How AI can enable a Sustainable Future

Microsoft

in association with pwc

Foreword

Today's information age is driving unbelievable advances at tremendous speed. AI will enable humans to harness vast amounts of data and make breakthrough advances in areas like healthcare, agriculture, education, and transportation. We're already seeing how AI-bolstered computing can help doctors reduce medical mistakes, farmers improve yields, teachers customize instruction, and researchers unlock solutions to protect our planet.

But as we've seen over the past 20 years, as digital advances bring us daily benefits, they also raise a host of complex questions and broad concerns about how technology will affect society. We have seen this as the internet has come of age and become an essential part of our work and private lives. And this seems certain to continue as AI evolves and the world focuses on the role it will play in society. As we look to the future, it's important that we maintain an open and questioning mind while we seek to take advantage of the opportunities and address the challenges that this new technology, and others like it, create.

How these technology advances will affect the planet is among those questions, and one we have a limited amount of time to answer given the urgency of challenges such as climate change and biodiversity loss. If you look at the past 200 years, a series of industrial revolutions have radically improved the standards of living for human beings. But each past industrial revolution has borrowed from the future to pay for the present by achieving economic growth through the degradation of our planet's health. Today's technological revolution must break this pattern, and for the first time deliver sustainable economic growth.

Microsoft and PwC have a shared belief that, with a great deal of urgency, we must address the diminishing health of our environment. We also share a belief that new technologies like AI can be a game-changer in this space. But to create the kind of global action needed, it needs to be more than a belief – it needs to be backed by data, by solutions, and by new partnerships.

That is why, together, we undertook this research. Applying our expertise in AI, data science, economics, and sustainability, we examined four sectors of the economy that are primed to be, or in many cases are already being, disrupted by AI to better understand the potential economic and environmental benefits. These sectors are Agriculture, Energy, Transport and Water.

For us, some key conclusions emerged.

First, there is enormous potential for AI to be an important tool in the effort to decouple economic growth from rising carbon emissions. In other words, there is a path towards a prosperous, just, and more sustainable future with advanced technologies.

Second, this outcome relies on bringing together several factors. The solutions we explore are not AI acting on its own; in most cases multiple complementary technologies come together, including robotics, the internet of things, distributed energy resources, electric vehicles, and more. AI also requires large amounts of compute power, which translate to energy consumption. Without new incentives that accelerate a market change towards clean energy – from renewables to electric vehicles – the efficiency gains from AI won't deliver their full emissions reduction potential for the world. On the flip side, our own projections of GDP and environmental gains could be

at the low end of what plays out in reality. The signals are that a more rapid and global low-carbon transition lies ahead than that reflected by our Business As Usual scenario, driven by the increasing cost-competitiveness of low carbon alternatives and continued ratcheting of environmental policy.

Third, there are important issues of justice to consider, to ensure that benefits are inclusive. The largest gains we see map to the countries that are already at the forefront of AI adoption, and are not evenly experienced today. Without incentives and policy change to ensure all regions are ready to capture these benefits, these economic and climate inequalities will be exacerbated. Just looking at jobs, the good news story of more high-skilled jobs also carries a reality of jobs displacement, and a pressing need for upskilling and reskilling to avoid leaving people behind.

This all means we need to think beyond the technology itself to address the wider implications on society and our environment. From the need for strong ethical frameworks, to the evolution of laws, the importance of education and training for new skills, and even labor market reforms – these must all come together if we're going to make the most of this new technology.

Finally, we need to address these issues together with a sense of shared responsibility. In part this is because AI technology won't be created by the tech sector alone. Creating a better future requires that people in government, academia, business, civil society, and other interested stakeholders come together to help shape this future. And increasingly we need to do this not just in a single community or country, but on a global basis. Each of us has a responsibility to participate – and an important role to play.

This report is just the first step in building a case for deeper exploration of how AI can create a more sustainable future. There are many additional sectors to examine and areas to explore, and we hope this research inspires others to conduct similar work. We have greater ambitions than driving academic research, however. Research should be a means to an end, and this case, that end should be global progress on climate change and nature. We know enough today from science to understand that there is a limited amount of time to make the kind of changes needed to allow the seven billion people on this planet to live, work, grow, and thrive.

We hope the pages that follow will help spark increased efforts to help make the fourth industrial revolution become the first one to deliver a better future for both society and our environment.

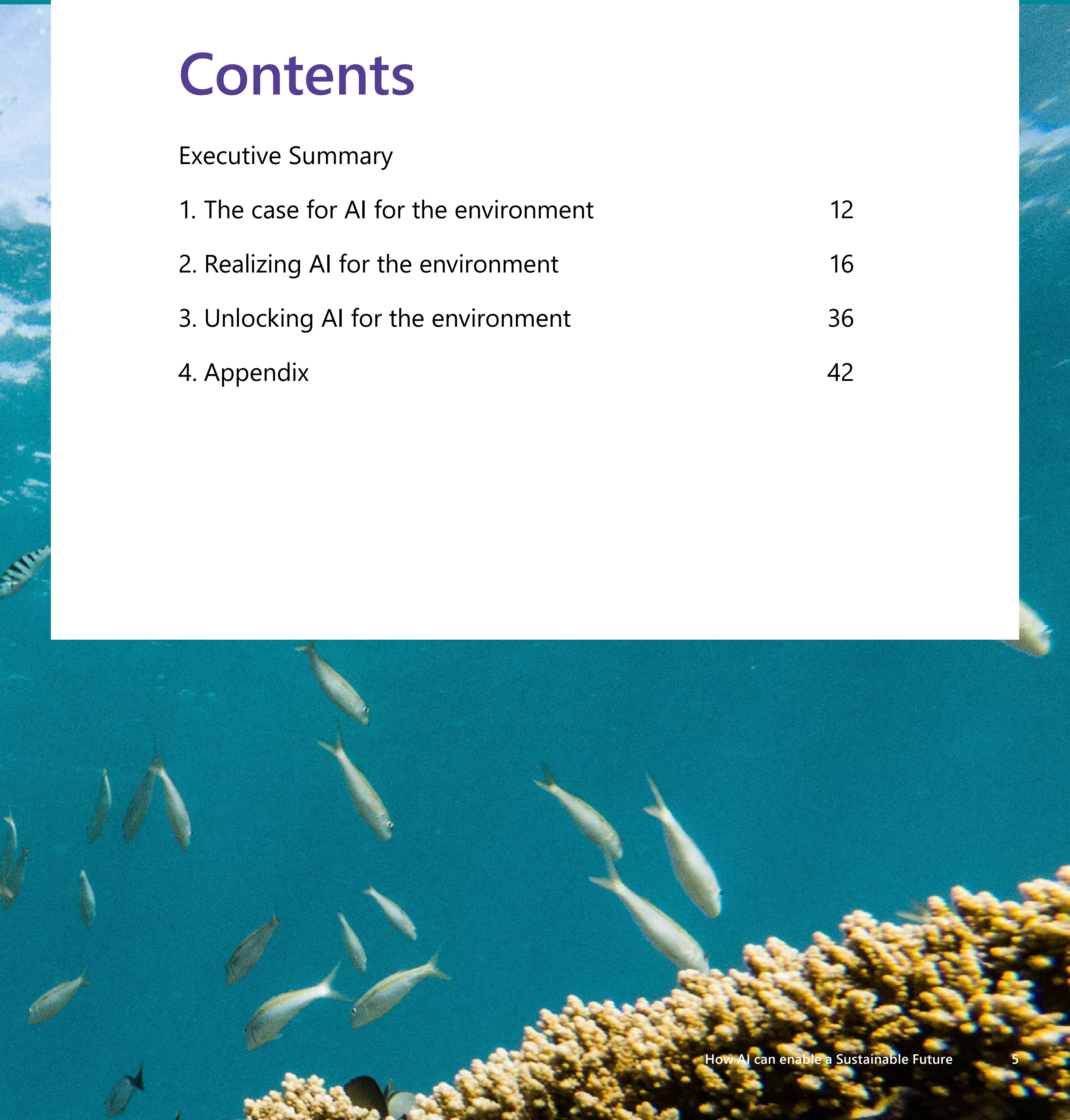
Lucas Joppa

Chief Environmental Officer, Microsoft

Celine Herweijer

Global Innovation & Sustainability Leader, Partner, PwC UK

Contents



A time of rapid change

The coming few decades look set to be a time of unprecedented change for humans. On one hand, our ingenuity has unleashed an information and intelligence age – where the ascendency of emerging technologies, including AI – is set to reshape industries, scientific discovery, human engagement and endeavor, and even economic power. On the other hand, the extraordinary advances of previous generations, which in the last century delivered exponential economic growth and huge strides in human welfare, have also left us with a planet that scientists warn is under unprecedented environmental strain. This has led to the so-called "Anthropocene" age – where human activity is the dominant influence on our environment and our natural systems are changing at unprecedented rates[1], from climate change to biodiversity loss, ocean warming and acidification, deforestation, and water and air pollution.

Today as we sit at the intersection of the Artificial Intelligence (AI) age and the Anthropocene age, not enough has been done yet to bring these two worlds together. And let's not forget that it's society today that will not only feel the impact of climate change first, but will also be the first to experience rapid digital transformation, automation and augmented human ingenuity. It is incumbent on us, therefore, to transform industries, markets, and behaviors to change the course of climate change; and to lay the foundations for a positive, safe, and responsible digital future. These priorities aren't isolated: powerful new technologies, including AI, can play a critical role in underpinning the solutions needed to tackle our most pressing societal challenges – from digital monitoring and enforcement for conservation, to decarbonizing energy and transport.

Much has been written about the impact of AI on society, economy, and jobs in particular. PwC's own report Sizing the Prize, for example, suggests that the potential contribution of AI to the global economy by 2030 could be as much as US$15.7 trillion, impacting millions of jobs and making it the biggest commercial opportunity in today's fast-changing economy. For climate change impacts on the economy and the environment, research is even more extensive and has underpinned the political commitment of 197 countries to limit the rise in global average temperature to "well below 2°C" as signatories to the UN Paris Agreement. Many assessments of the economic costs of climate change, from the early Stern review to the latest National Climate Assessment in the US – which shows potential costs to the US economy of over US$500bn per year in 2090 from doing nothing – demonstrate significant and growing economic costs of inaction.

Despite this growing body of evidence, less has been done to evaluate these two futures in parallel: to assess the economic and environmental gains that the AI era can help to harness, and to understand better how this new and powerful tool can help to shape our economy and environment against the backdrop of the Anthropocene.

What can AI do for our economy and environment?

As these two disruptive and powerful megatrends – digitalization and decarbonization – take hold globally, we have made a very preliminary assessment of some of the opportunities that AI can offer, for economic growth and emissions reduction potential, between now and 2030. We have done this for a small subset of sectors (four) that are critical to the economy, environment, and natural systems, namely agriculture, water, energy and transport. Within each, we have covered only a subset of potential AI levers and look at a business as usual growth trajectory. Across these, we assessed the speed and potential scale of impact, building on PwC's proprietary jobs automation models[2], 'AI for Earth' use case database[3], and proprietary economic models. Our analysis covers GDP[4] estimates, GHG[5] emissions, as well as the likely impact on jobs at a global scale and across seven regions[6].

We recognize that our research has limitations[7], and acknowledge the difficulties of fully capturing the impacts, including accurately estimating rebound effects and evolving sectoral interactions. We have attempted to be as transparent as possible and use a Computable General Equilibrium (CGE) modelling[8] approach that is widely employed by International Organizations and national governments to make these types of assessments.

Even within this narrow scope, we have reason to be optimistic: AI adoption in these sectors, even on current pathways, is predicted to deliver substantial economic and environmental benefits.

Today as we sit at the intersection of the Artificial Intelligence (AI) age and the Anthropocene age, not enough has been done yet to bring these two worlds together.

Figure 1ES: : AI for the environment headline results[9]

+4.4% GDP ($5.2Tr)

-4.0% GHGs (-2.4Gt)

+1.0% net jobs (+38.2 million)

Source: PwC analysis

Our main findings

- **Using AI for environmental applications has the potential to boost global GDP by 3.1 – 4.4%[10] while also reducing global greenhouse gas emissions by around 1.5 – 4.0% by 2030 relative to Business as Usual (BAU)[11].** Productivity benefits of AI applications across the four key sectors can generate an overall global economic uplift, yielding a potential gain of US$3.6 – 5.2 trillion[12] driven by optimized use of inputs, higher output productivity and automation of manual and routine tasks. In parallel, these applications can accelerate the move to a low-carbon world with a reduction in worldwide greenhouse gas emissions by 0.9 – 2.4 gigatons of CO_2e, equivalent to the 2030 annual emissions of Australia, Canada and Japan combined,[13] and an overall reduction in carbon intensity of 4.4 – 8.0% relative to BAU. The AI applications modelled will also create 18.4 – 38.2 million net jobs globally (broadly equivalent to the number of people currently employed in the UK), offering more skilled occupations as part of this transition.

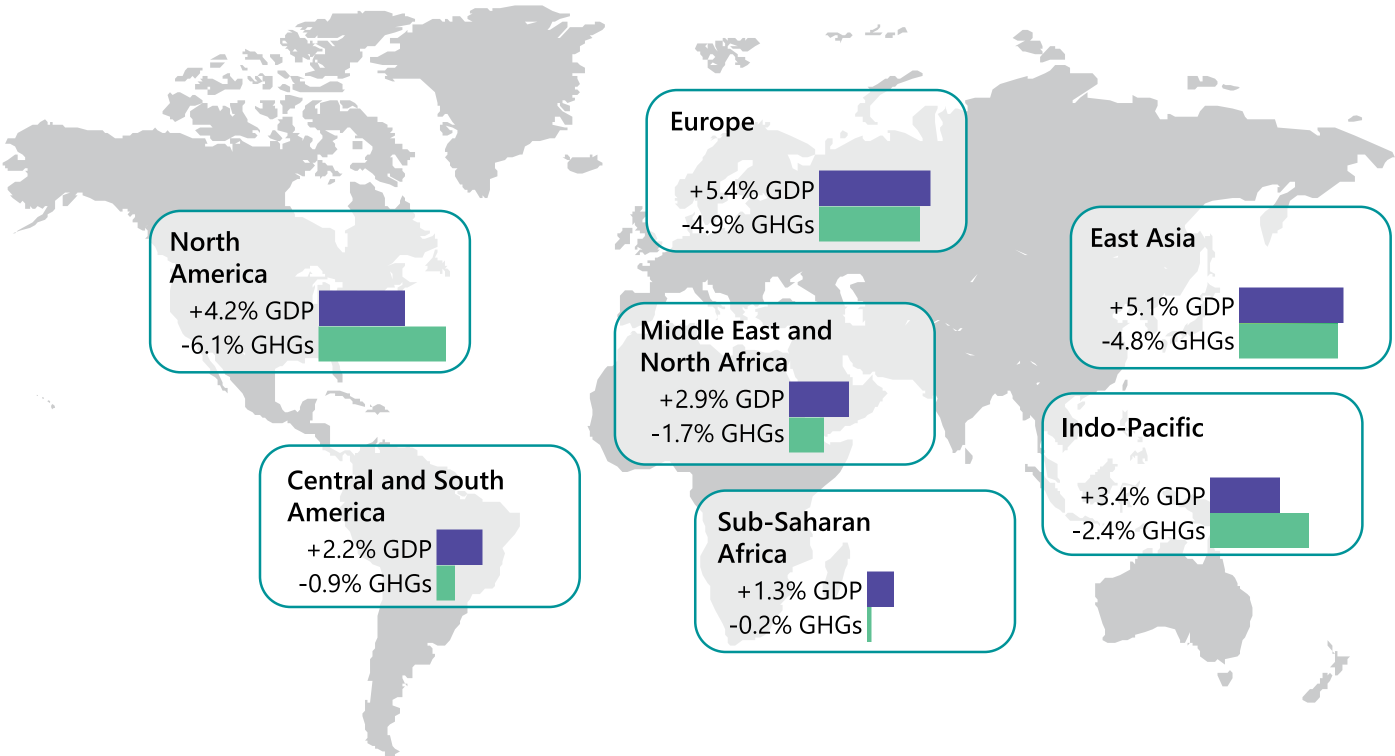
- **Economic benefits could be predominantly captured by Europe, East Asia and North America regions as they each achieve GDP gains in excess of US$1 trillion[14].** Latin America and Sub-Saharan Africa currently stand to gain the least. This distribution is due in large part to each region's current digital readiness, levels of tech adoption[15] and current policy trends. These gains could be higher if more rapid digital transformation can be realized. Nevertheless, this projected disparity highlights concerns over how gains from AI for environment can be more evenly distributed, particularly as these less affluent regions are also likely to be most adversely affected by the physical impacts of climate change. Environmentally-oriented AI applications carry a big GHG mitigation potential for almost all regions, with North America and East Asia potentially reducing their GHG emissions respectively by 1.6 – 6.1% and 2.7 – 4.8% in 2030.

