on sustainable development should not be overlooked. Quantum sensors provide new ways to monitor the environment that may be critical in the migration to cleaner and healthier ecosystems. For example, quantum sensors could be instrumental in detecting leakages in gas pipelines and reduce subsequently the emission of highly potent greenhouse gasses.

While Table 1 does indicate there could be particular benefits to using quantum technologies, we should perhaps, at this point, pause to reflect and add a note of pragmatic caution, because there are currently a number of roadblocks to the use of quantum generally and regarding sustainability that should be taken into consideration and the practical difficulties should not be underestimated.

- **Access to skills and resources:** Benefiting from quantum computing is highly dependent on access to resources: not only to the hardware, infrastructure, and software but also to scarce expertise and scientific skills. This will challenge any organization in buying in or building up the necessary skills and then leveraging them to develop and implement new products and services.
- **Equity of resources:** If the skills and access to scarce quantum devices resides with a few (largely first world) companies, this could lead to a significant commercial advantage over competitors. Resource inequities could give rise to "super" players with significant buying power, and quantum computers are unlikely to be made available to public use for the foreseeable future. We believe that an active effort to democratize access will ultimately benefit both industry and society and help to better implement these goals.
- **Run issues:** Quantum computers are very expensive to build and difficult to program. Currently, use is held back by run issues, such as loss of coherence, errors, and noise from the outside environment, and they need to be run and maintained at exceedingly low temperatures (negative 460 °F) to provide stability. But new models, such as QCaaS, are emerging that will make resources more affordable
- **Ambiguous Value Realization:** It's important also to recognize the need for a responsible attitude to quantum's use and its own environmental impact. Achieving benefits will not necessarily be straightforward, as there could be some unintended consequences such as the Jevons Paradox referenced by Capgemini colleagues Clément Brauner and Antoine Richelet in their blog on What role do quantum technologies have in securing a more sustainable future for business and society?

These challenges mean that it is important that governments and businesses take a balanced and responsible approach to the use of quantum technologies. In looking to use quantum, we believe that firstly it is essential to carry out impact studies on quantum projects that take into account environmental criteria such as energy use and impacts. Quantum computing is not designed to replace classical computers but to complement them, where the computational power of quantum is superior, and its use is justified by the superior outcomes on select use cases or applications.

Secondly, an incremental experimentation approach is advised – setting up small initiatives or proofs of concept first to prove the feasibility and the advantage of quantum technologies before scaling up. In this way, it will be the actual application or implementation where the true value will be evaluated and realized, rather than in the business case or proposition.

That said, considering the vast range of implications of sustainability challenges on human life, including climate change, it is incumbent upon governments, industry, and commerce – as well as individuals in science, academia and technology – to explore the potential of all emerging and breakthrough technologies, to address these pressing and critical challenges.

Quantum technologies in particular offer unprecedented capabilities that Capgemini believes are worth investigating further. Certainly there is an imperative to act and with a common will, to act now.

APPENDIX

ASSESSMENT OF EACH SUSTAINABLE DEVELOPMENT GOAL

SDG 1: No poverty

End poverty in all its forms everywhere.

This goal aims to eradicate every form of extreme poverty, including the lack of food, clean drinking water, and sanitation. Achieving this goal includes finding solutions to new threats caused by climate change and conflict. SDG 1 focuses not just on people living in poverty, but also on the services people rely on and social policy that either promotes or prevents poverty. Despite the ongoing progress, 10 percent of the world's population lives in poverty and struggles to meet basic needs such as health, education, and access to water and sanitation.

As part of our analysis, we found some direct applications of quantum technologies to help meet this goal around equal rights to basic services, technology, and economic resources (target 1.4). To address the basic services and needs like health, water, and sanitation, there are some relevant use cases. These relate mainly to the optimization of effective usage and allocation of resources across a number of categories with different level outcomes, where the processing power of quantum computers would be useful and could help to achieve this goal.

For example, quantum simulation can be used in materials science to advance the research into water filtration and membrane technologies, to provide potable water and wastewater treatment. Another target (1.5) is about building resilience to environmental, economic, and social disasters. Quantum computing could be very useful in carrying out complex risk modeling with various input parameters to assess the potential impact or water loss due to disastrous events.

In addition, quantum machine learning has a role to play in processing vast data sets of international populations and their demography from various sources across regions/countries and extracting relevant insights. This would help to predict and plan the resource allocation requirements more accurately.

SDG 2: Zero hunger

End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.

According to the SDG website, 2.37 billion people are without food or are unable to eat a healthy balanced diet on a regular basis. Children and women of reproductive age suffer from anemia due to nutrition deficiencies and the Covid-19 pandemic has worsened this state of malnutrition. The key purpose of this goal includes: ending hunger and improving access to food; ending all forms of malnutrition; increasing agricultural productivity; sustainable food production systems and resilient agricultural practices; genetic diversity of seeds, cultivated plants, and farmed and domesticated animals; and investments, research, and technology.

