Frontier technologies to protect the environment and tackle climate change

United Nations Educational, Scientific and Cultural Organization

UN environment
United Nations Environment Programme

United Nations Framework Convention on Climate Change

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Table of Contents

Abbreviations and Unit Symbols

°C	Degrees Celsius
4G	Fourth Generation
4IR	Fourth Industrial Revolution
5G	Fifth Generation
AI	Artificial Intelligence
ANFIS	Adaptive Neural-based Fuzzy Inference Systems
ANN	Artificial Neural Networks
APAC	Asia-Pacific
ATLAS	Advanced Topographic Laser Altimeter System
B.C.	British Columbia
BOEM	U.S. Bureau of Ocean Energy Management
BRS	Basel, Rotterdam and Stockholm Conventions
CCAFS	Climate Change, Agriculture and Food Security
CCS	Cloud Classification System
CCTNE	Climate Change: The New Economy
CGIAR	Consultative Group on International Agricultural Research
CHRS	Center for Hydrometeorology and Remote Sensing
CIAT	International Center for Tropical Agriculture
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COP	Conference of the Parties
DEWA	Dubai Electricity and Water Authority
DOB	De Oude Bibliotheek Academy
DSCE	U.A.E. Supreme Council on Energy
EIA	Environmental Impact Assessment
EMG	Environment Management Group
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPA	U.S. Environmental Protection Agency
ESA	European Space Agency
ESM	Environmentally Sound Manner

FAO	Food and Agriculture Organization of the United Nations
FG-AI4EE	Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies
GCF	Green Climate Fund
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GeSI	Global e-Sustainability Initiative
GHGs	Greenhouse Gases
GP	Genetic Programming
GPA	Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities
GPML	Global Partnership on Marine Litter
GPNM	Global Partnership on Nutrient Management
GPS	Global Positioning System
GPWM	Global Partnership on Waste Management
GSMA	Global System for Mobile Communications Association
GW	Gigawatt
GWI	Global Wastewater Initiative
HFCs	Hydrofluorocarbons
ICESat-2	Ice, Cloud and land Elevation Satellite-2
ICT	Information and Communication Technology
ICTP	Abdus Salam International Centre for Theoretical Physics
ICTs	Information and Communication Technologies
IEA	International Energy Agency
IISD	International Institute for Sustainable Development
IOC	Intergovernmental Oceanographic Commission of UNESCO
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISWA	International Solid Waste Association
IT	Information Technology
ITS	Intelligent Transport System
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector

JRC	Joint Research Centre of the European Commission
kg	Kilogramme
km^2	Square Kilometres
kph	Kilometres per Hour
KTOE	Kilotonne of Oil Equivalent
lbs	Pound
LDCs	Least Developed Countries
LMICs	Low-income and Middle-income Countries
M2M	Machine to Machine
M2P	Machine to Person
MDGs	Millennium Development Goals
ML	Machine Learning
MOOC	Massive Open Online Course
MPAs	Marine Protected Areas
mph	Miles per Hour
Mton	Metric Ton
MW	Megawatt
NASA	U.S. National Aeronautics and Space Administration
NCD	Non-communicable disease rates
NDC	Nationally Determined Contributions
NO_2	Nitrogen Dioxide
NOAA	U.S. National Oceanic and Atmospheric Administration
O_3	Ozone
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PM2.5	Small Particulate Matter
ppm	Parts per Million
PPP	Public-private partnership
PUB	Singapore Public Utilities Board
SBTi	Science Based Targets initiative
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SDGs	Sustainable Development Goals

SEA	Strategic Environmental Assessment
SEDB	Singapore Economic Development Board
SG	Study Group
SIDS	Small Island Developing States
SO_2	Sulphur Dioxide
SSC	Smart Sustainable City/Cities
TQT	Trieste Institute for Theoretical Quantum Technologies
U4SSC	United for Smart Sustainable Cities
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UN-DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
UNDRR	United Nations Office for Disaster Risk Reduction
UN-Habitat	United Nations Human Settlements Programme
UN-SPBF	United Nations Science Policy Business Forum
UNU	United Nations University
UN Women	United Nations Entity for Gender Equality and the Empowerment of Women
U.S.	United States (of America)
USD	United States Dollar
VR	Virtual Reality
WBCSD	World Business Council for Sustainable Development
WCDRR	World Conference on Disaster Risk Reduction
WEEE	Waste Electrical and Electronic Equipment
WEF	World Economic Forum
WHO	World Health Organization
WMO	World Meteorological Organization
WWF	World Wide Fund for Nature