- **AI applications in energy (up to -2.2%) and transport (up to -1.7%) have the largest impact on GHG emissions reduction of our sectors covered, but water and agriculture still have an important role to play for the environment more broadly:** our analysis suggests that agricultural AI applications can help reduce emissions by up to 160Mt CO_2e in 2030 whilst providing more food, and using fewer resources. Moreover, the agriculture and water sectors have a vital role in preserving the health of our Earth's natural systems, including biodiversity conservation, ocean health, freshwater quality, biogeochemical flows, forests and land system change, and related impacts on the security of food and water supply.

- These projections rely not just on AI, but on the adoption of a wider complementary technology infrastructure. For example, in the energy sector, AI-enabled distributed energy grids will reach their maximum potential with the adoption of related innovations in distributed grid infrastructure including distributed generation, distributed storage, Industrial IoT[16], electric vehicle charging, dynamic pricing, and smart meters. Likewise, in transport, AI-enabled autonomous vehicles must offer more than energy efficiency gains through smart navigation and eco-driving, but also ultimately be electric vehicles and incentivize ride-shares, to counter a potential rebound effect of increased vehicle miles.

These projections rely not just on AI, but on the adoption of a wider complementary technology infrastructure.

ES2: AI for the environment headline results[17] for global GDP and GHGs



Source: PwC analysis

- More broadly, we also explore how these AI applications can offer environmental benefits beyond GHG emissions, including impacts on water quality, air pollution, deforestation and land degradation, and biodiversity. For example, AI can analyze satellite data and ground-based sensors to monitor forest conditions in real-time and at scale, providing early warning systems for investigation of illegal deforestation, with potential to save 32 million hectares of forest globally by 2030. Air pollution is one of the largest environmental risks to human health, where using AI to provide more accurate and localized early-warnings of poor air quality can help reduce this burden. Our analysis estimates that using AI in this way could provide additional economic benefits of US$150m globally in 2030 in reduced healthcare costs and health impacts.

AI applications, therefore, offer a range of positive impacts for the environment. Or to put the headline results another way, there is a huge opportunity foregone if leaders and decision-makers do not help enable AI innovations for the environment.

Areas for further exploration

Our analysis and results raise a number of broader themes, which are important to bear in mind both to contextualize our findings, and to further develop and mature our understanding of how AI, the economy, and our environment intersect:

- **Sectoral coverage:** we look at a range of AI applications across four sectors, but do not cover wider sectors of the economy, including the traditional 'hard to abate' sectors (e.g. chemicals, steel and cement, shipping and aviation) where there could also be significant gains. There might also be AI levers that could work in the opposite direction and increase greenhouse gas emissions (e.g. mining).
- **Future energy supply:** our modelled BAU baseline includes a limited transition to renewables and a continued reliance on fossil fuels, including coal, in the future energy mix. In reality, the signals are that a more rapid low-carbon transition is underway, both in developed and developing countries. This is being driven by the increasing cost-competitiveness of low-carbon alternatives, and continued ratcheting up of environmental policy and carbon pricing following the global agreement of governments to limit warming to well below 2 degrees Celsius. Given many of the AI applications we look at link to electrification, the future energy mix of the grid will be crucial to maximizing emissions reduction as many AI applications use additional electricity.
- **Regional impacts and outlooks:** those regions which see the least potential benefits from AI for environment (e.g. Sub-Saharan Africa and Latin America) due to lower levels of digital readiness are also likely to see some of the more significant climate change impacts. However, there are two important factors to consider. First, the more that global emissions can be reduced, through AI and other means, the more these regions' economies will be bolstered through avoided impacts. Second, through targeted investment today in digital upskilling and digital infrastructure in these regions, there is an opportunity to leapfrog developed nations and far exceed these modelled projections to unlock substantial economic and environmental gain.
- **Measures of wealth:** many of the benefits from using AI for the environment are not fully captured by current economic frameworks. GDP is an annual measure that captures the 'flow' of income. To capture fully the benefits of AI (e.g. preserving the 'stock' of biodiversity and habitats etc.) alternative welfare and 'balance sheet' methods need to be developed and used alongside traditional GDP estimates.

Each of these factors are important areas for future research to better understand, and by extension unlock, the full opportunity of AI for our economy and environment.

What we can do and a ‘call to action’

We will need to move forward holistically on a number of broader areas, however, in order to realize fully any of the opportunities analyzed or identified. The positive scenario for our future won’t emerge unguided; there will be trade-offs, and challenges, as well as opportunities. The public and private sector alike, particularly technology firms and companies deep in their digital transformation, will need to champion responsible technology practices that consider social and environmental impact and long term value creation. We also need to consider the policy and market reforms needed to make new solutions scale over incumbent practices and systems, and the role of different stakeholders, including governments and regulators.

We believe that to unlock the potential of AI for the environment, five principle ‘enablers’ will be key:

1. **Facilitating awareness, value alignment, collaboration and multi-disciplinary partnerships** (including technologists, industry, scientists, civil society, governments).
2. **Ensuring that we start with ‘Responsible AI’ and extend this principled approach to include societal and environmental impact.**
3. **Addressing digital infrastructure needs, access to AI tools and data, and wider complementary technologies.**
4. **Providing opportunities and training for upskilling and reskilling to adapt to sectoral transformations.**
5. **Encouraging R&D from research to scalable commercial deployment.**

All stakeholders across the public, private and third sectors must be involved in unlocking AI to tackle environmental challenges to its fullest potential. Each has a role to play in creating this ‘enabling environment’ to accelerate economic and environmental progress. Specifically, we outline actions the following stakeholders can play to create an improved enabling environment:

- **Governments:** take an agile approach to targeted regulation and policy support on items including data access, R&D and digital infrastructure and skills investment, in addition to wider environmental policy.
- **Tech developers:** take actions to create, provide and improve data assets and provide access to AI tools, data and wider complementary technologies.
- **Companies:** embed environmental impact considerations into AI strategies and deployment, identify disruption and transformation needs, and embrace upskilling and reskilling of workforces.
- **Academia:** encourage multi-disciplinary focus, combining AI and domain-relevant education and research, and industry partnerships.
- **Non-Governmental Organizations:** develop partnerships with technologists, invest in digital upskilling, and explore where AI and wider complementary technology innovations can create benefits.

While there are a range of recommendations explored in this report, the impact of AI on jobs – and the skills challenge – has to date received the most attention from the media and from society at large. All stakeholder groups are affected, and the pace of change is fast. With digitization, automation and augmentation already transforming sectors, markets and global value chains, it is critical that companies and countries think ahead about both the markets and the workforce of the future.

We hope this work is a first step in a larger conversation to inject attention and investment into a tech-first approach to our most pressing environmental challenges. Moreover, we hope this report motivates others to build on this initial analysis to develop more comprehensive numbers around this topic. Both these efforts need to happen at speed for our planet, and for society, to survive and thrive.

1 The case for AI for the environment

Introduction and overview

Advances in artificial intelligence (AI) give rise to the ongoing digital transformation of our economies and societies. Today's AI era has just begun and already touches on many aspects of our lives. As AI capability accelerates and spreads, transforming enterprises and sectors, it is critical to think ahead about the real opportunities, and threats, that AI will create for our economy, society and environment.

We take AI as a collective term for technologies that can sense their environment, think, learn, and take action in response to what they're sensing and their objectives. Applications can range from automation of routine tasks; to augmenting human decision-making; and beyond to automation and discovery – huge amounts of data to spot, and act on patterns, which are beyond our current capabilities.

The profound changes to our sectors, markets and society that will take shape in the AI era will occur against the backdrop of transformations required to address pressing societal challenges, including climate change, rapid biodiversity loss, resource depletion, and food and water security (see Box 1: 'A Planet Under Stress'). These challenges enhance the need to monitor, model, and better manage the Earth's natural systems.

The key question business leaders are asking is: to what extent will AI transform and disrupt my organization and markets, and how quickly will this take hold? Business are concurrently facing growing pressure (regulatory, reputational and market-driven) to transform business models and embrace the shift to a low-carbon, sustainable future. For example, achieving a zero net emissions economy by 2050, as signed up to by 197 governments,[18] will require radical transformation in every sector of the economy.

As these two disruptive and powerful megatrends – digitalization and decarbonization – take hold globally, therefore, we have made a very preliminary assessment of some of the opportunities that AI can offer, for economic growth and emissions reduction potential, between now and 2030. We have done this for a small subset of sectors (four) that are critical to the economy, environment, and natural systems, namely agriculture, energy, transport and water. Within each, we have covered only a subset of potential AI levers and look at a business as usual growth trajectory. Across these, we assessed the speed and potential scale of impact, building on PwC's jobs automation models,[19] 'AI for Earth' use case database,[20] and proprietary economic models. Our analysis covers gross domestic product (GDP) estimates, greenhouse gas (GHG) emissions, as well as the likely impact on jobs at a global scale and across seven regions.[21]

We recognize that our research has limitations,[22] and acknowledge the difficulties of fully capturing the impacts, including accurately estimating rebound effects and evolving sectoral interactions. We have attempted to be as transparent as possible and use a Computable General Equilibrium (CGE) modelling[23] approach that is widely employed by international organizations and national governments to make these types of assessments.

Realizing economic and environmental value

Figure 1: : AI for the environment headline results

By 2030, environmental applications of AI in agriculture, energy, transport and water have the potential to...

+4.4% GDP ($5.2Tr)

-4.0% GHGs (-2.4Gt)

+1.0% net jobs (+38.2 million)

Source: PwC analysis

relative to the projected baseline

Even within that narrow scope, we have reason to be optimistic: AI adoption in these sectors, even on current pathways, is predicted to deliver substantial economic and environmental benefits. AI for the environment solutions – represented here by 18 `levers'[24] across four sectors (agriculture, water, energy and transport) – could contribute up to $5.2 trillion USD to the global economy in 2030, a 4.4% increase relative to Business as Usual. Deploying those AI levers globally can in parallel reduce worldwide GHG emissions by up to 4.0% in 2030, an amount equivalent to 2.4 Gt CO_2e, equivalent to the 2030 annual emissions of Australia, Canada and Japan combined.[25] At the same time this could create up to 38.2 million net new jobs across the global economy (see next section for full results).[26] Put simply, AI can enable our future systems to be more productive for the economy and for nature. This supports the proposition that we can use AI to help 'decouple' economic growth from GHG emissions.

Furthermore, our analysis found gains of 0.1% by 2030 and 0.2% by 2100 in global GDP due to avoided climate impacts as a result of the environmental applications of AI (see Box 4: The Climate Baseline). It is worth noting that this estimate is a lower bound, as the climate impacts model only attempted to take into account sea level rises, changes in agricultural productivity, and key health effects from increased temperatures. Other significant impact channels, such as economic damages due to the increasing severity and frequency of extreme events, the spread of invasive species, and the costs of significant migration between regions, are not included.

Beyond the global results, we outline the world regions that are set to gain the most, and the AI-enabled levers of highest economic and environmental potential in each of the four focus sectors. We also look at the job implications – not just numbers, but the types of jobs our future sectors will need, and the implications for education, upskilling and reskilling. However, the AI for environment opportunity at its core is about harnessing one of the most powerful tools humans will have created to counter environmental degradation, contribute to a low-carbon transition, and help protect our planet.

Companies and countries that embrace the advent of the AI era and sustainable economies are set to gain most from the upcoming changes and opportunities. From a macroeconomic and development point of view, there are opportunities for emerging markets to harness AI-enabled innovations to leapfrog developed counterparts, investing first in AI-enabled systems and digital infrastructure, and reaping sizable productivity and sustainability gains.

Making it happen

While AI has a lot of potential to offer to the environment, its applications and uses could also exacerbate existing threats or create new risks. For instance, those broader AI-risks relating to performance (e.g. bias, errors), security (e.g. cyber and privacy) and control (e.g. rogue AI) are all potential risks to the environment. In addition, there are substantial and wide-reaching barriers relating to these sectors that need to be overcome to realize the full potential of AI for environmental applications. We take a look at these and outline what an "enabling environment" might consist of.

The positive scenario for our future will not emerge unguided; there will be trade-offs and challenges as well as opportunities. For example, AI with its focus on efficiency through automation might potentially lead to 'over exploitation' of natural resources (e.g. precision agriculture, precision dairy farming, precision mining) if not carefully guided and managed. AI, especially deep learning and quantum deep learning, could also lead to increased demand for energy, which could be counter-productive for sustainability goals, unless that energy is renewable (from wind, solar, hydro etc.) and that electricity generation is developed hand-in-hand with application deployment.

We need to be clear about the policy and market reforms needed to make new solutions scale over incumbent practices and systems. This is also about managing second order implications and unintended consequences on society and our environment. We need technologists, industry, and governments alike to adopt strong principles around fairness, accountability, transparency and ethics (FATE), and those principles need to include, and embed, consideration of environmental impacts. Regulations and laws need to evolve and continually keep pace with the technology, training for new skills will be fundamental, and even labor market reforms as sectors undergo rapid transition will be crucial. This must all come together if we're going to make the most of this new technology's potential for our economy, environment and society.

Box 1: A Planet Under Stress

Advances in scientific monitoring, data collection, and modelling over recent decades has enabled scientists to better assess and forecast the impact of human development on the Earth. The findings are worrying. As a result of the historical, cumulative human footprint, there is mounting scientific evidence that Earth systems are under unprecedented environmental stress:

- Climate Change. Today's greenhouse gas levels may be the highest in 3 million years. If current Paris Agreement pledges are kept, global average temperatures in 2100 are still expected to be 3°C above pre-industrial levels,[27] well above the 1.5C threshold needed to avoid the worst impacts of climate change.[28]
- Biodiversity. The Earth is rapidly losing its biodiversity at "mass extinction" rates, such that species' populations have declined by around 60% since 1970.
- Deforestation. Current deforestation rates in the Amazon Basin could lead to an 8% drop in regional rainfall by 2050, triggering a shift to a "savannah state", with wider consequences for the Earth's atmospheric circulatory systems.
- Oceans. The chemistry of the oceans is changing faster than at any point in perhaps 300 million years. The resulting acidification and rising temperatures of the ocean is having an unprecedented impact on corals and fish stocks.
- Nitrogen cycle. We are suffering from arguably the largest and most rapid impact on the nitrogen cycle for 2.5 billion years, as widespread nitrogen and phosphate pollution from fertilizers has washed into seas. This has affected fish stocks and created so-called "dead zones" in 10% of the world's oceans.
- Water. The global water cycle is facing similarly severe impacts through over abstraction and uncontrolled pollution, with related analysis suggesting that the world may face a 40% shortfall in the freshwater needed to support the global economy by 2030.
- Clean air. Around 91% of the world's people live in places that fail to meet World Health Organization (WHO) air quality guidelines.

These are wide-ranging, serious and urgent impacts on the Earth's systems resulting from human activity. Traditional policy and market responses have to date been inadequate to drive the scale and urgency of the systems and sectoral transformations required.

Technology as critical to the response

The role of technology and innovation is increasingly being seen as critical to the response. Radical transformation of sectors and systems is required to decarbonize faster (see, for example, the work of the Energy Transitions Commission), and tackle environmental degradation. In parallel, radical innovation and collaboration to broaden and deepen the solution set will be needed.

Today's technological revolution offers an era of unprecedented innovation and systems' change. If harnessed in the right way, emerging technologies, with AI at the vanguard, could be transformational in efforts to tackle some of the world's most pressing environmental challenges. Examples include AI-infused clean distributed energy grids, to smart urban mobility, precision agriculture, sustainable supply chains, environmental monitoring and enforcement, and enhanced weather and disaster prediction and response. Perhaps harnessing AI for environmental applications is the biggest challenge to set AI – as without a "safe Earth" our future on this planet is in question.

2 Realizing AI for the environment

AI can be harnessed across the global economy within a wide range of sectors to better manage our environment. In this section we present our simulations of the potential **economic, emissions and employment impacts** of environmental applications of AI that **could be realized by 2030** in **four key sectors**: agriculture, energy, transport and water.

Environmental applications of AI have, in these sectors, a high potential to contribute to mitigating the environmental challenges that the Earth is facing. Combined, these four sectors represent around three-fifths of GHG emissions and are critical to our environmental and Earth systems in other important ways. For example:

- Global population and economic growth continues to drive demand for food – both in terms of quantity and resource intensity. AI can transform **agricultural** production by better monitoring and managing environmental conditions and crop yields.
- AI has the potential to drive higher efficiency in the **energy** sector through intelligent grid systems, that utilize deep predictive capabilities to manage demand and supply and optimize renewable energy solutions. In this way, AI has the power to support decarbonization, as well as contributing to the UN's Sustainable Development Goals by ensuring a supply of affordable, reliable, and clean energy to all.
- AI applications in the **transport** sector can allow cargo and people to move between places more safely, efficiently, and sustainably in an increasingly globalized and urbanized world. For example, AI technologies have a large role to play in enabling more accurate traffic prediction, real-time journey planning, and autonomous vehicle technologies.
- Applying AI in **water** resource prediction, management and monitoring can help to ameliorate the global water crisis by reducing or eliminating waste, as well as lowering costs and lessening environmental impacts.