One of the most well-known and promising quantum use cases that can be applied to this goal is the use of quantum computing in improving the efficiency and economics of the production of ammonia, employed in making fertilizers to increase agricultural productivity. The current Haber-Bosch chemical industrial process of artificial nitrogen fixation used to produce ammonia for fertilizer is a century old and has been significantly enhanced since its invention. But it is estimated to consume about 2-3% of total global energy and also contributes increased CO_2 release into the atmosphere.

However, nature can undertake this complex process with minimum resources using biological nitrogen fixation through specific bacteria. As quantum computers are naturally suited for simulating natural processes, like chemical reactions, it is anticipated that it will be possible one day for quantum computing to use simulation to produce a catalyst or improve the process for producing ammonia fertilizers through more economic and environmentally friendly ways.

Other use cases or applications of quantum simulation impacting this goal include:

- **More resilient plant species for increased food production:** It is likely to be possible to directly identify the genes responsible for specific traits. Quantum simulation of plant genomes could potentially improve characteristics such as resilience to changing weather conditions or maximize crop yields, so that farmers can apply sustainable practices and give agricultural land back to nature.
- **Weather and extreme events simulation for better planning:** Quantum computers are expected to be able to model more accurately the impact of extreme weather, drought, flooding, and other natural disasters. This could have a positive impact on planning for agriculture and related food production and processing.
- **Precision farming for better yield-to-inputs ratio:** Quantum machine learning capabilities can be used in the process of precision farming – most notably for optimal water usage and optimal fertilizer application and yield prediction through the application of IoT, drones, and visual analytics. These capabilities can also help in shaping increased automation in large-scale farming activities to enhance food production.
- **Efficient routing of food delivery:** One of the major challenges in the food value chain is how to get perishable goods to consumption points in an efficient and timely manner that both minimizes waste and also reduces the resultant carbon footprint. We see an opportunity for quantum route and supply chain optimization to determine in part the most effective route from farm to fork.
- **Efficient use of land and other resources:** Optimization of land resource usage and the allocation for different purposes is critical to ensuring that food productivity is the best it can be. The total potential of carbon sequestration (putting carbon back in the ground) through sustainable agricultural practices is between 300 and 400 giga tonnes, almost ten times the world's emissions in 2021. Quantum computers are capable of helping to find the best

possible use of sites, spaces, and resources by leveraging quantum optimization algorithms.

Quantum sensing technology also has significant potential in the following applications:

- **Sensing ground water:** Gravimetry and gyroscopic devices can be used to identify gravity anomalies and earth observation for different conditions to help in water location and extraction.
- **Tracing E. coli:** Quantum magnetometry can be used in tracing bacteria and other contaminants in food production, involving magnetic nanoparticle tracers and quantum wildlife monitoring magnetometers.
- **Monitoring of wildlife**: Quantum imaging technologies can be used in aerial or satellite imaging, through tree canopy and cloud cover, with improved resolution, together with other imaging methods for monitoring movement and migration of wildlife. Tracking wildlife in this way can be used to notify farmers before animals make their way onto farming land.
- **Photosynthetic radiation:** A photosynthetic active radiation (PAR) meter is another type of quantum sensor that can be used for measuring active photosynthetic radiation. This could be useful in green houses and growth chambers in the horticulture sector, for efficient utilization of light for increased productivity.

SDG 3: Good Health and Well-being

Ensure healthy lives and promote well-being for all at all ages.

This goal aims to achieve universal health coverage and seeks equitable access to healthcare services for all men, women, and children. The targeted outcomes include: the reduction of maternal mortality; ending all preventable deaths under five years of age; fighting communicable diseases; ensuring the reduction of mortality from non-communicable diseases and promoting mental health; prevention and treatment of substance abuse; reducing road injuries and deaths; granting universal access to sexual and reproductive care, family planning, and education; achieving universal health coverage; and reducing illnesses and deaths from hazardous chemicals and pollution.

There are many use cases of quantum computing that are being explored in the field of life sciences and healthcare. They have the potential to significantly improve the process of in silico drug discovery, the design and development of new drugs through accurate molecular dynamics simulation, and the optimization of the chemical and biological processes.

Another application of quantum computers in drug discovery is in the area of the prediction of protein folding, considered to be very difficult using classical computers. Quantum computing can help in precision medicine through genomic analysis and also facilitate the development of enhanced therapies and target-specific or tailored patient treatments. The process of genome sequencing could also be made significantly faster.

Quantum machine learning algorithms are also being developed to classify genomic data, which can complete the task of classification at an unprecedented speed compared to conventional methods. These quantum machine learning methods can significantly enhance automation of pathology and imaging analysis as part of the diagnostics process. We also envisage using quantum computers to optimize and streamline clinical trials; some pharma companies are already investigating the prediction and simulation of improved patient outcomes in shorter timeframes and a more cost-effective manner.

Recognizing this potential quantum advantage, leading industry players in the life sciences and pharma industry came together to form QuPharm in 2020 to advance the implementation of quantum computing in the pharmaceutical industry.

As well as computing, quantum sensing can be used in the following application areas:

- **Medical imaging:** Magnetoencephalography (MEG) is a test to measure magnetic fields produced by the brain's electrical currents. Quantum magnetometry has the potential to improve such medical imaging applications, especially useful in brain health analysis for aging populations.
- **More accessible monitoring devices:** Quantum magnetometry can also be used in mechanomyogram (MMG) to observe mechanical signals from the surface of muscle contractions. This could lead to the development of more accessible monitoring devices, capable of being deployed outside a clinical environment, which could both improve access to such medical monitoring and reduce the capital cost of healthcare services.
- **MRI devices:** With a combination of quantum sensing and quantum machine learning, there is now the prospect of a new generation of MRI devices with enhanced sensing and real-time tracking of fluctuating magnetic fields.
- **In vitro diagnostics:** Quantum sensors can help in developing improved lateral flow sensitivity with functionalized nano diamonds for in vitro diagnostics. This could help to detect diseases or other conditions and be used to monitor a person's overall health, potentially helping to cure, treat, or prevent diseases.
- **Brain imaging:** Near-infrared (NIR) imaging through quantum dots can be used in the imaging of blood in the brain to detect cerebral oxygenation and other conditions.

SDG 4: Quality Education

Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

Education is seen as a force for sustainable development, nation building, and peace. It enables upward socioeconomic mobility and is a key to escaping poverty. This goal aims to provide children and young people with quality and easily accessible education, plus other learning opportunities.

Adoption of quantum machine learning (QML) can help in achieving personalized adaptive learning methods and making informed decision on the student learning needs by leveraging student data. In addition, QML in combination with optimization algorithms can also help in defining and predicting the necessary learning path for students to gain relevant skills or the necessary learning outcomes for decent jobs and entrepreneurship (as required for target 4.3 and 4.4).

Also, QML can help in processing/analyzing vast data sets of populations across countries with details of their education levels and needs and plan for effective resource allocation across different programs to maximize the return on investments or outcomes.

SDG 5: Gender Equality

Achieve gender equality and empower all women and girls.

This goal aims to achieve equal rights for women and girls and opportunities to live freely without discrimination, including workplace discrimination or any violence. This includes providing women and girls with equal access to education, health care, decent work, and representation in political and economic decision-making processes, which will fuel sustainable economies and benefit societies and humanity at large.

Any advanced technology, like QML or AI, is essentially a power tool that can be harnessed to enhance equality. For example, AI-powered gender decoders could help employers use more gender-sensitive and more inclusive language to increase diversity. Quantum optimization can also be used in efficient allocation of economic and other resources for various initiatives empowering women and their development. QML can be utilized to derive insights from various data sources across nations for effective decision-making.

The question of quantum computing in video analytics and surveillance is perhaps more problematic. Quantum computing can be used for intelligent video surveillance, with video analytics capabilities leveraging machine learning to increase the safety of the public and more specifically that of women and girls in public spaces.

However, it can also be argued that QML/AI could pose a significant threat, as evidenced by some experiences of AI-powered recruitment software that has been found to discriminate against women or in video surveillance more generally by certain types of states and governments applying a high degree of control and discrimination.

SDG 6: Clean Water and Sanitation

Ensure availability and sustainable management of water and sanitation for all.

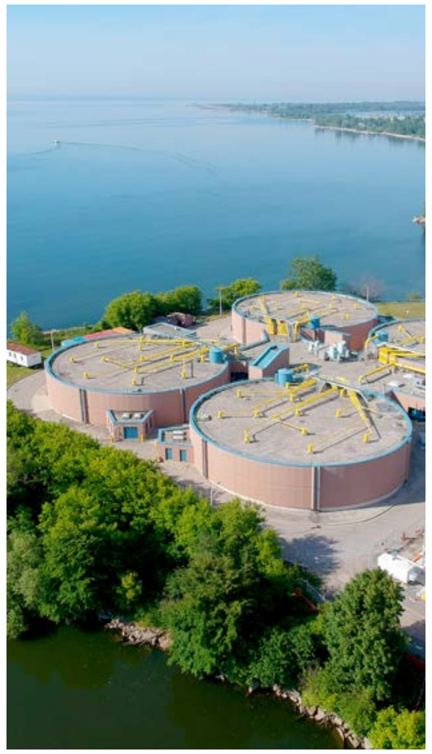
As per UN reports, two billion people do not have access to safe drinking water, 3.6 billion people lack safely managed sanitation, and 2.3 billion people do not have access to a basic hand-washing facility. The UN also explains that clean water is a basic human need that everyone should have access to. Poor infrastructure is the major reason why millions of people have inadequate access to water, sanitation, and hygiene, which is a significant cause of diseases and related deaths. SDG 6 aims to ensure safe drinking water and sanitation for all, focusing on the sustainable management of water resources, wastewater, and ecosystems and

acknowledging the importance of an enabling environment.

Quantum computing has the potential to optimize the management and distribution of water supply, from different sources to the people in need, with minimum wastage, thus reducing the level of water scarcity. Quantum material research can be used to develop new materials for cost-effective water purification and wastewater treatment processes. In addition, according to the World Resources Institute, a third of the world's population is living with high levels of water stress, which is a situation when the demand for water exceeds the available amount during a certain period or when poor water quality restricts its use.