By focusing on these four sectors, we capture a significant subset of the possible impacts of leveraging AI for the environment. However, we do not only seek to gauge or demonstrate the economic and environmental potential of the environmental applications of AI in the four key sectors. We recognize that AI will also have a role to play in other sectors – including some hard-to-abate industries (e.g. heavy-industry, including steel and cement manufacturing) – with repercussions for the environment, the economy and jobs.

We discuss further gains that could materialize as a result of applying AI for the environment more broadly across the economy in more detail in the Wider impacts and areas for further exploration section.

Box 2: Our high-level approach: How we gauged the impact of AI for the environment

Our analysis builds on the methodology PwC established as part of their earlier Sizing the Prize research on the economic impact of AI. We began by identifying what our experts believed to be some of the most impactful AI levers – in agriculture, energy, transport, and water – by 2030, built up from our database of over 150 environmental AI applications; and scored each against their degree of impact and pace of adoption.

We used PwC's global CGE model to assess the direct and indirect impacts of these AI levers on the economy, on the environment, and on jobs. CGE modelling is the go-to macroeconomic modelling tool favored by governments and international organizations when forecasting the economic impact of policy and investment interventions. It captures the indirect knock-on impacts across different regions and sectors: for example, if agriculture can use fossil fuels more efficiently, agricultural output can expand while demand for fossil fuels will decrease, and so on. It also captures the demand effect of changes in consumer income.

We also incorporated recent scientific models on the links between temperature rise and GDP, showcasing how the climate benefits of AI lead also to quantifiable economic benefits via avoided damages.

We set out our methodology in more detail in the Appendix.

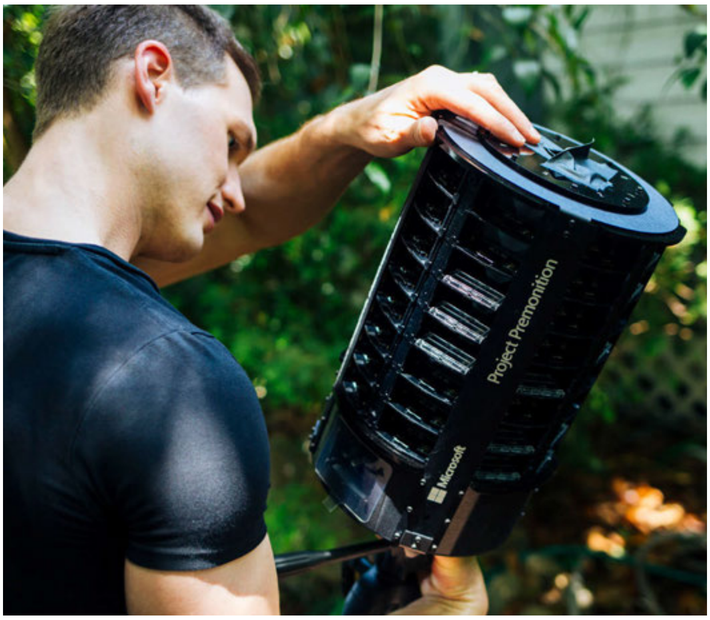
In this report, we present two sets of projections, each of which is underpinned by a scenario of how environmental applications of AI might materialize in the global economy:

- In our "**Gradual**" scenario we assume progressive growth continues in the adoption and application of environmental AI. Each environmental application of AI is assumed to have an impact around the mid-point of our assessed range, in line with PwC's previous "Sizing the Prize" report.
- In our "**Expansion**" scenario, we assume a step change in the utilization of AI in the four sectors and therefore assume greater efficiencies are generated in the sector in question compared to the "Gradual" scenario. In terms of our modelling exercise, each environmental application of AI is assumed to have an impact around the upper bound of our assessed range.

We present all of our results as a range of impact between these two scenarios unless otherwise stated.

In the remainder of this section, we outline our key results including:

- The GDP contribution and GHG emission mitigation potential of AI in environmental applications;
- Regional impacts;
- Results by sector;
- A deep dive into the jobs impacts; and
- A discussion of the wider impacts and areas for further exploration.



GDP contribution and GHG emission mitigation potential

AI for the environment has the potential to contribute to future global GDP by up to 4.4%, while also reducing global greenhouse gas emissions by up to 4.0%, by 2030 relative to the baseline.

Figure 2: Global impact of environmental AI on GDP and GHG emissions in the "Expansion" scenario

By 2030, environmental applications of AI in agriculture, energy, transport and water have the potential to...

+4.4% GDP ($5.2Tr)

-4.0% GHGs (-2.4Gt)

relative to the projected baseline

Source: PwC analysis

Box 3: A guide to interpreting our results

We simulated the impact of environmental AI levers in the four sectors in a dynamic global general equilibrium model that takes into account demand and supply changes in the economy as a whole, and not in isolation. Our analysis attempts to capture the knock-on effects on regions and sectors that may not be directly affected; for example, if the energy sector becomes more efficient and electricity becomes available at a lower cost, fuel demand in the transport sector may rise and offset part of the positive environmental impacts.

In our baseline, the world economy grows in line with PwC's analysis in the World in 2050 report, while our environment baseline is modelled after the IPCC's middle scenario of global GHG concentration, with GHG levels assumed to follow the "Current Policy" scenario developed by the Climate Action Tracker organization. These together form our assumptions for "baseline" economic growth and implied reduction in GHG intensity.

In light of this background, we carried out a simulation exercise to derive plausible estimates of the impact that environmental AI applications in agriculture, water, transport, and energy may have on economic performance and global emissions between now and 2030. Our simulations attempt to isolate the impact of environmental AI applications assessed in this report, and should be interpreted as the net impact of the AI levers in agriculture, water, transport, and energy, relative to a baseline in which these, and other, sectors' economic performance and GHG intensities are growing in line assumptions we set out above. Therefore, our results show the economic impact of these AI applications only – they may not show up directly in future economic growth figures as there will be many positive or negative forces that either amplify or cancel out the potential effects (e.g. shifts in global trade policy, financial booms and busts, major commodity price changes, geopolitical shocks etc). We also did not consider the possible impact of AI applications in other sectors specifically.

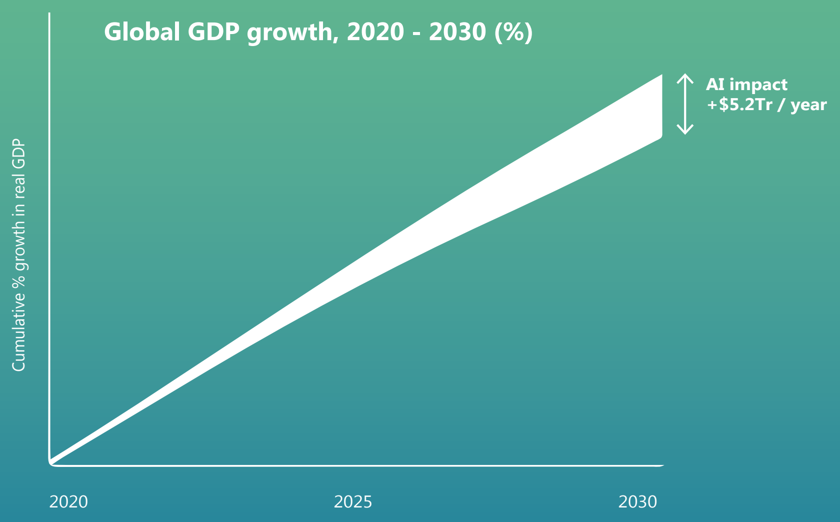
We recognize that AI applications outside the scope of this report could support further potential gains in the economy as a whole, and we did not assess their impact on global GHG emissions.

We also recognize that some or all of the environmental AI levers considered in this report could already be a part of the baseline economic growth and carbon intensity change. It's very difficult to separate out the extent to which the assessed AI levers help economies to achieve the baseline growth rates (implying the contribution from existing technologies phase out over time) or are additional to baseline growth rates (given that these will have factored in major technological advances of earlier periods). These two factors mean that our results should be interpreted as the potential impacts of environmental applications of AI we assessed in this report, as opposed to direct estimates of future economic growth. We do not expect the potential impacts to be materially different in both absolute and percentage terms between the two interpretations above.

GDP impacts

Our results indicate that by 2030, environmental applications of AI in agriculture, energy, transport, and water (hereafter referred to as "the four sectors") have the potential to generate future GDP gains of $3.6 – $5.2 trillion USD relative to the baseline, or 3.1% – 4.4%. This aligns with our previous research that suggests global GDP could be up to 14% higher (equivalent of an additional $15.7 trillion) in 2030 as a result of AI applications across all sectors of the economy.

Figure 3: GDP impact of environmental applications of AI in the "Expansion" scenario by 2030, relative to the baseline



Source: PwC analysis

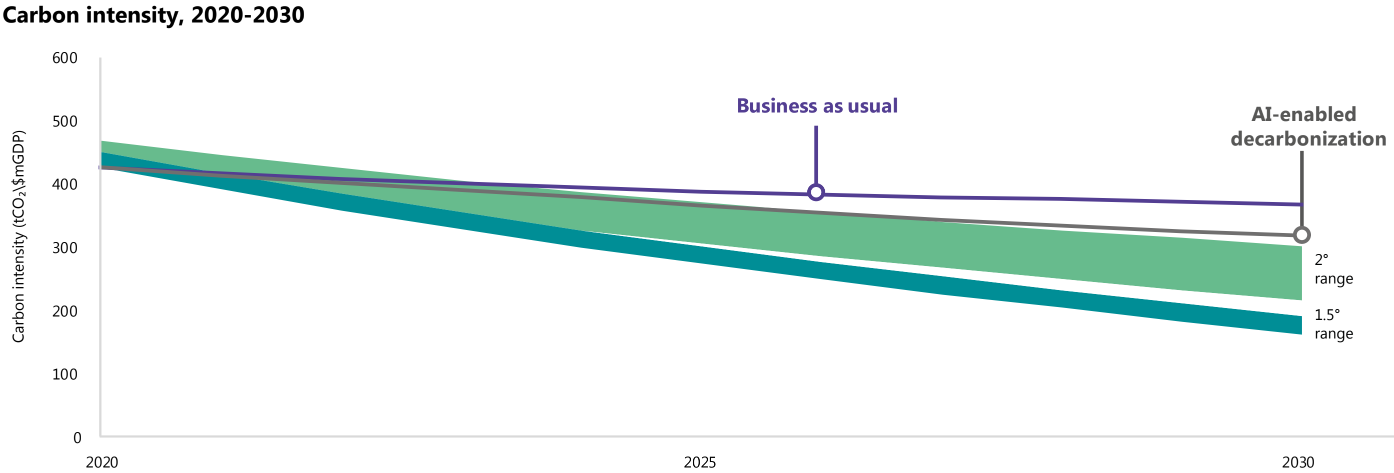
This economic impact of environment-oriented AI applications is achieved through three main channels:

- Optimizing use of inputs as new AI tools enable more precise monitoring and control of the production process, therefore boosting output and creating opportunities for cost savings. For example, precision monitoring in agriculture can enable savings of specific inputs such as fertilizers and water used for irrigation;
- Higher output productivity as innovative technologies enable new and more efficient processes, enabling greater output to be produced for a given set of inputs. For example, AI-enabled smart grids managing distribution across multiple energy sources on localized grids can maximize operational efficiency; and
- Automation of manual and routine tasks in given sectors can reduce errors, increase the efficiency of the labor force, and result in higher output with lower labor costs. For example, the use of autonomous deliveries and agricultural robotics can boost labor productivity in the sectors and free up workers to focus on more value-adding work.

These direct productivity impacts lead to 'secondary' indirect effects elsewhere through interlinkages across sectors and countries. Business growth will create new jobs; more attractive and more affordable goods and services would increase consumer demand and trade; and knowledge spillovers will generate ripple effects of productivity and efficiency throughout the economy. This will result in larger household incomes (due to higher profits and wages) and higher output globally (due to additional demand).

We discuss the sectoral and regional distribution of these GDP gains in the following sections.

Figure 4: Global impact of AI on net global decarbonisation trajectory (carbon emission), "Expansion" scenario[33]



GHG emissions mitigation potential

Our results indicate that AI applications in the four sectors have the potential to lower global GHG emissions by 1.5% – 4.0% in 2030, relative to the projected baseline.[29] This would contribute to closing 7.9%- 15.7% of the gap between our baseline projection of GHG emissions and the trajectory required to meet the UN's 2°C target by 2100.

Beyond the benefits of higher productivity and GDP, the real power of AI tools lies in their potential to tackle some of the growing pressures on our planet by accelerating a low-carbon transition. The environmental applications of AI can reduce GHG emissions via the following channels:

- Reduction of GHG intensity[30] of the use of specific fossil fuels and/or in the overall production process. For example, the GHG intensity of cars could be reduced with cleaner engines that emit less non-carbon GHGs.
- Higher efficiency of energy use by households and given industry sectors. For example, more fossil fuel efficient power plants produce the same amount of electricity with less fossil fuel, lowering the overall demand for fossil fuels.
- Change in energy mix in given sectors, especially in the currently fossil fuel intensive sectors of transport and energy. AI tools enable renewables to become more cost-effective and motivate the shift away from fossil fuels to cleaner energy sources to produce a given level of output.

However, some applications of AI may indirectly raise GHG emissions through the following channels:

- Rebound effect: an industry that achieves higher efficiency in the use of inputs would, as a result of a lower cost base, expand production. We estimate that output would increase across the whole economy as a result of AI. In particular, across the four sectors in our study, we project output in 2030 to be 2.6 – 4.7% higher in the "Gradual" scenario, and 3.2 – 7.4% in the "Expansion" scenario. As a result, the percentage reduction in GHG emission level is likely to be lower in magnitude than in GHG intensity.
- Income effect: as productivity increases, businesses and households would receive higher profits and incomes, which they would at least partly spend on further investment and consumption. The additional demand for goods and services would increase economic activity and consequently GHG emissions.

On net terms, however, we find that these AI applications can accelerate the move to a low-carbon world with a potential reduction in worldwide GHG emissions of **0.9 – 2.4 gigatons of CO_2 equivalent ($GtCO_2e$) in 2030**, i.e. 1.5 – 4.0% of projected global GHG emissions in the baseline. This implies a potential overall reduction in carbon intensity of 4.4 – 8.0% relative to the baseline.

This projected fall in GHG emissions can help us get closer to the UNFCCC's targets by pushing down on the current emissions trajectory. The Paris Agreement saw 192 nations commit to keep a global temperature rise this century to below 2°C, with ambitions to limit it further to 1.5°C. However, absolute GHG emissions are still projected to rise between now and 2030 in the baseline; the ambition to limit emissions to within 2°C could be slipping away.[31] We need bold new approaches, such as AI, to support climate change mitigation and adaptation.

Our analysis shows that utilizing AI, from the levers we analyzed, could contribute to lower global temperatures, helping, in some way, to close the gap with the 1.5°C and 2°C targets. Given the reduction in stocks of CO_2 emissions that such technologies could yield, we estimate that global temperatures have the potential to be 0.005°C – 0.01°C lower by 2030; this equates to a fall of around 0.5%. Looking further forward to the end of the century, the impact on global temperatures could be 2.5% – 4.1%, falling by 0.08°C – 0.12°C.