Researchers can use quantum computing to simulate water level stress, taking into consideration factors such as local climate conditions, population, and sources, and therefore predict the degree of water stress in a specific place or region. In addition, with IoT and smart meters, there is a huge volume of data associated with water utilities, so quantum machine learning can be used to process this vast aggregation of data to derive insights, including indicators for predictive maintenance, and therefore more effectively manage water leakage and wastage in a network. Quantum simulation techniques could be used to produce new materials/products (dry cleansing, effluent treatment, etc.) for sanitation purposes.

Quantum sensors also have a role. Some use cases include observation of the earth with gravity sensors to find ground water reserves and contamination in water as well as gravimetry for monitoring leakage in water supply systems.



SDG 7: Affordable and Clean Energy

Ensure access to affordable, reliable, sustainable, and modern energy for all.

Access to energy is a very important pillar for the wellbeing of people, as well as to economic development and poverty alleviation. It is central to nearly every major challenge and opportunity the world faces today, including for example adaptation to climate change, food security, health, education, sustainable cities, jobs, and transport. According to the UN, 13% of the global population still lacks access to electricity via modern infrastructure and almost 3 billion people rely on wood, coal, charcoal, or animal waste for cooking and heating.

The key aim of this goal is to provide universal access to modern energy. To do this, there will need to be an increase in the global production of, and access to, renewable energy, double the improvement in energy efficiency, plus the promotion of access to research, technology, and investments in clean energy, and the expansion and upgrade of energy services for developing countries. This would mean providing access to affordable and reliable energy, while increasing the share of renewable energy in the global energy mix, plus improving energy efficiency and enhancing international cooperation and investment for clean energy technology infrastructure.

However, this needs to be set against the still rising use of fossil fuels, as seen in recent years, which will continue to have significant implications for global climate change. What is also evident is that necessary actions to mitigate greenhouse gasses will be critical. As per the UN, energy is the dominant contributor to climate change and accounts for almost 60% of global greenhouse gas emissions. Thus, energy efficiency and the increase in the use of renewables for energy are vitally important.

We believe that quantum computing has the potential to have a positive impact, particularly on optimization, simulation, and machine-learning-related applications of energy. Examples of optimization include optimization of power grid operations to improve performance and efficiency of transmission and distribution, optimization of portfolio of electric energy generation across different sources (renewable and non-renewable mix), optimization of energy consumption for smart cities applications, and operations scheduling to optimize the processes in industries and automotive systems, thus reducing power consumption.

Simulation using quantum computing algorithms can be applied to industrial and materials science applications, such as battery design, discovery of new materials like superconductors, gaining better understanding of the properties of hydrocarbons to chemicals used in oil and gas production, and solutions to corrosion and solid formations that impact flow assurance and could improve safety and reduce costs. In the energy sector, quantum simulation can also be used in materials science to improve the efficiency of solar panels and conductivity of electricity with near zero losses, simulation of transmission and distribution networks, and simulation of high-energy nuclear physics and also to improve nuclear fission reactors and pave the way for nuclear fusion.

Quantum machine learning-related applications focus on predictions in supply, price, and demand, including effective demand prediction for efficient management, generation, distribution, and supply chains as well as the prediction of prices of energy and resources to optimize the cost of access to energy. There are also uses in maintaining infrastructure, including: predictive maintenance for efficient generation and operation of power plants, industries, and appliances; anomaly detection across distribution networks, and generation systems and plants; grid security and theft

detection; and the improved prediction of outages.

In the monitoring of energy infrastructure, quantum sensors can be used for the measurement of critical parameters of interest via a combination of range, resolution, and sensitivity. Power grid monitoring with magnetometers can be attached directly onto power lines to record leakage current measurements, for diagnosing early breakdown of insulators in transformers. These devices have the potential to improve grid durability.

Quantum gravimetry can be used for prospecting and the cleanup of boreholes in legacy oil extraction and decommissioning and prospecting for carbon capture and storage with geological imaging with gravity anomalies. Gravimeters can also be used to discover new oil reserves and develop optical gas imaging systems to detect and locate gas leaks.

Finally, quantum sensors have the potential to be deployed in nuclear power plants to improve plant efficiency and safety. For example, an atom interferometric quantum sensor could be used for detecting isotopes in nuclear energy plants, and to detect early stages of radiation breaches, enabling remote monitoring of the safety aspects of the plant.

Capgemini's Julian van Velzen provides a further exploration of the use of quantum in energy production and consumption in his blog on Addressing the challenges of achieving Net-Zero.

SDG 8: Decent Work and Economic Growth

Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

As the UN explains, nearly half of the world's population lives on the equivalent of about $2 per day. Sustained and inclusive economic growth can drive progress, create decent jobs for all, and improve living standards. This goal aims to ensure that the economic sector of every country provides the necessary elements for its citizen to have a good life, irrespective of their background, race, or culture.

One of the targets of this goal is to achieve higher levels of economic productivity through diversification, technological upgrading, and innovation. Quantum computing as a technology has a high potential to enhance economic productivity and trigger innovation to create new economic activities (target 8.2).