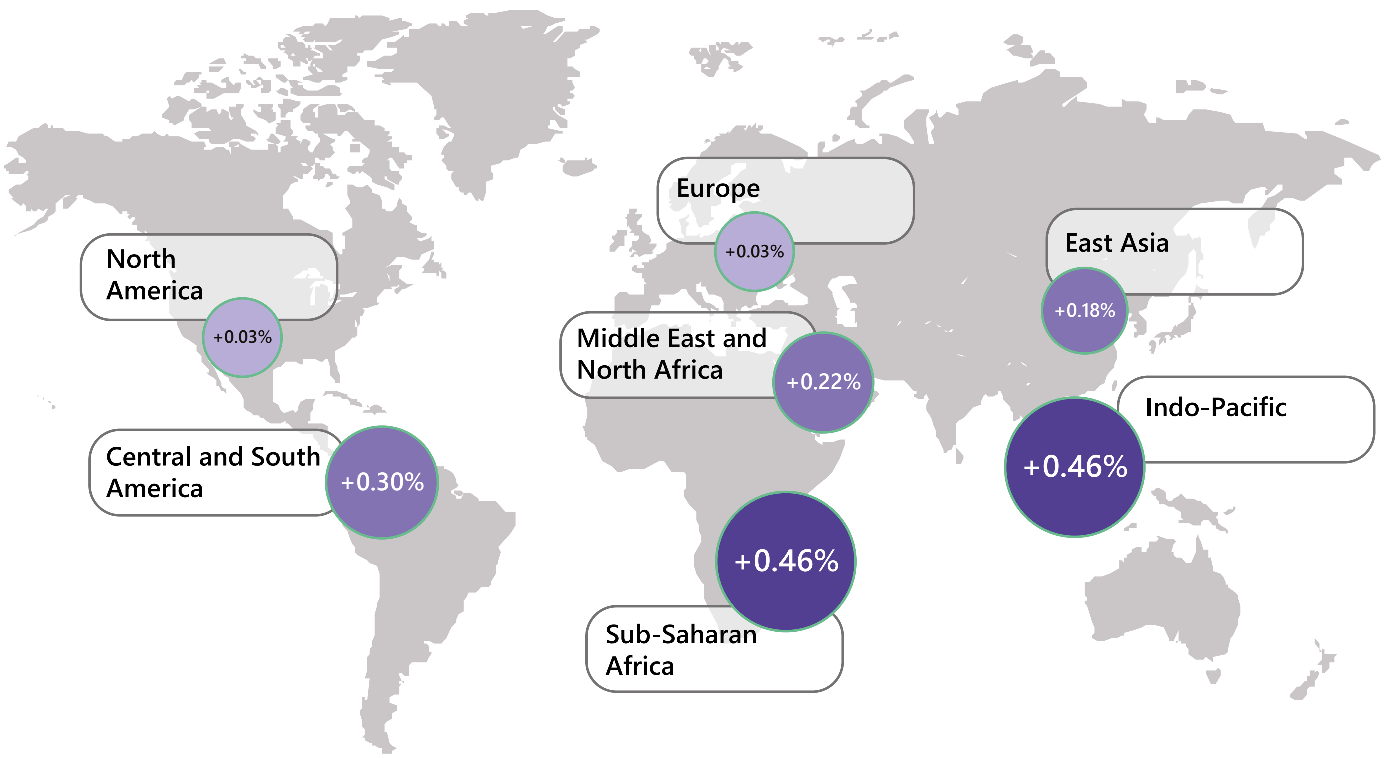
More specifically, AI applications in the four sectors have the potential to contribute to the 2°C target by 7.9% – 15.7% by the end of the century, and 6.8% to 13.4% to the 1.5°C target. Figure 4 illustrates the trajectories of GHG emissions associated with the 1.5°C and 2°C targets, and the contribution of AI environmental applications, in the "Expansion" scenario, to meeting these required trajectories, relative to the Business As Usual baseline.

Box 4: The climate baseline: factoring in the costs of avoided climate impacts

Our economic analysis does not fully factor in an important real-world feedback loop between avoided GHG emissions, reduced global warming and avoided economic losses due to extreme climate events. Put simply, the global GHG emissions savings due to the AI applications modelled would contribute to lower global average warming, which would in turn lead to an aversion of economic losses arising from the increased physical climate impacts in a warmer world.

We have undertaken an estimate of this feedback using a well-respected climate impacts model (the integrated assessment model from Kompas *et al*. 2018),[32] which finds gains of up to $15bn (+0.01%) in global GDP by 2030 due to avoided climate impacts from the environmental AI applications. By 2100, this rises even further up to +0.16%; or, put another way, in the absence of the AI applications for the environment being implemented and scaled, global GDP could be up to 0.16% lower by 2100. Regionally, the additional benefits of avoiding unabated climate damages will be higher in tropical regions such as Sub-Saharan Africa and the Indo-Pacific, due to both increased hazard and reduced resilience. Our estimate of this "avoided climate impact" benefit for each region is set out below:

Figure 5: Regional GDP gains in 2100 due to averted climate impacts, vs. baseline ("Expansion" Scenario)



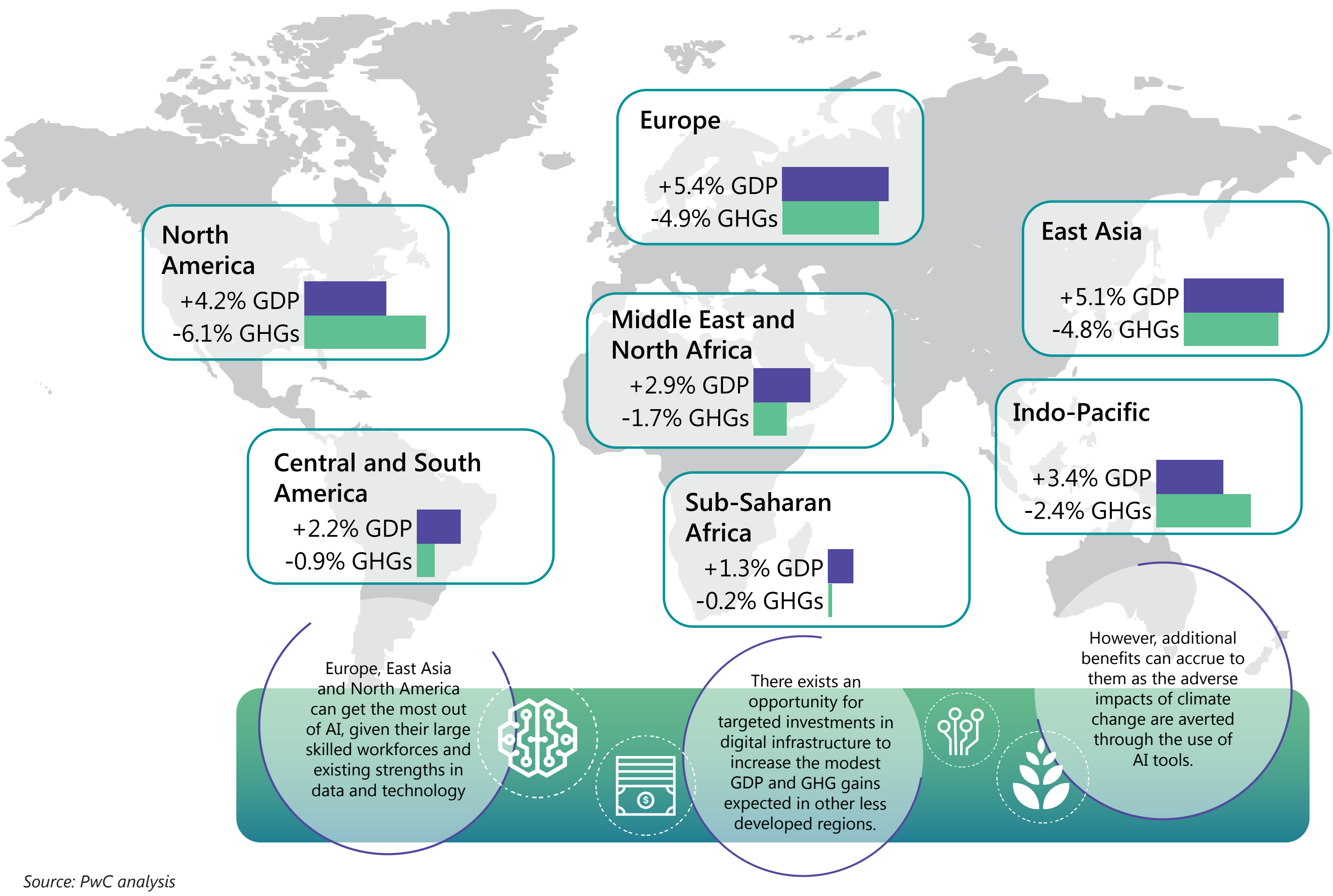
Source: PwC analysis

Note that this estimate is a lower bound, as the climate impacts model only attempted to take into account sea level rises, changes in agricultural productivity, and key health effects including from increased temperatures. Other significant impact channels, such as economic damages due to the increasing severity and frequency of extreme events (e.g. floods, windstorms), the spread of invasive species, and the costs of significant migration, are not included.

Regional impacts

Economic benefits are likely to be realized in Europe, East Asia and North America, as they each have the potential to achieve GDP gains of around $1 trillion by 2030 in both our scenarios. Environment-oriented AI applications also carry a big GHG mitigation potential for almost all regions, with Europe, East Asia and North America potentially reducing their GHG emissions by over 5% in 2030 in the "Expansion" scenario.

Figure 6: Summary of regional GDP and GHG impacts relative to the baseline by 2030 in the "Expansion" Scenario



Source: PwC analysis

Economic impacts

We analyzed the GDP and GHG impact of AI for the environment applications across 7 regions – North America, Latin America, Europe, Middle East and North Africa, Sub-Saharan Africa, East Asia and Indo-Pacific.[34] All regions are estimated to experience a GDP gain, with the largest benefits expected in advanced regions where the propensity to adopt and utilize AI, and the potential to innovate, is expected to be the highest; namely, Europe, East Asia and North America, where the gains could be up to 5.4%, 5.1% and 4.2% respectively.

These regions have a greater potential to get the most of our of AI; they have large skilled workforces that are able to utilize AI technologies, as well as strengths in complementary sectors, such as technology, which allows for the generation of huge volumes of data to enable AI to reach its potential. These regions also tend to have stronger institutions in place which are able to develop the appropriate legal, regulatory and ethical frameworks required to deal with associated issues such as privacy, discrimination and safety.

Countries such as China are also able to reap more value from AI due to high rates of capital investment. The surge in AI patents filed in China in recent years[35] demonstrates how Chinese businesses are embracing AI and investing profits in developing capabilities.

Less developed regions currently stand to make comparatively smaller gains in the near and medium term. The gains for the Indo Pacific and the Middle East and North Africa are expected to be around 3-3.5% (or $200-300 billion), while Latin America and Sub-Saharan Africa are likely to experience gains of around 1-2% of GDP.

Looking forward, there exists a substantial opportunity to increase these expected gains, as workers and infrastructure in these regions become more ready to adopt technological advances. This will come through government support and targeted investments, enabling countries to exceed these modelled projections. For example, investment in education and training to support workers in augmenting their work with AI, and to enable businesses to understand the benefits of investment in AI will be key.

China is a driving force in this regard with its AI ambitions. The government plans to create an AI industry worth 1 trillion RMB (around $150 billion) through education and training and developing laws and regulations to support growth and investment in AI. As leading countries and regions, such as East Asia and the US, continue to invest and develop AI capabilities, it will be essential to encourage international knowledge spillovers, and support less developed countries in utilizing new technologies.

Less developed and more tropical regions will, however, derive additional economic benefits from the fall in GHG emissions and the mitigation of the adverse effects of climate change (as highlighted in the Box 4: The Climate Baseline), to which AI for environment levers are expected to contribute. Rising global temperatures are expected to disproportionately affect poorer countries located closer to the equator, for example due to rising temperature variability and an increase in the likelihood of natural disasters. By 2030, climate change impacts through lower agricultural productivity, health effects and sea level changes are modelled to cost the tropical regions (Indo-Pacific, Sub-Saharan Africa and Central & South America) 1.0% of their GDP.[36] The more global emissions can be reduced, through AI and other means, the more these regions' economies are estimated to be bolstered through avoided negative impacts of climate change.

Emissions impacts

Looking at the climate impacts, we estimate that environmental AI applications will lead to a reduction in GHG emissions of 2.4 GtCO$_2$e relative to the baseline in 2030 in the "Expansion" scenario. This global reduction is primarily a result of potential reductions in North America, Europe, and East Asia, of around 5% in the "Expansion" scenario. The extent to which GHG emissions are expected to reduce, relative to the baseline, varies by regions, with GHG emission reductions in the Middle East, North Africa and Latin America expected to be comparatively lower at around 0.5% – 1.5% in the "Expansion" scenario.

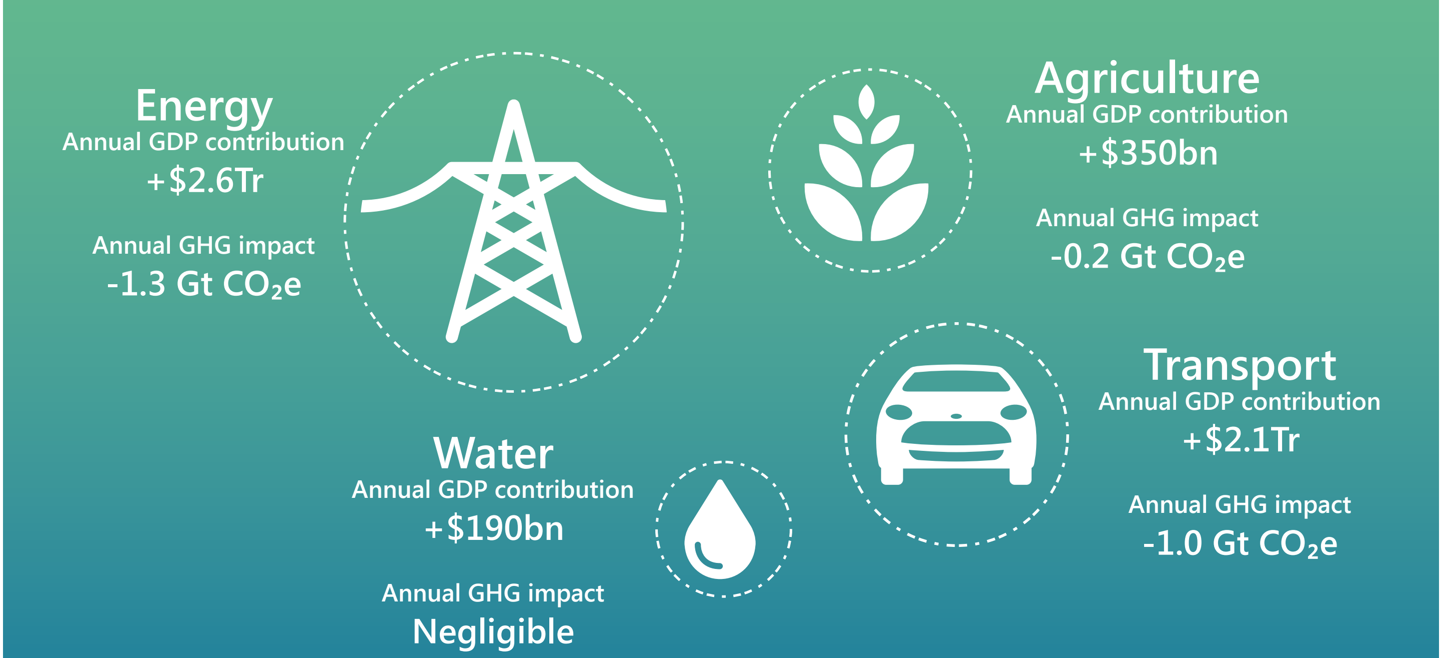
These variations in GHG impacts are mainly driven by differences in sector composition and industry focus across regions. For example, we found that:

- In Europe and North America, the net reduction in GHG emissions are primarily driven by AI applications that improve the efficiency of fossil fuel usage in energy and transport. To illustrate, around 80% of US energy is generated using fossil fuels.[37]
- In East Asia, most of the GHG reductions were achieved through AI applications in the energy sector: as they alone generate a potential emissions reduction of 3.0% – 4.0% in the region. These technologies make the production, distribution and use of electricity less carbon-intensive. As manufacturing and related industries are more prevalent in East Asia – for example, "industry"[38] contributes 40% to GDP in China and 30% in Japan[39] – improvements in the energy sector are likely to have a greater impact on reducing emissions.
- The estimated GHG reductions in Latin America and Sub-Saharan Africa are relatively small in both absolute and percentage terms. There are two potential reasons for this: firstly, these regions are relatively less industrialized, and fossil fuel efficiency in transport and energy therefore has a smaller impact. Secondly, they are also expected to adopt AI at a slower rate, and as a result some of the efficiencies achieved in other regions should result in a demand effect on products from these regions.
- However, as discussed above, the environmental gain in Latin America and Sub-Saharan Africa extends beyond these measured emissions reductions. Since they are likely to be the most affected by the physical impacts of climate change, environmental applications of AI are set to bring more benefits to these regions.

Results by sector

AI for environment levers across all four sectors can generate substantial economic and environmental benefits. Levers in energy and transport are expected to offer the greatest GDP gains, contributing to future global GDP by 2.2% and 1.8% respectively by 2030, relative to the baseline in the "Expansion" scenario. In addition, energy levers are likely to achieve the largest reductions of 2.2% in global GHG emissions in 2030 in the "Expansion" scenario.