Quantum simulation techniques can be used to simulate various micro- and macro-economic models for analysis of economic conditions and the growth of any nation.

Quantum optimization algorithms have the potential to help meet target 8.5 – that of global resource efficiency in consumption and production with an optimized material consumption footprint.

Finally, quantum risk modeling can be used to strengthen financial institutions and to encourage and expand access for all to banking, insurance, and financial services (target 8.10) through efficient risk assessment and resource credit allocation.

SDG 9: Industry, Innovation and Infrastructure

Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

A functioning and resilient infrastructure is the foundation of every successful community. It provides the basic physical systems and structures essential to the operation of a society or enterprise. This goal aims to: provide every society with access to good and resilient infrastructure; promote sustainable industrialization that can drive economic growth, create jobs, and reduce poverty; and foster innovation to advance technological capabilities to sustainable solutions to economic and environmental challenges.

It recognizes that humanity's ability to connect and communicate effectively, move people and things efficiently, and develop new skills, industries, and technology is crucial to overcoming the many interlinked economic, social, and environmental challenges. To meet these aims and the future challenges, industries and infrastructure (both hard and soft) need to be upgraded and should employ innovative, sustainable technologies.

Considering the wide scope of this goal, quantum computing technologies can potentially address many areas across infrastructure, industry, and innovation with a resultant positive impact. Examples of use cases and applications include the optimization of systems across public transport systems, utilities (viz., water, electricity, gas, etc.), distribution systems, and telecommunications, including internet access. It also offers the potential to improve the prediction of future demand through simulation for efficient planning of investments and more.

In industry, across multiple sectors, there is a wide range of use cases. There are multiple examples of optimization, including real-time routes, optimization, production flows, routing of warehouse robots, demand forecasting, supplier risk modeling, predictive maintenance of assets in industrial plants, and more.

Simulation also offers many opportunities for improvement, such as using quantum simulation to find the right combination of polymers to make stronger concrete, finding better and more efficient catalysts for hydrogen production for steel manufacturing, and also simulation of fluid dynamics, FEM analysis/simulation, materials science and synthesis, heat and mass transfer simulation, and simulation of electro-mechanical systems.

In addition, quantum sensors can be used in better sensing of critical parameters for predictive and preventative maintenance (IoT/IIoT sensors).

SDG 10: Reduced Inequalities

Reduce inequality within and among countries.

Reducing inequalities and ensuring no one is left behind are integral to achieving the Sustainable Development Goals. Income inequality between countries is higher than that within a large majority of countries, such that individual incomes are still largely associated with a person's citizenship and location. Wide and often mutually reinforcing disparities are also evident within countries, such as between rural and urban communities, and within household wealth, gender, ethnic minorities and indigenous people, migrant status, and disability.

This goal aims to reduce inequalities in income as well as those based on age, sex, disability, race, ethnicity, origin, religion, or economic or other status within a country. The goal also aims to address inequalities among countries, including those related to representation, migration, and development assistance.

Under this goal, some targets (10.5 & 10.b) around the improvement of regulation and monitoring of global financial markets and institutions could benefit to some degree from quantum.

Simulation and machine learning can be used to model the risks, fraud detection, and derivative pricing of financial instruments, and thus help to improve financial soundness indicators. In addition, quantum machine learning can be used to process economic data of various nations and derive insights for effective decision-making.

SDG 11: Sustainable Cities and Communities

Make cities and human settlements inclusive, safe, resilient and sustainable.

The world is becoming increasingly urbanized; more than half the world's population is now living in cities, and this percentage is expected to increase to 68% by 2050. This trend is accompanied by an increased pressure on the environment and increased demand for basic services. But cities are particularly vulnerable to climate change and the impacts of natural disasters given the high concentration of people, infrastructure, housing, and economic activities. Building resource-efficient cities with urban resilience is crucial to avoid human, social, and economic losses, while improving the sustainability of urbanization processes is also needed to protect the environment and mitigate disaster risk and climate change.

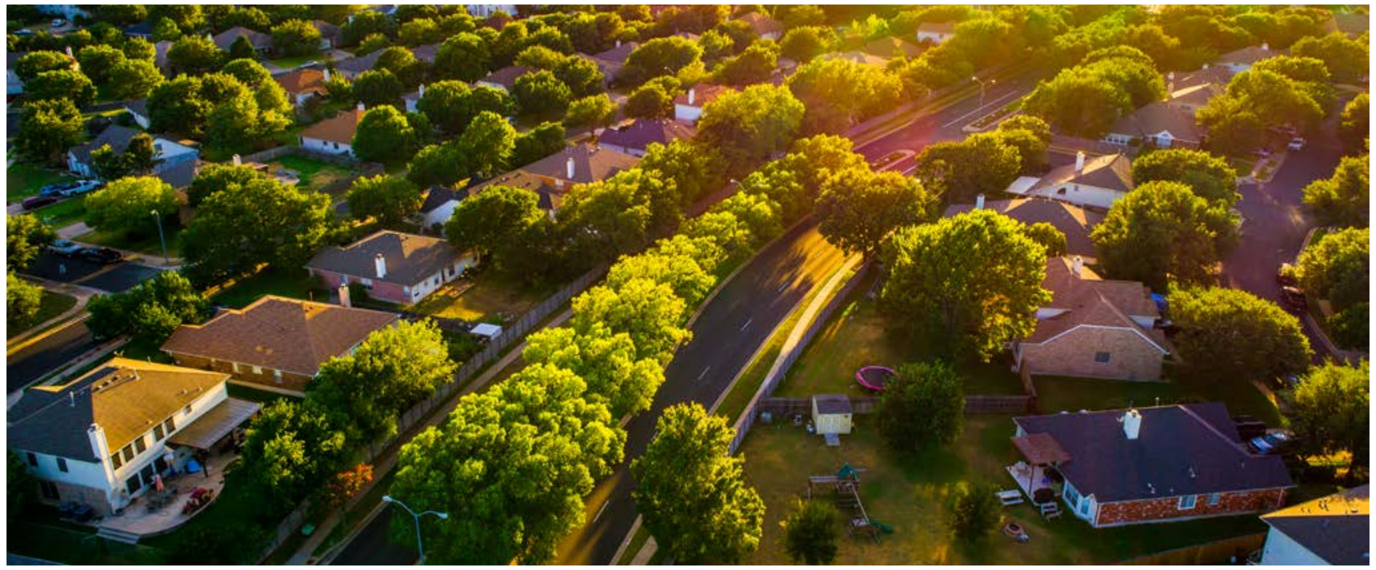
Goal 11 includes investment in public transport, creating green public spaces, and improving urban planning and management in participatory and inclusive ways. The aim of this goal includes safe and cost-effective housing, affordable and sustainable transport systems, inclusive and viable urbanization, protection of the world's cultural and natural heritage, reduction in the adverse effects of natural disasters, reduction of the environmental impacts of cities, and access to safe and inclusive green and public spaces.

There are many quantum technology use cases and applications with potentially positive impacts, many focused on smart city optimization. These largely focus on optimization in the areas of traffic routes, critical services (last mile) delivery, public transport scheduling, consumption of land and other resources for different usages, water distribution, and more. Quantum computing processing and algorithms can also be used in fundamental materials science research to produce more economical building materials with the necessary strength, and simulation of atmospheric parameters including air quality or inner-city heat-stress.

In addition, potential use cases using application quantum machine learning capabilities include predictive maintenance of assets and equipment, intelligent surveillance, and analytics for crowd management. Other applications encompass demand/load forecasting of public utilities and services, adaptive workplaces to improve wellness, smart street lighting, and improving the prediction of natural disasters through climate modeling and thus reducing adverse effects.

Quantum gravimeters can be used in monitoring buildings, bridges, and similar physical structures for their integrity and condition. These sensors can also be used in improved seismic monitoring for predicting earthquakes and by utilities in detecting underground pipes and cables to reduce the cost of construction of infrastructure.

In the mobility sector, quantum gyroscopes can enhance driving accuracy and reduce reliance on satellite navigation for autonomous vehicles. Quantum sensing can be used in improving air quality through chemical sensing and the identification of sources of pollution, and in identifying/monitoring contaminant hotspots to reroute traffic dynamically, thereby keeping people safe and healthy.



SDG 12: Responsible Consumption and Production

Ensure sustainable consumption and production patterns.

Global production and consumption are the key forces of a global economy that is based on the use of natural resources. Our planet has abundant natural resources, but our pace of utilization is far beyond what this planet can provide to us in the long term, and this will almost certainly have a destructive impact on the planet. It is widely acknowledged that we must adopt different consumption and production practices to help reverse the harm inflicted on the planet over the recent decades.

Sustainable consumption and production are about doing more and better with less. It is also about decoupling economic growth from environmental degradation, increasing resource efficiency, and promoting sustainable lifestyles. It requires minimizing the natural resources and toxic materials used, and the waste and pollutants generated, throughout the entire production and consumption process.

This goal encourages more sustainable consumption and production patterns through various measures, including specific policies and

international agreements on the management of materials that are toxic to the environment. The efficient management of our shared natural resources and the way we dispose of toxic waste and pollutants are important targets if this goal is to be achieved. Encouraging industries, businesses, and consumers to recycle and reduce waste is equally important, as is supporting developing countries to move towards more sustainable patterns of consumption.

This goal is heavily interlinked with other UN goals where quantum technologies have a potential advantage and some optimization use cases relating to supply chains, utilities distribution, and more efficient use of raw materials in the production of consumer goods, are applicable. We can also envisage the use of quantum computing in the production of energy efficient equipment and devices, and in the simulation of chemicals and catalysts manufacture, to optimize the production processes and reduce both wastage and pollution. In addition, quantum machine learning capabilities can be used in the prediction and management of water and energy demand and consumption, across agriculture, industries, and households.

Quantum magnetometry can be used in applications of detecting and monitoring contaminants, such as leaching from coal mines into ground water and rivers. Quantum gravimetry can be used in identifying good refuse sites by tracking adjacent water flow, thus reducing water contamination through run-off.