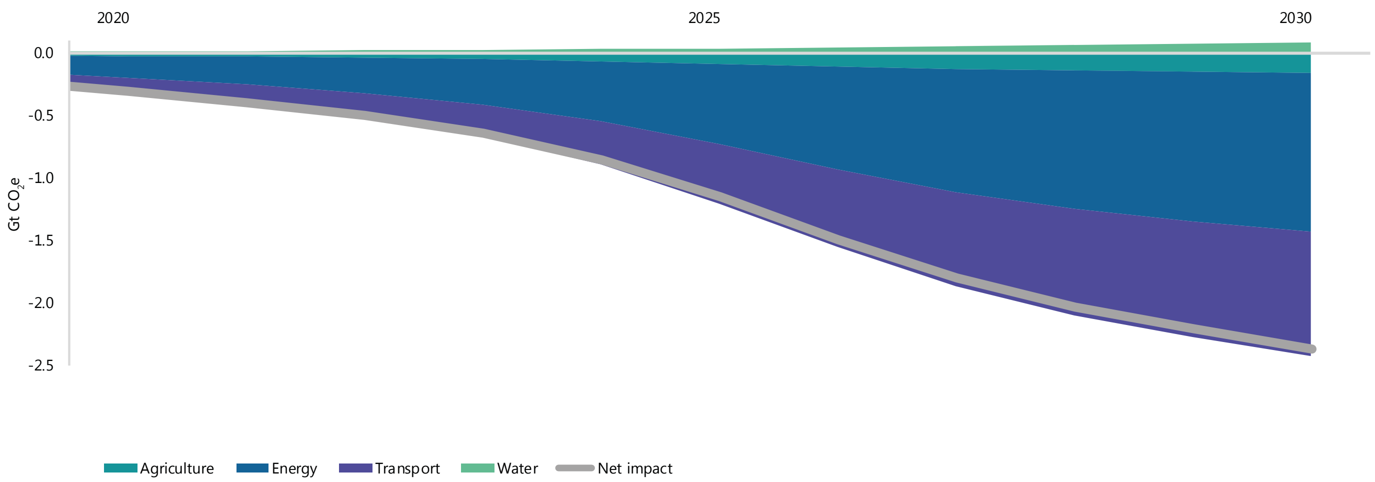
Figure 7: : Key sectoral results - impact on GDP and GHG emissions by 2030 in the "Expansion" scenario



Source: PwC analysis

Figure 8: Annual GHG impact by sector lever, 2020-2030

Annual impact on GHGs by sector lever, 2020-2030 (Gt)



Source: PwC analysis

Note: This excludes the GHG emissions impact of some environmental AI levers that we assessed outside the CGE model. Please refer to 'Wider impacts and areas for further exploration' for details on those impacts

The economic and environmental impacts of levers in the four sectors vary considerably (as shown in Table 1). Levers in energy and transport have the largest impact, primarily because they result in substantial efficiencies and consequently cost savings in terms of labor, capital and energy use. Though the modelled impacts of levers in agriculture and water are small, they have significant effects on natural resources and biodiversity, as shown in later sections. We discuss each sector in turn and detail the levers that are the most impactful in each.

Table 1: Impact of AI for environmental applications in each sector

	Expected impact on Global GDP in 2030 against baseline (% of baseline GDP)	**Expected impact on Global GHG in 2030 against baseline (% of baseline emissions)**
Agriculture	0.2% – 0.3%	- 0.1% to – 0.3%
Energy	1.6% – 2.2%	- 1.6% to – 2.2%
Transport	1.2% – 1.8%	0.3 % to – 1.7%
Water	0.04% – 0.2%	0.0% to 0.2%
All AI applications studied in this report	**3.1% – 4.4%**	**- 1.5% to – 4.0%**

Source: PwC analysis

Note: Due to rounding, numbers presented throughout this report may not add up precisely to the totals. We present results from the “Gradual” and “Expansion” scenarios as the lower and upper bounds of our ranges.

Impact of agricultural AI levers on the economy and environment

The UN's Food and Agriculture Organization (FAO) forecasts that global agricultural production must more than double by 2050 to prevent mass food shortages.[40] AI forms a central part of the technological innovations that are transforming agricultural production by responding to growing demand in a way that limits social and ecological trade-offs.

The key AI levers we study within agriculture are:

- Agricultural robotics: This includes AI robotics that are programmed to carry out agricultural tasks autonomously with optimal timing. For example, an autonomous tractor picking fruit only when ripe.
- Precision monitoring of environmental conditions for agriculture and forestry: This includes utilizing field sensors to precisely measure the impact of environmental factors and inputs on agricultural and forestry activities, and provide agri-advisory services. Examples include monitoring local weather conditions to predict the impact on yield and tailor required inputs.
- Land-use planning and management: This involves using AI for mapping agricultural and forestry activities over time for better farm management and better enforcement of regulation.
- Monitoring of crop, soil and livestock health: This deals with monitoring conditions of agriculture (e.g. crop health, prevalence of pests, disease among livestock) to inform better management of crop habitats, and of livestock. For example, monitoring and identification of pests in real time to inform use of pesticides, including volume needed, specific locations on a farm that pesticides are needed etc.

Taken together, these agricultural AI levers have the potential to increase global GDP by 0.2% – 0.3% and reduce global emissions by up to 0.1% – 0.3% in 2030 relative to baseline. The GDP impact is mainly driven by applications that enable precise monitoring of environmental conditions and tools that automate manual tasks in farming and forestry. Precision monitoring enables savings of specific inputs such as fertilizers and water required to produce a given output level, resulting in cost reductions for the sector. Similarly, automation can produce labor-cost savings and increase the efficiency of workers through the use of complementary technologies.

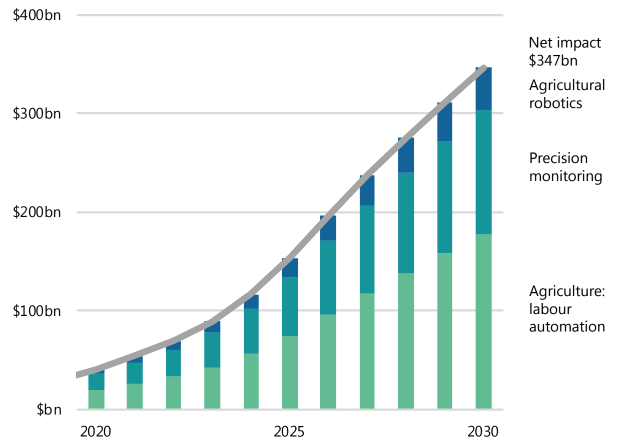
The lower cost base and increased productivity are expected to boost agricultural production and contribute towards fighting food shortages. This is going to be more critical in developing nations where rapidly increasing population is putting pressure on the existing resources.

Levers such as **agricultural robotics** are key in achieving the projected reductions in GHG emissions as they reduce fossil fuel usage in agricultural activities. **AI tools for land-use planning** are also very important in reducing emissions as they optimize the use of, and help protect, natural resources such as forests, as explained further in the next section. Besides emissions, these applications minimize the negative environmental effects associated with the overuse of inputs such as water and chemicals.

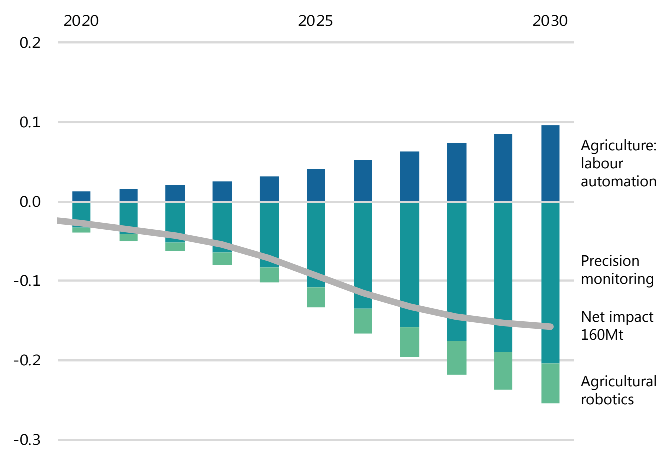
Achieving these gains, however, requires the right infrastructure and complementary technologies for AI to flourish. Access to data is key to driving these AI gains, and this will require sensors connected to the Internet of Things (IoT) continually pulling in masses of information on temperature, moisture, soil conditions, and so on. The infrastructure for transmitting and processing this data will also need to develop in parallel, given many rural agricultural areas still face limited digital connectivity.

Figure 9: Global impact of environmental AI in the agriculture sector on GDP and GHG emissions in the "Expansion" scenario

GDP impact



GHG impact (Gt CO_2e)



Source: PwC analysis

Note: This excludes the impact of land-use planning and monitoring on GHG emissions. Refer to Section 'Wider Impacts and areas for further exploration' for details of the off-model assessment of those impacts.

Impact of energy AI levers on the economy and environment

One of the biggest challenges of the modern world is to supply affordable, reliable energy to all, whilst minimizing the negative impact on the Earth such as GHG emissions and air pollution. By applying AI to improve efficiencies in the energy sector across all fuels and regions, technology can help develop a cleaner and less fossil-fuel dependent energy sector that can lead to a world with a more prosperous economy and less climate change.

The key AI for environment levers we study within energy are:

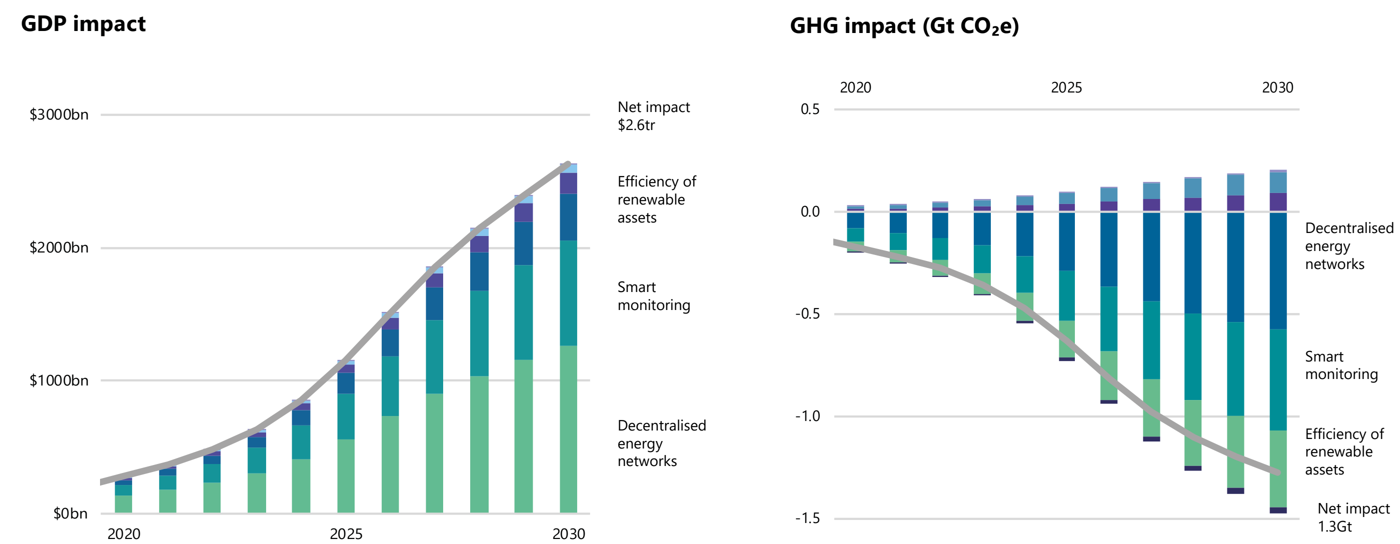
- Smart monitoring and management of energy consumption: AI and IoT technologies are used to monitor, actively manage and optimize energy use by automating price responsiveness to market signals.
- Energy supply and demand prediction: AI is used to better forecast the short- and long-term energy needs of an area, including prediction of weather conditions to manage fluctuations.
- Coordination of decentralized energy networks: Integration of AI into increasingly localized energy grids can automate operations required to manage these systems, improving overall operational efficiency and reducing energy waste.
- Predictive maintenance: AI and IoT technologies are used to monitor the need for maintenance of energy infrastructure through early fault prediction and prediction of external disruptions – solar flares, hurricanes and earthquakes – allowing for better preparation.
- Increased operational efficiency of renewable assets: AI is used to enhance the efficiency and energy production of renewable assets. For example, hyperlocal weather modelling is used to monitor and adjust the positioning of solar panels and wind turbines to maximize power generation.
- Increased operational efficiency of fossil fuel assets: AI is used to enhance the efficiency of existing oil and gas production – including through more targeted exploration, intelligent management of oil pipeline assets, and improving combustion efficiency.

AI levers in energy are expected to deliver the largest economic uplift, amounting to a 1.6% – 2.2% boost in global GDP by 2030 relative to the baseline. The greatest contribution to the GDP impact is achieved by levers that enable **smart monitoring of energy use and coordination of localised energy grids**. By allowing energy prices to respond to market signals in real-time, smart monitoring has the potential to optimize electricity consumption by not just key sectors but also households and governments. Lower energy costs can result in output expansion by businesses and higher demand by consumers and boost economic activity. Similarly, decentralised energy networks can significantly improve the process of electricity transmission and distribution, resulting in higher productivity for the sector, and boost overall electricity production by enabling faster uptake of renewables.

These applications are also the key drivers behind the substantial projected GHG reductions achieved by the levers in the energy sector, amounting to a 1.6% – 2.2% reduction from the baseline in 2030. Automatic pricing of electricity reduces electricity wastage across the economy, lowering emissions. Furthermore, greater use of renewables, enabled by localised grids and AI technologies that improve the effectiveness of renewable assets, reduces fossil fuels' share in energy production and shifts the energy mix towards less carbon intensive energy sources.

It is important to note that these projections do not rely only on AI, but also on the adoption of a wider set of complementary technologies. For example, AI-enabled distributed energy grids will only reach their maximum potential if related technologies – such as distributed generation, distributed storage, Industrial IoT, electric vehicle charging, dynamic pricing, and smart meters – are adopted in electricity transmission and distribution.

Figure 10: Global impact of environmental AI in the energy sector on GDP and GHG emissions in the "Expansion" scenario



Source: PwC analysis

Impact of transport AI levers on the economy and environment

Achieving safe, efficient and sustainable mobility of cargo and people remains a prominent challenge in an increasingly globalized and urbanized world. Transport accounts for between 20-30%[41] of global energy consumption and CO_2 emissions. AI applications can be used to facilitate and accelerate the roll-out of sustainable transport systems.

The key AI for environment levers we study in the transport sector are:

- Autonomous vehicles: AI tools are used to enable autonomous or semi-autonomous transport, offering eco-driving features, vehicle platooning, and vehicle sharing services.
- Autonomous deliveries: Driverless long-haul and last mile deliveries require AI. Examples of this include autonomous trucking and autonomous delivery robots.
- Traffic optimization of connected vehicles: AI is used to monitor and optimize traffic flows in real-time, reducing queuing, and enforce real-time smart pricing for vehicle tolls. Examples of this include variable rate congestion charges depending on time of day, level of congestion, number of passengers and efficiency of vehicles.
- Demand prediction and logistics planning: AI-enabled forecasting is used to predict demand, and to design optimal logistics strategies.
- Predictive maintenance for vehicles: AI and IoT technologies are used to monitor and predict the need for maintenance of vehicle components. This can help avert vehicle downtime, making it both economically and logistically beneficial.

The impact of AI levers in transport on GDP ranges from 1.2% – 1.8% increase relative to the baseline and +0.3% to -1.7% impact on GHG emissions against baseline in 2030.

The GDP impact is mainly driven by **autonomous vehicles, autonomous deliveries and technologies that enable traffic optimization**. While use of autonomous vehicles can offer substantial cost savings related to labor and capital within the transport sector, reduction in queuing due to better traffic control through traffic optimization can save energy costs for vehicles. Such efficiencies support output expansion in other sectors as well as higher consumption by consumers, resulting in boosts to GDP.

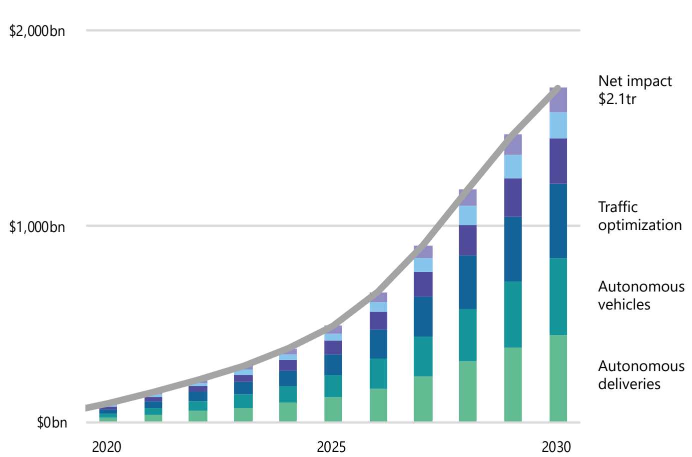
A large share of the GHG benefit in the "Expansion" scenario can be achieved by **autonomous vehicles**. For their full benefit to be realized, they would predominantly have to be electric and materialize in a world where ride-sharing is incentivized. In other words, they must offer more than energy efficiency gains through smart navigation and eco-driving to counter a rebound effect of increased vehicle miles and deliver positive environmental impacts (see Box 5: Autonomous vehicles and the rebound effect).

The literature review we carried out suggests that users' behavioral response to autonomous vehicles is highly uncertain. Energy demand may increase or decrease depending on a number of factors, such as (i) the value of convenience derived from not having to drive a car and (ii) the market share of electric cars. In the "Gradual" Scenario, we consider autonomous vehicles to have zero net impact, i.e. the "mid-point" of our findings from literature. In the "Expansion" Scenario, we simulate the more positive end of impacts of what literature suggests is plausible.