SDG 13: Climate Action

Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy.

Our civilization is facing an undeniable catastrophic threat from the effects of climate change. This is impacting natural and human systems worldwide, through the increase of averaged surface temperature globally, changing precipitation patterns, rising sea levels, and ocean acidification. It is increasing the frequency and intensity of extreme weather events such as heat waves, droughts, floods, and tropical cyclones, aggravating water management problems, reducing agricultural production and food security, increasing health risks, damaging critical infrastructure, and interrupting the provision of basic services such water and sanitation, education, energy, and transport.

This goal aims to strengthen resilience and adaptive capacity to climate-related disasters, as well as to integrate climate change measures into policies and planning, and to build knowledge and capability to meet the challenges of climate change. It also aims to strengthen the global response to the threats by keeping the global temperature rise, during this century, to well below 2 degrees Celsius above pre-industrial levels.

To achieve this, the world must transform its energy, industry, transport, food, agriculture, and

electricity systems, automotive and transportation, and industrial and environmental monitoring. For example, a policy white paper on quantum technologies in space from the European Space Agency says that: "Given the extreme effects of global warming that mankind is facing, Earth observation is maybe the most important scientific endeavor of our times... However, it has become clear that the classical measurements cannot be pushed much further…. With quantum technologies… stepping-stones were placed in developing methods for space-borne high-precision gravity sensing. These sensors promise to improve Earth observation by their long-term stability and low drift."

In addition, gravimetry, based on atom interferometry, is capable of performing highly sensitive and accurate measurements of gravity for usage in geodesy, hydrology, and climate-monitoring missions in spacecrafts with significant space constraints. These sensors can be very compact and used to collect data sets for understanding the earth's water cycle and its response to climate change. Gravimeters can also be used to monitor volcanic hazard by measuring density changes caused by rising magma.

forestry systems to ensure that cumulative net emissions are significantly reduced, in order to reach global net-zero emissions by the second half of this century. We can use quantum computers for climate and associated risk modeling to assess/analyze the potential impact of physical and transition risks to different industries.

Industries may be able to contribute to this goal in many ways by adopting quantum computing technologies. The potential use cases are to carry out material research, and capture emissions in industrial processes and electricity generation, and thus prevent CO_2 release to the atmosphere. Other use cases include the development of equipment and devices to decarbonize air through carbon sequestration in an efficient manner, and the optimization of operations and supply chains using quantum optimization algorithms. Furthermore, the use of simulation techniques to enhance the performance of wind turbines in design and development, material research to increase the efficiencies of solar panels, and research into battery storage also offer potential benefits.

In this context, quantum sensors are expected to be able to deliver transformative impacts across

SDG 14: Life Below Water

Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

Oceans are the source of life of the planet and the global climate system regulator, and they are vital for making the planet livable. But the sustainability of oceans is under severe threat due to pollution, fishery, acidification, eutrophication, and ocean warming. It is therefore essential to manage carefully such a global resource for the planet's sustainable future. There are many aims of this goal: to reduce marine pollution, protect and restore ecosystems, reduce ocean acidification, promote sustainable fishing, conserve coastal and marine areas, end subsidies contributing to overfishing, and increase the economic benefits from sustainable use of marine resources.

Quantum computing can be used in the simulation of the ocean acidification process and in the assessment of its impacts. Quantum machine learning algorithms can also be applied to assist in the estimation and prediction of fish stocks and other species living under the water, to help inform policies to maintain sustainable levels and manage fishing and other human activities in the sea. It is also possible to use visual analysis through drones or satellite images of the level of floating plastic debris and therefore, with this more accurate assessment, take necessary actions to clean up the oceans as much as possible.

Quantum simulation used in materials science can shape the production of new materials for effective effluent treatment and to reduce marine pollution. In addition, quantum imaging sensors can be used in murky environments and difficult to view environments in order to better understand the life below water in the ocean and other water bodies. Sensors also have a role in the early detection (and therefore repair) of damaged underwater pipelines, thus preventing large-scale environmental pollution events.

SDG 15: Life on Land

Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss.

The purpose of this goal is securing sustainable livelihoods that will be enjoyed for generations to come. The outcomes expected from this goal are: to conserve and restore terrestrial and freshwater ecosystems; end deforestation and restore degraded forests; end desertification and restore degraded land; ensure conservation of mountain ecosystems, protect biodiversity, and natural habitats; protect access to genetic resources and fair sharing of the benefits; eliminate poaching and trafficking of protected species; prevent invasive alien species on land and in water ecosystems; and integrate ecosystems and biodiversity in governmental planning.

There are a limited number of direct applications of quantum computers for this goal, but some of the use cases relating to agriculture, discussed in SDG-2, would also be relevant here. In addition, quantum optimization algorithms can be used for the efficient use of financial and other resources to conserve biodiversity and ecosystems, and sustainably use forest management (target 15.a & b). Satellite and drone image analysis through machine learning could provide a better assessment of the state of various terrestrial and freshwater ecosystems (forests, wetlands, mountains, drylands) and quantum sensors can be used to monitor sustainable use of land and changing patterns of land usage through earth observations.