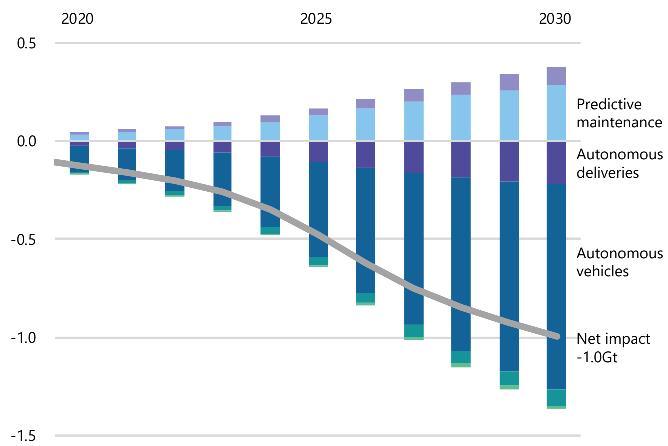
In the "Gradual" scenario, in which we assume autonomous vehicles to have no emissions impact, all other environmental AI levers in the transport sector can together result in a small increase in GHG emissions in net terms. Some AI levers we considered, e.g. predictive maintenance of vehicles, make the transport sector more efficient and productive. They increase both demand for transport services and income in the economy. As a result, output in the economy expands, leading to a higher net emissions level.

Figure 11: Global impact of environmental AI in the transport sector on GDP and GHG emissions in the "Expansion" scenario

GDP impact



GHG impact (Gt CO_2e)



Source: PwC analysis

Box 5: Autonomous vehicles and the rebound effect

Autonomous vehicles (AVs) stand out compared to the other AI levers, with their future impact being more uncertain and dependent on the behavior of users and the actions of policymakers.

In our "Expansion" scenario, we assume accelerated change: a world where the majority of AVs are electric and utilized more than standard vehicles, contributing to a marked shift towards lower emissions travel (despite AVs making up a relatively small proportion of vehicles on the road). In addition, AVs are primarily used for ride-sharing and mobility on demand, potentially reducing overall vehicle miles. We also see more immediate benefits from AVs, driven by eco-driving, smart navigation, and reduced congestion. Taken all together, this leads to a potential reduction in the use of fossil fuels.

However, these benefits are uncertain. It's plausible to imagine that, as AVs eliminate the 'inconvenience factor' of driving, overall passenger numbers and journeys will increase – along with emissions. In our "Gradual" scenario, we model this "rebound effect" as offsetting the positive impacts AVs bring about – or in other words, we assume a net neutral impact.

Beyond 2030, the impact of AVs has the potential to go either way. They could enable an electric-powered revolution of shared mobility on demand; but poorly regulated and managed, they could lead to more cars on the road, driven more frequently and with fewer passengers per vehicle.

Impact of water AI levers on the economy and environment

As pollution, rapid urbanization and climate change affect the global water cycle, it is forecast that global demand for freshwater will exceed supply – falling 40% short of the quantity required to support the global economy by 2030.[42] Applying AI in water resource prediction, management and monitoring can ameliorate this global water crisis by eliminating wastage.

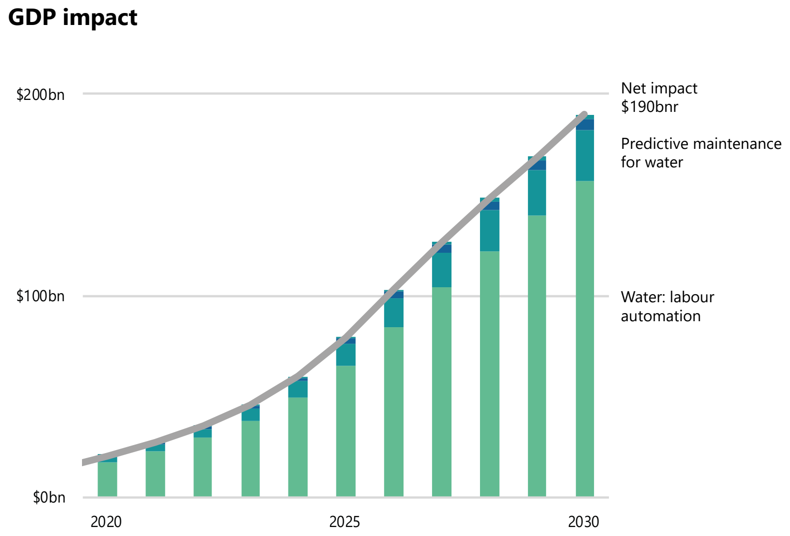
The key AI levers we study within water are:

- Predictive maintenance of water infrastructure: Real-time monitoring of infrastructure, prediction of faults and identification of management activities for optimized water systems.
- Monitoring and predicting water demand: New monitoring tools to track actual water use on an industrial and household level and allow suppliers to pre-empt water demand, reducing both wastage and shortages.
- Monitoring wastewater sources: AI is used to optimize operating conditions and can model water treatment and desalination processes, enabling reuse of greywater.

The water sector has the potential to reap labor productivity benefits as AI technologies automate routine processes and can optimize use of specific inputs such as pipes through tools that enable real-time monitoring of water infrastructure. Furthermore, levers that predict and monitor water demand can reduce electricity consumption by the water sector, allowing it to reduce its emissions. While AI-enabled water levers are estimated to have a small impact on global GDP (0.04% – 0.2% by 2030) and a negligible impact on global GHG emissions, they are expected to play a vital role in preserving the health of our Earth's natural systems, such as freshwater resources, forests, oceans, etc., as explained in Section 'Wider Impacts and areas for further exploration'.

These benefits of water savings will not be achieved solely through AI, but will also require the adoption of a wider set of complementary technologies. Predictive maintenance, for example, can reduce water losses from leaks, but will need sensors built into water infrastructure and connected to the IoT to feed dynamic data. This presents a particular opportunity for developing regions to leapfrog their developed counterparts – with a greater proportion of infrastructure to be built over the coming decade, sensors can be included in planning and integrated from the start, at a much lower marginal cost than retrofitting existing networks.

Figure 12: Global impact of environmental AI in the water sector on GDP and GHG emissions in the "Expansion" scenario



Source: PwC analysis

Note: The impact on GHG emissions of water levers as assessed in the CGE model is negligible. Please refer to Section 'Wider Impacts and areas for further exploration' for a discussion on off-model impacts and non-pecuniary benefits of water levers

Deep dive: A special focus on job impacts

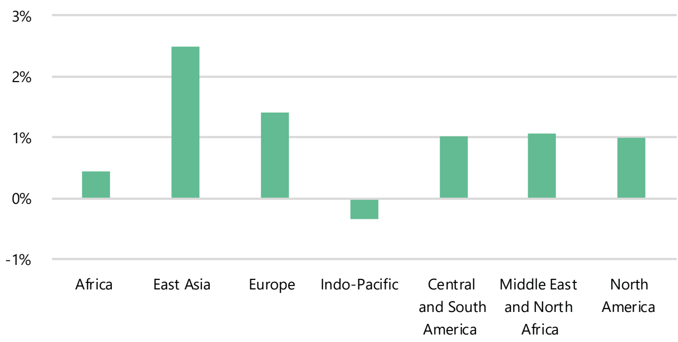
Our results indicate that AI for the environment levers can lead to estimated net gain of 18.4 – 38.2 million jobs globally by 2030. This is relatively small in number as a share of global employment (0.5% – 1.0%) but a ray of positive light in contrast to the many negatives headlines in recent years on job displacement that AI may usher in. Indeed, in our "Expansion" scenario, the global employment impact is close to the number of people currently employed in the UK. Notwithstanding this overall impact, there are likely to be many changes to the types of employment and differences across sectors and geographies.

Geographic impact of AI for the environment levers

The applications of AI for the environment indicate a marginally better employment picture with net job gains globally, albeit with some regional differences. Most net job gains are expected to be in East Asia, with net job gains estimated to be 16.0 – 25.1 million workers by 2030 (1.6% – 2.5% of regional employment). However, this is primarily driven by higher demand for goods and services as a result of higher productivity and incomes, and are mainly accounted for by indirect job growth in sectors outside of those in this study. In PwC's previous research we noted that globally, and across sectors, the net impact on jobs is expected to be approximately equal as a result of larger and wealthier economies,[43] and that this will vary from sector to sector[44] and from country to country.[45]

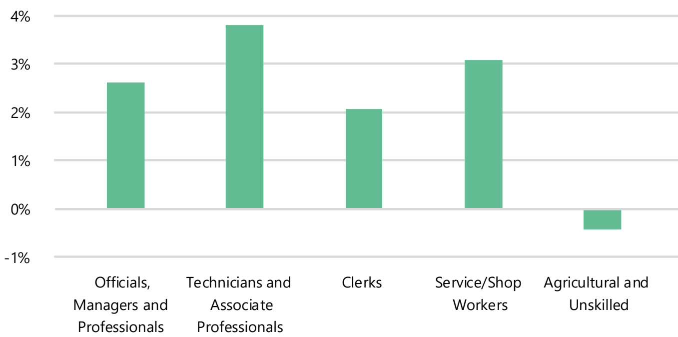
In most regions, the net job impacts are net positive and modest, at around 0.5% – 1.0% of employment on average. There are slightly lower net gains in Sub-Saharan Africa of 0.3%-0.4%, where despite notable net gains in agriculture (0.3% – 0.8% compared to cross-region average net losses in agriculture of 2.6% to 1.7%), the region shows weaker income effects in other sectors. However, the exception is the Indo-Pacific region, with AI for the environment levers expected to result in net job losses (of 0.7% to 0.3%). As with the Sub-Saharan Africa region, the Indo-Pacific region has a prominent share of employment engaged in lower-skilled agricultural work (24%). This sector, however, is expected to see net job losses globally of 2.6% to 1.7% with the nature of work, and other economic factors, more directly replacing rather than augmenting employment. However, while the number of jobs and hours worked may change in different directions in each sector and occupation type, automation of repetitive tasks may also have positive effects on quality of life.

Figure 13: Impact on net employment by region by 2030, relative to the baseline in the "Expansion" scenario



Source: PwC analysis

Figure 14: Impact on net employment by skill level by 2030, relative to the baseline in the "Expansion" scenario



Source: PwC analysis

Sectoral impact of AI for the environment levers

The direct impact of AI actually indicates net job losses in each of the four sectors covered; however, this is compensated by job gains in other sectors of the economy. In particular, transport is likely to see a large decline in employment of 15.2% – 21.3% net losses globally, whilst other sectors are expected to see smaller net losses, namely energy (4.6% to 6.2%), water (8.0% to 5.0%) and agriculture (2.6% to 1.7%) in the "Gradual" and "Expansion" scenarios respectively. However, we also expect the extra wealth from GDP growth to create demand for jobs across the global economy, which will at least offset the displacement of jobs in these sectors.

In some cases, AI will alter the nature of jobs significantly, but not displace humans entirely; and for other industries, demand for human labor will increase for some occupations, but decrease for others. For example, while in agriculture, forestry and fishing we expect to see net job losses, there will be net job creation in managerial and professional skills occupations that are presently only a small percentage of the sectoral employment share (1.6% globally). Nevertheless, overall we expect many of those displaced in these sectors to shift employment away from these sectors to those that see net job growth. This will require both business and governments to provide support to displaced workers affected by these technological advances to retrain and start new careers – see the Unlocking AI for the Environment section for a fuller coverage of the challenges to realize AI for the environment, and recommendations by stakeholder group.

Wider impacts and areas for further exploration

AI for environment levers are expected to deliver significant benefits beyond the coverage considered in our main economic and GHG model (see Broader societal and environmental impacts), as well as impacts beyond the scope of this analysis, including other sectors and how policy evolves (see Areas for further exploration).

Broader societal and environmental impacts

In this section we take a look at some of the impacts not captured in traditional economic models – for instance, impacts on human health, or on ecosystem conservation. We present separate assessments of these impacts below, analyzed through a more bespoke approach. These results are intended to supplement the main results to help form a more holistic view of the likely broader benefits available from harnessing AI for the environment. These results illustrate the benefits which can be realized in the "Expansion" scenario; in which enabling factors allow the full potential of AI to be realized.

Air pollution monitoring and forecasting

Air pollution is one of the largest environmental risks to human health; ambient (outdoor) air pollution causes an estimated 4.2 million deaths annually (WHO).[46] Accurate and local early-warnings of poor air quality are vital to reduce this health burden, both for governments to support policy and regulation, and vulnerable populations to reduce exposure risk. High-quality localized data is in short supply, particularly in emerging economies which typically have a shortage of ground-based sensors.[47] AI provides an opportunity for low-cost, and hyper-local, global pollution monitoring and forecasting. Machine learning models can ingest data from existing sensors, combined with satellite-derived spectroscopy, to "fill-in" the gaps of ground-based sensors. Our analysis estimates that using AI in this way could provide **additional economic benefits of $150m globally in 2030** through reduced healthcare costs and health impacts.

Prevention of illegal deforestation and forest damage

An estimated 80,000 and 150,000 square kilometers of the world's forests are lost every year to human activities, with up to 90% of tropical deforestation due to illegal activities.[48] NGOs and technology companies have begun using AI to address this challenge, by monitoring and managing forest disturbances more quickly and efficiently than ever before. AI can analyse satellite data, or ground-based sensors, to monitor forest conditions in real-time and at scale, providing early warning systems for priority investigation and pattern analysis. We estimate **32 million hectares of forest could be saved globally by 2030,** if governments maximize the use of AI in supporting law enforcement, resulting in a **reduction of 29 Gt CO_2e of emissions**, and wider benefits of forests to protect indigenous rights, generate water supplies, foster biodiversity, conserve species and provide valuable ecosystem services.

Natural disaster resilience from flood and storm damages

AI has the potential to significantly reduce the impact from extreme weather events, which are increasing in frequency and intensity due to climatic change. An estimated 250 million people are already affected by flooding annually.[49] Our analysis estimates that AI-enabled improvements to forecasting could enable flood early warning systems which would save over 3,000 lives, result in 1.2m fewer people made homeless and mitigate $14m economic damages between now and 2030.[50] Similarly, more accurate forecasting through machine learning of storm damage in forestry could help management to improve storm resilience, and thus reduce forest wind damage, which currently accounts for around half of all forest damage in Europe,[51] **by 2 million m^3 (thus preventing the loss of 800,000 tons of carbon uptake)**. Similar applications, while only emerging, could also be on the horizon for drought – and earthquake – resilience.

Areas for further exploration

Our analysis and results raise a number of broader themes, which are important to bear in mind both to contextualize our findings, and to further develop and mature our understanding of how AI, the economy, and our environment intersect.

Additional sectoral coverage

Above and beyond the four main sectors captured in the main findings of this report, AI is likely to play a role across the whole economy. Two other major areas that are crucial to the climate challenge in particular, are the built environment and industry, which make up the bulk of remaining GHG emissions – 'residential and commercial' and 'industry' sectors account for around one-third of global GHGs.[52] Ultimately, decarbonizing all sectors will be crucial to reach net-zero GHG emissions by mid-century.

Industry, and particularly heavy-industry, is often called out as 'hard to abate' alongside heavy transport. These sectors (e.g. including cement, steel, chemicals, aviation and shipping) tend to have fewer or more expensive low-carbon alternatives. Decarbonizing industry, as well as aviation and shipping (we cover only surface transport in our analysis) represent a particular challenge given fewer low-carbon substitutes are readily available than, for example, energy (solar and wind renewable energy) and surface transport (electric vehicles). A recent report from the Energy Transitions Commission[53] sets out some of the technology innovations that are already being developed in certain 'hard to abate' sectors. AI is increasingly part of that suite of options. Four emerging examples:

- Cement: AI, often combined with advanced sensors, is being used for predictive asset management to maximize the efficiency, operation, and management of production assets;
- Steel: AI systems are increasingly being tried and tested in process and operational controls to supplement traditional controls, increasing efficiency and optimizing system operations;
- Chemicals: AI, often combined with traditional controls and new sensors, is being deployed for predictive maintenance in chemicals manufacturing, maximizing efficiency and minimizing resource use in chemicals processes; and
- Shipping: AI can be used in the maritime sector a range of ways, including for predictive vessel management and maintenance, real-time voyage optimization, and fuel monitoring and management.

These are early examples; AI and other emerging technologies need to be more fully harnessed across hard-to-abate sectors to accelerate, and scale, innovative low-carbon AI solutions, which can help drive faster economy-wide decarbonization.

Elsewhere, AI has an important role to play across the built environment, which alone account for around one-tenth of global GHG emissions and have a wider impact through urban energy and transport use. AI is already being used in a variety of ways, from machine-automated urban land-use detection, to optimized building design and auditory-cue lighting and heating to maximize efficiency. Across our urban environment, AI is also being used for intelligent energy and waste forecasting and management to improve resource use. More broadly, AI is at the core of the 'smart city' in helping to manage and process vast quantities of data for better urban decision-making and management.

The estimated overall economic and environmental impact of AI for environment, therefore, could be much larger than that reported in this study. On the other hand, there might also be AI levers that could work in the opposite direction and increase GHG emissions (e.g. mining).

Future policy and energy mix

Our modelled BAU baseline includes a limited transition to renewables and a continued reliance on fossil fuels, including coal, in the future energy mix. In reality, the signals are that a more rapid low-carbon transition is underway, both in developed and developing countries. This is being driven by the increasing cost-competitiveness of low carbon alternatives, and continued ratcheting up of environmental policy and carbon pricing following global agreement of governments to limit warming to well below 2 degrees Celsius. Given many of the AI applications we look at link to electrification, the future energy mix of the grid will be crucial to maximizing emissions reduction as many AI applications use additional electricity. Moreover, many countries are actively developing and deploying scaled-up innovation policies to harness emerging technology. These policies could further accelerate adoption of AI and increase the impacts found in this report. A future policy scenario might include both rapid renewables uptake and accelerated innovation to gauge the upper bound potential of AI for environment levers.

Regional impacts and outlooks

Those regions which are expected to see the smallest potential benefits from AI for environment (e.g. Sub-Saharan Africa and Latin America), due to lower levels of digital-readiness, are also likely to see some of the more significant climate change impacts. However, there are two important factors to consider. First, the more global emissions that can be reduced, through AI and other means, the more these regions' economies will be bolstered through avoided impacts. Second, through targeted investment today in digital upskilling and digital infrastructure in these regions, there is an opportunity to leapfrog developed nations and far exceed these modelled projections to unlock substantial economic and environmental gain.

Measure of wealth

Many of the benefits from using AI for the environment are not fully captured by current economic frameworks. GDP is an annual measure that captures the 'flow' of income. To capture fully the benefits of AI (e.g. preserving the 'stock' of biodiversity and habitats etc.), alternative welfare and 'balance sheet' methods need to be developed and used alongside traditional GDP estimates.

Each of these factors are important areas for future research to better understand, and by extension unlock, the full opportunity of AI for our economy and environment.

3 Unlocking AI for the environment

Introduction and overview

A broader agenda on 'AI for Good' is emerging to harness the power of AI to help to tackle many of the world's challenges e.g. health and education, often under the umbrella of sustainable development, with a number of technology firms announcing initiatives in this space, including to support the delivery of commitments to tackle environmental issues (e.g. Microsoft's own AI for Earth program, or the Step Up coalition).[54]

As with any new wave of technology, alongside huge opportunities, challenges need to be identified and addressed for AI's full potential to be realized for the environment. Challenges range from increasing climatic change, to biodiversity loss, through to pollution and acidification of our oceans. Central to this is creating the conditions that enable solutions to be developed and commercialized at scale, and to ensure that risks are mitigated, and unintended consequences managed; i.e. creating the right 'enabling environment'.

While AI itself faces a number of risks to deployment, scaling and positive impact that need to be addressed (e.g. security, performance, control, ethics), we have identified here specific considerations for advancing AI for environmental applications. In this section, we set out some of the prominent challenges, including the key enablers that are critical to overcoming them. We then focus in on the stakeholders that are crucial to unlock opportunities, and provide high-level recommendations across key stakeholder groups.

AI for environment challenges

Many identified challenges are related to governance, resources for R&D and deployment, collaboration, as well as to the maturity of data and infrastructure. The challenge landscape is detailed in Table 2 below.

Table 2: AI for environment challenge landscape

People	**Lack of awareness, engagement and prioritization:** Governments, companies, academics and investors are not currently focused on, or prioritizing, AI for environmental applications. **Changing labor demands:** Insufficient pool of domain and technical expertise; risks associated with changing job requirements and job displacement; and the evolving demands for re-skilling and upskilling the workforce undergoing structural change.
Process	**Complexity of interdisciplinary working:** Limited collaboration between technologists, environmentalists, business, and government hinders interdisciplinary solutions. **Ability to innovate:** R&D and innovation is hampered by constrained resources, including limited data availability, funding, technical know-how and talent shortages. Innovation requires a culture where failure is acceptable in the exploration of new approaches and applications. **Relative lack of investment:** Low investment appeal in comparison to broader structural issues such as healthcare and education. Current finance models are also not always structured or incentivized for blended finance and / or certain types of supportive impact investing. **Inadequate governance and policy:** AI oversight is struggling to keep up with the pace and scale of rapid change. Regulators in many jurisdictions act individually when potential harm is foreseen (e.g. EU and GDPR), resulting in differences across jurisdictions, where a globally coordinated governance architecture would be more beneficial. **The value cost of AI solutions:** Decision-makers not factoring in the 'opportunity cost' of not using AI solutions in impact assessments, instead opting for the 'status quo' default even though those solutions might be higher cost, less efficient, and offer slower environmental progress. **Insufficient focus on delivering Responsible AI:** An absence of shared values results when ethical principles are not agreed and contextualized; the current emphasis around Responsible AI tends to center around human-related priority areas such as bias, and less around broader social priority areas, particularly those pertaining to the environment. **Accountability, transparency and bias:** AI adoption and scaling of AI applications can be limited by a lack of trust caused by a lack of transparency around approach, accuracy of output, perceived bias and imperfect data.
Technology	**Access to citizen developer AI tools:** AI development traditionally requires significant AI expertise. Simplified AI tools that 'democratize AI', enable and empower, non-experts to develop their own AI-enabled solutions aren't widely available to many start-ups, academics, civil society and wider interested non-technical stakeholders. **Unequal scaling of infrastructure:** Cloud infrastructure build tends to be in developed countries who are leading AI R&D and deployment. Developing countries could have less required infrastructure, such as widespread internet access or expensive on-premises computing, leading to an unequal distribution of benefits, potentially accelerating the digital and urban/rural divide.
Data	**Generating fit-for-purpose data:** Large quantities of data are required to train AI applications. In many cases, there is poor availability of labelled data, limited data accessibility, and disparate or sparse collection. Data ownership and licensing may limit sharing of fit-for-purpose data. **Ensuring data quality:** Inconsistent data governance across organizations lead to data quality issues. Without standard governance, data can be prone to selection and reporting bias, which further impacts the quality and applicability to a wide array of use cases.

Enablers and recommendations

To address the range of challenges identified and to overcome risks, we believe that five principle 'enablers' will be key to unlock the potential of AI for the environment:

- **Facilitating awareness, value alignment, collaboration and multi-disciplinary partnerships:** including technologists, industry, scientists, civil society, governments; through establishing cross-industry and international standards, region-specific goal prioritization, collaborative working frameworks and public-private initiatives to develop and (safely) deploy AI for environmental solutions.
- **Ensuring that we start with 'Responsible AI' and extend this principled approach to include consideration of societal and environmental impact:** to ensure that sustainability principles are embedded alongside wider considerations of AI safety, ethics, values and governance.
- **Addressing digital infrastructure, data and technology access, and wider complementary technologies:** through building appropriate cloud-providing infrastructure, including satellites, and data infrastructure, facilitating fit-for-purpose data access and annotation, along with responsible data management, as well as supporting other emerging technology deployment to maximize AI's potential.
- **Providing opportunities and training for upskilling and reskilling to adapt to sectoral transformations:** not only to unlock new innovations and scale applications, but to manage and govern AI-based systems to best serve people and the planet for markets, and the workforce of the future.
- **Encouraging R&D from research to scalable commercial deployment:** with a focus on connecting stakeholders (industrial, academic and government research agencies) and encouraging interdisciplinary research and development that leads to scalable commercial deployment.

All stakeholders across the public, private and third sectors must be involved in unlocking AI to tackle environmental challenges to its fullest potential. Each has a role to play in creating this 'enabling environment' to accelerate economic and environmental progress. Specifically, we outline actions the following stakeholders can play to create an improved enabling environment:

- **Governments**: take an agile approach to targeted regulation and policy support on items including data access, R&D and digital infrastructure and skills investment, in addition to wider environmental policy. Including: consideration of AI for sustainability in national development plans and AI strategies; innovation and R&D funding; supporting re-skilling and upskilling; and ensuring 'AI-ready' data governance, access, and regulation relevant to the environment.
- **Tech developers:** take actions to create, provide and improve data assets and provide access to AI tools, data and wider complementary technologies. Including: embedding environment into design principles alongside wider AI risks; investing in collation of better quality data assets e.g. access, processing, annotation and labelling); encourage co-innovation with entrepreneurs and making the building blocks of AI available to stakeholders.
- **Companies**: embed environmental impact considerations into AI strategies and deployment, identify disruption and transformation needs, and embrace upskilling and reskilling of workforces. Including: developing company and AI strategies that build in and optimize AI for sustainability; taking a leadership role in developing Responsible AI best practice; upskilling and reskilling workforces in data science, digital skills and machine learning basics, including along companies' value chains.
- **Academia**: encourage multi-disciplinary focus, combining AI and domain-relevant education and research, and industry partnerships. Including: facilitating multidisciplinary research and learning across technical and domain expertise; encouraging open access data sharing between institutions; communicating priorities of AI for the environment, and encouraging industry partnerships for skills training, and data and knowledge sharing.
- **Non-Governmental Organizations:** develop partnerships with technologists, invest in digital upskilling, and explore where AI and wider tech innovations can create benefits. Including: identifying which problems funders, researchers, and the private sector ought to prioritize; explore where AI and wider tech can create benefits; and shaping and developing consortia to build multi-purpose shared infrastructure for companies to then create their own specific applications.

Conclusion

- While there are a range of recommendations explored in this report, the impact of AI on jobs – and the skills challenge – has to date received the most attention from the media and from society at large. All stakeholder groups are affected, and the pace of change is fast. With digitization, automation and augmentation already transforming sectors, markets and global value chains, it is critical that companies and countries think ahead about both the markets and the workforce of the future.
- Achieving AI for the environment will also need increased collaboration between those that create the AI tools and know it better than anyone, and the users in industry, academia, and government who understand the problems and real-world systems that need to be addressed.
- Ultimately, AI will only reach its full potential for society and the planet, if each stakeholder group participates with a shared responsibility to shape the future of AI and of the future systems and business models it underpins.
- We hope this work is a first step in a larger conversation to inject attention and investment into a tech-first approach to our most pressing environmental challenges. Moreover, we hope this report motivates others to build on this initial analysis to develop more comprehensive numbers around this topic. Both these efforts need to happen at speed for our planet, and for society, to survive and thrive.

Appendix: Modelling methodology

This Appendix explains key features in the methodology that we have followed in our simulation exercise to assess the GDP, jobs, greenhouse gas (GHG) emissions, and wider impacts that environmental applications of AI can potentially bring. Our analysis combines both top-down and bottom-up analysis, and focuses on the four key sectors of agriculture, energy, transport and water.

Broadly, there are five steps in our methodology.

Step 1 is to define AI levers by grouping AI use cases in agriculture, water, transport and energy. These formed the basic units of our assessment; we then assessed the first-round and indirect effects of AI applications for each lever..

Step 2 is to score the direct impacts of each AI levers against a set of Key Performance Indicators (KPIs: We assessed the direct impacts by formulating KPIs that related to environmental impacts, productivity impacts and labor impacts. Within each set of impacts, we disentangled the effect of each AI lever along key dimensions such as emissions intensity and use of natural resources like land within environmental impacts, and efficiency in the use of capital within economic impacts. This allowed us to comprehensively capture the first-round impacts of all AI levers, e.g. the percentage of fossil fuel used per unit of output that the agriculture sector could save by adopting agricultural robotics in 2030. The list of KPIs we considered is as follows:

1. **Fuel efficiency and/or GHG intensity improvement** per unit of output;
2. **Efficiency in the use of natural resources** such as land and water per unit of output;
3. **Efficiency in the use of other inputs** per unit of output, e.g. capital or another good or service;
4. **Overall efficiency not attributed anywhere else,** i.e. increase in output given the same combination of inputs; and
5. **Productivity gain through labor automation.**

We assessed the potential impact of each lever in 2030 in the region with the highest adoption rate. For **KPIs 1-4** above, we first identified broad ranges of potential impacts through a deeper dive on a selection of levers in each sector. Based on these ranges, our AI experts then used their experience and knowledge to score each of the levers against the KPIs based on estimated 2030 impacts, taking into account expectations on levels of maturity by 2030 in terms of both technology and uptake. For **KPI 5**, we applied PwC's existing framework to assess the potential impact of job automation that builds on previous academic studies, but with a specific focus on AI for environmental applications.

Step 3 is to assess the indirect impacts of environmental applications of AI. In Step 2, we only assessed the 'first round' impacts without considering how they ripple across the economy. For example, if agriculture becomes more fuel-efficient, the sector may expand its production and lower its price. From that, consumers and related industries would react, creating a ripple effect in the economy.

We translated all the scores for every lever and KPI combination into

- Changes in an input-specific efficiency, i.e. lower requirement for labor, capital, land, energy or other inputs to produce a unit of output in a given sector;
- Changes in overall efficiency, i.e. higher output for a given combination of inputs; or
- Changes in GHG intensity in the use of fossil fuels by businesses, households or government, or in given industry's overall production process, according to the Table A1 opposite.

Table A1: Conversion table between KPI scores and 'first round' impacts in the model

Score	-4	-3	-2	-1	0	+1	+2	+3	+4
Assessed range of impacts	-100% to -75%	-75% to -50%	-50% to -25%	-25% to -10%	-10% to +10%	+10% to +25%	+25% to +50%	+50% to +75%	+75% to +100%
Value adopted in "Gradual" Scenario	-87.5%	-62.5%	-37.5%	-17.5%	0%	+17.5%	+37.5%	+62.5%	+87.5%
Value adopted in "Expansion" Scenario	-100%	-75%	-50%	-25%	0%	+25%	+50%	+75%	+100%

Source: PwC analysis

The percentage is interpreted as follows:

- the **numerator** is the estimated impact in 2030 in the region of the highest adoption rate, in terms of either GHG intensity reduction or in monetary values.
- the **denominator** is the total monetary value / GHG emissions of a given economic activity, e.g. purchase of a product (e.g. coal) by an industry (e.g. electricity). This impact is in terms of GHG intensity reduction for KPI 1, and in terms of monetary value for all other KPIs.

We then adjust these raw changes downwards by multiplying them by a coverage ratio – e.g. if a certain lever with Score 1 only covers farming within agriculture, the 17.5% / 25% shock was scaled down appropriately so that it can be applied to the whole agriculture sector. Since the scores were defined for the best region, the impacts were applied to the rest of the regions using Global Innovation Index[55] as a proxy for each region's AI adoption rate.

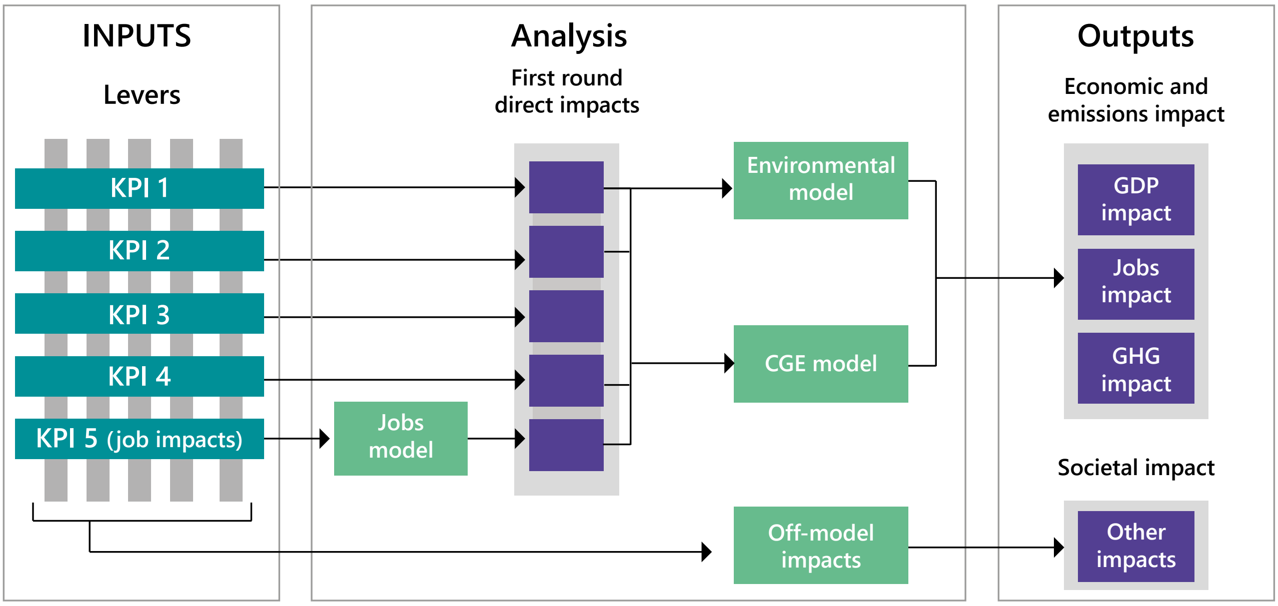
We use a CGE model to capture the indirect impacts and 'rebound' effects across industry sectors and regions originating from the direct impacts of each environmental AI lever. The CGE methodology is regularly used by governments and institutions such as the Intergovernmental Panel on Climate Change (IPCC), the World Bank, the Organization for Economic Co-operation and Development (OECD), the World Trade Organization (WTO), and the International Monetary Fund (IMF).