SDG 16: Peace, Justice and Strong Institutions

Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

A better understanding of the links between the environment and human security is vital for effective conflict prevention, post-conflict reconstruction, and the promotion of peaceful and inclusive societies.

SDG 16 aims to: reduce violence; protect children from abuse, exploitation, trafficking, and violence; promote the rule of law and ensure equal access to justice; combat organized crime and illicit financial and arms flows; substantially reduce corruption and bribery; develop effective, accountable, and transparent institutions; ensure responsive, inclusive, and representative decision-making; strengthen the participation in global governance; provide universal legal identity; ensure public access to

information; and protect fundamental freedoms.

Quantum machine learning can be used to reduce illicit financial flows through application machine learning around detection of money laundering, and fraudulent transactions through anomaly detection (target 16.4). This could reduce the potential flow of money towards various kinds of organized crimes.

Usage of machine learning in cybersecurity and quantum communications can help to strengthen national institutions against potential cyber threats from rogue states, terrorists, and other criminal organizations. In addition, quantum machine learning can help in generating insights from various sources of data representing all forms of violence, corruption and bribery instances, and related laws, and their implementation, across nations, can help in effective decision-making for introducing effective laws and regulations.

SDG 17: Partnerships for the Goals

Strengthen the means of implementation and revitalize the global partnership for sustainable development.

A successful development agenda requires inclusive partnerships – at global, regional, national, and local levels – built upon principles and values, and a shared vision and goals, placing people and the planet at the center. This goal refers to the need for cross-sector and cross-country collaboration in pursuit of all the goals. The vision of this goal is for improved and more equitable trade, as well as coordinated investment initiatives to promote sustainable development across borders.

It is about strengthening and streamlining cooperation between nation-states, both developed and developing, using the SDGs as a shared framework and a shared vision for defining that collaborative way forward. This partnership aims at working across five categories, namely

finance, technology, capacity building, trade, and systemic issues, and the specific targets are defined for each of these areas.

Quantum computing can help in strengthening domestic resource mobilization through tax and other revenue collection by levering machine learning algorithms to detect and correct money laundering and other tax evasion situations (target 17.1). Quantum simulation can be used in assisting countries to attain long-term debt sustainability through effective risk modeling around credits/debt financing (target 17.4).

Quantum computing and related technologies offer a great opportunity for nations to collaborate and cooperate to innovate and enhance knowledge across science, technology, and innovations (target 17.6). Quantum machine learning can also help in the development of an effective macroeconomic dashboard through processing and analysis of data across demographics and regions (target 17.18).

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CAPGEMINI'S QUANTUM LAB

Capgemini is a leading expert in the application of quantum technologies, helping clients to solve previously intractable business and societal problems and to explore the potential of three Quantum fields: computing, communications and sensing.

Although much of the potential of quantum is still to be realized, we expect benefits of the Quantum Advantage will include:

- Tackle business problems previously unimaginable, and process complex data with incredible speed through carefully designed quantum algorithms and computing power
- Transform sensing, detection and imaging – from autonomous transport to brain imaging – through superior accuracy in critical measurements
- Advance cybersecurity to new levels unobtainable with traditional techniques - greater communication security in a post quantum world.

Our Quantum Lab is a global network of quantum experts, partners and specialist research facilities, in the UK, Portugal and India, running research programs and developing capabilities aimed at the advancement of quantum technologies.

Find out more at
www.capgemini.com/quantum

CAPGEMINI SUSTAINABILITY SERVICES

As one of the world's leading business transformation experts, Capgemini has the responsibility to reduce its own environmental footprint. But we are also in a strong position to help our clients deliver their low carbon transition, ensuring maximum positive environmental impacts while enhancing their value chain.

In 2020, we announced our ambition: to help our clients save 10 million tons of CO^2eq by 2030 and to achieve this, we developed a practical and dedicated sustainability offering framework to support them throughout their net zero journey, from commitments to sustainable achievements.

This framework relies on a three-part structure:

- Commit: To define a net zero strategy, build the underlying organization, embark all relevant stakeholders internally and externally, while adjusting business models accordingly;
- Act: To operationalize this strategy by eco-designing products and services, refining their operations and supply chain to reduce environmental footprint, and by switching the IT legacy to a green IT capability;
- Monitor and report: To leverage reliable data to model, track and report on the evolution of greenhouse gas emissions and continually adjust the strategy to ensure positive achievements.

Find out more at
www.capgemini.com/services/sustainability

About Capgemini

Capgemini is a global leader in partnering with companies to transform and manage their business by harnessing the power of technology. The Group is guided everyday by its purpose of unleashing human energy through technology for an inclusive and sustainable future. It is a responsible and diverse organization of over 325,000 team members more than 50 countries. With its strong 55-year heritage and deep industry expertise, Capgemini is trusted by its clients to address the entire breadth of their business needs, from strategy and design to operations, fueled by the fast evolving and innovative world of cloud, data, AI, connectivity, software, digital engineering and platforms. The Group reported in 2022 global revenues of €18 billion.

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