Step 4 is to estimate the "disaster mitigated" benefits. Most academic literature suggests that more emissions would lead to increased climate impact related damages in the future, and they in turn imply a higher economic cost on a global level. Lower emissions therefore imply less GDP lost due to climate-related risks. In other words reduced negative physical climate impacts carry an economic benefit. It doesn't include the damages due to increased extreme events (e.g. flood and windstorm damages) and as a result is a conservative estimate of the GDP gains due to reduced emissions.

Step 5 is to estimate the wider impacts of environmental applications of AI. Our "off-model" impact measurement approach uses a flexible framework encompassing a range of methods that allow the measurement of a wide range of social, environmental and economic impacts. Impact pathways are developed for use cases (identifying: inputs, outputs, outcomes, impacts), in order to model the full value chain to impacts. Bespoke and dedicated research is conducted to assess the individual impact along a specific value chain, and scaled as appropriate from the relevant use case in question. Impacts are scaled up globally where possible.

The overall methodology of our study is set out in the chart below.

Figure A1: Modelling methodology



Source: PwC analysis

Regional Breakdown

Table A2 shows the countries covered within each region.

Table A2: Full list of countries covered within each of the seven regions

Region	Countries/territories
North America	Bermuda; Canada; Greenland; Mexico; United States of America
Central and South America	Anguilla; Antigua and Barbuda; Argentina; Aruba; Bahamas; Barbados; Belize; Bolivia; Brazil; British Virgin Islands; Caribbean; Cayman Islands; Chile; Colombia; Costa Rica; Cuba; Dominica; Dominican Republic; Ecuador; El Salvador; Grenada; Guatemala; Guyana; Haiti; Honduras; Jamaica; Montserrat; Netherlands Antilles; Nicaragua; Panama; Paraguay; Peru; Puerto Rico; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and Grenadines; Suriname; Trinidad and Tobago; Turks and Caicos Islands; Uruguay; US Virgin Islands; Venezuela
Europe	Albania; Andorra; Austria; Belarus; Belgium; Bosnia and Herzegovina; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Faroe Islands; Finland; France; Germany; Gibraltar; Greece; Guernsey ; Holy See; Hungary; Iceland; Ireland; Isle of Man; Italy; Jersey; Latvia; Liechtenstein; Lithuania; Luxembourg; Macedonia, Republic of; Malta; Moldova; Monaco; Montenegro; Netherlands; Norway; Poland; Portugal; Romania; Russia; San Marino; Serbia; Slovakia; Slovenia; Spain; Sweden; Switzerland; Ukraine; United Kingdom
Middle East and North Africa	Afghanistan; Algeria; Armenia; Azerbaijan; Bahrain; Egypt; Georgia; Iran Islamic Republic of; Iraq; Israel; Jordan; Kazakhstan; Kuwait; Kyrgyzstan; Lebanon; Libya; Morocco; Oman; Pakistan; Palestinian Territory; Qatar; Saudi Arabia; Syria; Tajikistan; Tunisia; Turkey; Turkmenistan; United Arab Emirates; Uzbekistan; Yemen
Sub-Saharan Africa	Angola; Benin; Botswana; Burkina Faso; Burundi; Cameroon; Cape Verde; Central African Republic; Chad; Comoros; Congo, Democratic Republic of the; Congo, Republic of the; Cote d'Ivoire; Djibouti; Equatorial Guinea; Eritrea; Ethiopia; Gabon; Gambia; Ghana; Guinea; Guinea-Bissau; Kenya; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Mauritius; Mayotte; Mozambique; Namibia; Niger; Nigeria; Rwanda; Saint Helena; Sao Tome and Principe; Senegal; Seychelles; Sierra Leone; Somalia; South Africa; Sudan; Swaziland; Tanzania; Togo; Uganda; Zambia; Zimbabwe
East Asia	China (Mainland); Hong Kong, SAR of China; Japan; Korea, D.P.R. of; Korea, Rep. of; Macau, SAR of China; Mongolia; Taiwan
Indo-Pacific	American Samoa; Australia; Bangladesh; Bhutan; Brunei Darassalam; Cambodia; Cook Islands; Fiji; French Polynesia; Guam; India; Indonesia; Kiribati; Laos; Malaysia; Maldives; Marshall Islands; Micronesia, Federated States of; Myanmar; Nauru; Nepal; New Caledonia; New Zealand; Niue; Northern Mariana Islands; Palau; Papua New Guinea; Philippines; Pitcairn; Samoa; Singapore; Solomon Islands; Sri Lanka; Thailand; Timor-Leste; Tokelau; Tonga; Tuvalu; Vanuatu; Vietnam; Wallis and Futuna Islands

Industry Sector Definition

Table A3 shows the composition of each of the sectors we defined in this analysis. They are defined as aggregations of products defined in the GTAP9 database, which is developed by the Global Trade Analysis Project (GTAP), an international academic collaboration coordinated by Purdue University.

Table A3: Definition of sectors in this report

Broad sectors	Sectors in model	GTAP9 products covered
Agriculture	Agriculture	Paddy rice; Wheat; Cereal grains nec; Vegetables, fruit, nuts; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec; Bovine cattle, sheep and goats, horses; Animal products nec; Raw milk; Wool, silk-worm cocoons
	Forestry and Fisheries	Forestry; Fishing
Energy	Coal Mining	Coal
	Oil, Gas, and Refined Products	Oil; Gas; Petroleum, coal products
	Electricity	Electricity
Water	Water	Water
Transport	Transport	Water transport; Air transport; Transport nec
Other	Energy-Intensive Industries	Minerals nec; Chemical, rubber, plastic products; Mineral products nec; Ferrous metals; Metals nec
	Other industries	Bovine meat products; Meat products nec; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products; Textiles; Wearing apparel; Leather products; Wood products; Paper products, publishing; Metal products; Motor vehicles and parts; Transport equipment nec; Electronic equipment; Machinery and equipment nec; Manufactures nec; Gas manufacture, distribution; Construction; Trade; Communication; Financial services nec; Insurance; Business services nec

Source: PwC analysis

Note: The full list of 57 GTAP9 products can be accessed via this link:
https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

Acknowledgements

PwC and Microsoft would like to acknowledge the valuable contributions of the following people in the development of this document:

Lead authors

Celine Herweijer (PwC UK), Benjamin Combes (PwC UK), Jonathan Gillham (PwC UK)

PwC project team

Denise Chan (PwC UK), Tarik Moussa (PwC UK), Edmond Lee (PwC UK), Saloni Goel (PwC UK), Anand Rao (PwC US), Ilana Golbin (PwC US), Robert Moline (PwC US), Richard Berriman (PwC UK), Alastair Macpherson (PwC UK), Hannah Audino (PwC UK), Duncan Mckellar (PwC UK), Sophie Davie (PwC UK), Mary Davies (PwC UK), Max Dillon (PwC UK), Laura Gatz (PwC UK).

Microsoft project team

Lucas Joppa, Josh Henretig, Jacob LaRiviere, Rahul Dodhia.

Other contributors

Alma Cardenas (Microsoft), Allen Kim (Microsoft), Anne Ewing (Microsoft), Dean Kain (Microsoft), Matthew Smith (Microsoft), Michelle Lancaster (Microsoft), Michelle Patron (Microsoft), Thomas Roca (Microsoft), Sam Fankhauser (LSE, Grantham Research Institute), Dimitri Zenghelis (LSE, Grantham Research Institute and Cambridge University, Bennett Institute), Juan Miguel de Joya (REDDS Capital)

Main contacts

Celine Herweijer

Global Innovation & Sustainability Leader, Partner, PwC UK

E: celine.herweijer@pwc.com
Twitter: @CHerweijer

Lucas Joppa

Chief Environmental Officer, Microsoft

E: lujoppa@microsoft.com
Twitter: @lucasjoppa

Endnotes

1 UNFCCC Paris Agreement, 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

2 Developed based on the public OECD/PIACC database.

3 A PwC-developed database of over 150 applications of AI being used for the environment across geographies and sectors.

4 North America; Central and South America; Europe; Middle East and North Africa; Sub-Saharan Africa; East Asia; and Indo-Pacific.

5 AI applications outside the four sectors analyzed could support further potential gains in the economy as a whole, and we did not assess their impact on global GHG emissions, either positive or negative. We also recognize that the environmental AI levers considered in this report could be already part of the baseline economic growth and carbon intensity change: whether this were the case, it is not expected to have a material impact on our results, both in absolute and percentage terms.

6 Our analysis has been conducted using a general equilibrium model. This means that the impact of environmental AI levers in our four sectors has been analyzed considering demand and supply changes in the economy as a whole, and not in isolation. Our model takes into account economic growth across regions and sectors that may not be directly affected, e.g. energy demand may rise if the power sector becomes more efficient and electricity becomes available at a lower cost, offsetting part of the positive environmental impacts..

7 We have defined an AI lever as "a cohesive application of different AI use cases, which combine together to achieve a specific impact". For example, the 'demand prediction and logistic planning' lever combines computer vision and the Internet of Things (IoT) (to analyse shipments or stock space), machine learning (to identify patterns in purchasing) and prescriptive analytics to reduce waste and maximize sales.

8 2030 annual emissions estimates for these countries are based on Climate Action Tracker's Country Assessments 2018, under current policy projections and excluding LULUCF. http://climateactiontracker.org.

9 These results relate to our "Expansion" scenario, as defined in the 'Realizing AI for the environment' section.

10 CO_2 concentrations have now passed 403ppm, while the Holocene baseline was 280ppm, according to the World Meteorological Organization, https://public.wmo.int/en/media/press-release/greenhousegas-concentrations-surge-new-record

11 IPCC, Special Report on Global Warming of 1.5 Degrees, 2018, https://www.ipcc.ch/sr15/

12 WWF, Living Planet Report 2018, 2018, https://wwf.panda.org/knowledge_hub/all_publications/living_planet_report_2018/.

13 Zemp, D. C., et al., 'Deforestation effects on Amazon forest resilience', Geophysical Research Letters, June 2017, available at http://onlinelibrary.wiley.com/doi/10.1002/2017GL072955/abstract

14 International Institute for Applied Systems Analysis, Stockholm Resilience Centre and Stockholm University, Global Commons in the Anthropocene: World Development on a Stable and Resilient Planet, October 2016, https://www.iucn.org/sites/dev/files/globalcommonsanthropocene2016.pdf

15 Arc Centre of Excellence for Coral Reef Studies, James Cook University, Scientists assess bleaching damage on Great Barrier Reef [Media Release], 26 October 2016, https://www.coralcoe.org.au/mediareleases/scientists-assess-bleaching-damage-on-great-barrier-reef.

16 Zielinski, Sarah, "Ocean Dead Zones Are Getting Worse Globally Due to Climate Change", Smithsonian.com, 10 November 2014, available at http://www.smithsonianmag.com/science-nature/ocean-deadzones-are-getting-worse-globally-due-climate-change-180953282

17 UNEP (2016) Options for decoupling economic growth from water use and water pollution, https://www.unenvironment.org/resources/report/options-decoupling-economic-growth-water-use-and-water-pollution-report-water

18 Energy Transitions Commission, Mission Possible, 2018, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

19 World Economic Forum, PwC, and Stanford Woods Institute for the Environment, Harnessing the Fourth Industrial Revolution for the Earth, 2017, http://www3.weforum.org/docs/WEF_Harnessing_the_4IR_for_the_Earth.pdf

20 IPCC, AR5 WG3 2014, 2014, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

21 Sizing the prize, PwC https://www.pwc.com/gx/en/issues/data-and-analytics/publications/artificial-intelligence-study.html

22 Unless otherwise specified, graphs and diagrams in this report reflect results in the "Expansion" scenario. Detailed results for both scenarios can be explored in the Power BI tool https://blogs.microsoft.com/on-the-issues/2019/04/15/were-increasing-our-carbon-fee-as-we-double-down-on-sustainability/

23 BAU is defined based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Please refer to Box 3: 'A guide to interpreting our results' for more information.

24 It can be accessed via this link: https://www.pwc.com/gx/en/issues/economy/the-world-in-2050.html (accessed 11 Apr 2019)

25 We refer to the IPCC's RCP6 scenario, available here: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html [last downloaded 08/04/2019]

26 It can be accessed via this link: https://climateactiontracker.org/global/temperatures/ (accessed 11 Apr 2019)

27 In this report, all economic figures are reported in 2017 prices and under market exchange rates.

Endnotes

28 Sizing the Prize – What's the real value of AI to your business and how can you capitalise? – Rao and Verweij – PwC, 2017 https://www.pwc.com/gx/en/issues/analytics/assets/pwc-ai-analysis-sizing-the-prize-report.pdf

29 The projected baseline is based on figures from the Climate Action Tracker: Global emissions time series 'Current Policy Projections' available at https://climateactiontracker.org/

30 GHG intensity refers to GHG emissions per unit of output produced or GHG emissions per unit of fossil fuel burnt.

31 The Low Carbon Economy Index 2018 – Tracking the progress G20 countries have made to decarbonize their economies (PwC, 2018) https://www.pwc.co.uk/sustainability-climate-change/assets/pdf/low-carbon-economy-index-2018-final.pdf

32 Kompas, T., Pham, V. H., & Che, T. N. (2018). The effects of climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord. Earth's Future, 6(8), 1153-1173.

33 AI-enabled decarbonization includes the impact of AI on deforestation (see section "Wider impacts and areas for further exploration"). The 1.5°C and 2°C ranges are based on GDP in the BAU scenario.

34 For a full list of countries / territories in each of the regions, please refer to the Appendix.

35 China is now second behind the US in AI patent filings, a key indicator of long-term trends in technology. Source: 'The Global Race for Artificial Intelligence – Comparison of Patenting Trends', Wilson Center, 1 March 2017 (https://www.wilsoncenter.org/blog-post/theglobal-race-for-artificial-intelligence-comparison-patenting-trends)

36 PwC derivations based on modelling results published by Kompas et al. (2018) The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord

37 US Energy Information Administration, "US Energy Facts Explained" – https://www.eia.gov/energyexplained/?page=us_energy_home

38 "Industry" comprises sectors such as manufacturing, mining, construction, energy and water.

39 World Development Indicators: Structure of Output 2017 – Table 4.2 (World Bank)

40 http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

41 P Agarwal and M A Alam 2018 IOP Conf. Ser.: Earth Environ. Sci. 150 012032

42 https://www.pwc.com/gx/en/sustainability/assets/ai-for-the-earth-jan-2018.pdf

43 Will robots really steal our jobs? An international analysis – Berriman and Hawksworth – PwC, 2018 https://www.pwc.co.uk/economic-services/assets/international-impact-of-automation-feb-2018.pdf

44 What will be the net impact of AI and related technologies on jobs in the UK? – Hawksworth and Fertig – PwC, 2018 https://www.pwc.co.uk/economic-services/ukeo/ukeo-july18-net-impact-ai-uk-jobs.pdf

45 What will be the net impact of AI and related technologies on jobs in China? – Hawksworth and Fertig – PwC, 2018 https://www.pwc.com/gx/en/issues/artificial-intelligence/impact-of-ai-on-jobs-in-china.pdf

46 World Health Organization, available at https://www.who.int/airpollution/en/

47 Group on Earth Observations, Earth Observation Priorities: Air Quality and Health Final Report, 2010, available at https://sbageotask.larc.nasa.gov/AirQuality_US0901a-FINAL.pdf

48 Nellemann, C., INTERPOL Environmental Crime Programme (eds). 2012. Green Carbon, Black Trade: Illegal Logging, Tax Fraud and Laundering in the Worlds Tropical Forests. A Rapid Response Assessment. United Nations Environment Programme, GRIDArendal. www.grida.no. Available at https://twosidesna.org/wp-content/uploads/sites/16/2018/05/The-vast-majority-of-deforestation-and-illegal-logging-takes-place-in-the-tropical-forests-of-the-Amazon-basin-Central-Africa-and-Southeast-Asia.pdf

49 United Nations Office for Disaster Risk Reduction (UNISDR)

50 Based on historical baseline data from EM-DAT: The Emergency Events Database – Université catholique de Louvain (UCL) – CRED, D. Guha-Sapir – www.emdat.be, Brussels, Belgium

51 Gardiner B. et al.. (eds). Living With Storm Damage to Forests. What Science Can Tell Usno. 3. European Forest Institute, ISBN: 978-952-5980-09-7 (2013).

52 IPCC, AR5 WG3 2014, 2014, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

53 Energy Transitions Commission, Mission Possible, 2018, http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

54 https://stepupdeclaration.org/thecoalition

55 The Global Innovation Index is annually co-published by Cornell University's SC Johnson School of Business, INSEAD and World Intellectual Property Organization (WIPO). Strategy&, part of the PwC network, is a knowledge partner. It can be accessed via this link: https://www.globalinnovationindex.org/.

Notes

Notes