Executive summary

This report defines frontier technologies as new, innovative and disruptive technologies. It explores the vast potential of frontier technologies to help assess, mitigate and adapt to climate change. Leveraging these technologies to engineer new solutions to address climate change represents a significant opportunity to accelerate efforts to achieve Sustainable Development Goal (SDG) 13: 'Take urgent action to combat climate change and its impacts,' especially at the city level.

Several UN bodies have worked closely on this report, including: the International Telecommunication Union (ITU); United Nations Educational, Scientific and Cultural Organization (UNESCO); UN Environment; United Nations Framework Convention on Climate Change (UNFCCC); United Nations Global Compact; United Nations Industrial Development Organization (UNIDO); United Nations Human Settlements Programme (UN-Habitat); United Nations Entity for Gender Equality and the Empowerment of Women (UN-Women) and with the support of the United Nations Economic Commission for Europe (UNECE). This report collates observations from the real-world deployment of eight key emerging technologies in tackling climate change: artificial intelligence (AI), Internet of Things (IoT), 5G, clean energy technology, digital twins, robotics, Space 2.0 technologies, as well as digitalization and Big Data within cities and urban regions.

The applications of these technologies are wide ranging and include addressing: the effects of compromised air quality on public health, the long-term outcomes of the increasing levels of carbon dioxide, greenhouse gases and air pollutants, the ramifications of water shortages and loss through supply network and infrastructure inefficiencies, the wide-ranging consequences of fossil fuel consumption, the costs associated with increasing disaster risk stemming from natural, man-made and technological hazards, the implications of biodiversity loss, the global consequences of sea level rise, and climate change-related threats to global food security. Indeed, the transformative potential of frontier technologies is so significant that the UN is calling for public and private sector actors to join forces to build a digital ecosystem for the planet. The technologies covered by this report are defined briefly in Box 1.

The report has concluded that, although still considered frontier or emerging, the eight technologies covered by this report offer real and innovative solutions to meet the needs of the world's population, while addressing some of the needs of our planet. Continual assessment of the potential of emerging technologies and scalable deployment of existing frontier solutions should play a part in any city's resilience strategy. Introducing these technologies could bring about concrete results for city authorities and for local populations. Buy-in from, and investments by, governments are critical to ensuring the continued progression and proliferation of frontier technologies for fighting climate change and improving the response. Lastly, due to their reliance on IoT and AI, ensuring the affordable and wide-scale deployment of these two particular emerging technologies will spur further advancements in and wider adoption of all other frontier technologies to combat climate change. It is hoped that the findings and conclusions of this report will be valuable in stimulating further research into the success of frontier technologies to combat climate change, especially at the local or city level.

Box 1: Some definitions of Key frontier technologies used in this report [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [27] [28] [29] [30]

Artificial Intelligence (AI): Artificial intelligence makes it possible for machines to learn from experience. Intelligent systems use a combination of Big Data analytics, cloud computing, machine-to-machine communication and the Internet of Things to learn to perform cognitive tasks: sensing, processing of oral language, reasoning, decision-making, displacement and manipulation of objects, etc. AI is empowering new kinds of software and robots to act as self-governing agents capable of operating much more independently from the decisions of their human creators and operators than any machine has ever done. There is also potential for them to adapt to new working environments without any reprogramming.

Internet of Things (IoT): The Internet of Things is a concept that enables advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies. IoT is essentially about measuring and remotely controlling previously unconnected "things". It reaches people and objects that older technology could not.

5G: 5G mobile and internet technology is the next generation of mobile internet connectivity promising much faster data download and upload speeds, wider coverage and more stable connections. It is all about making better use of the radio spectrum and enabling far more devices to access the mobile internet at the same time.

Clean Energy Technologies: The term 'clean energy technologies' often refers to technologies that produce or utilize renewable energy, such as wind farms, electric vehicles and biofuels.

Digital Twin: A digital twin is the virtual representation of a physical object or system across its life cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making.

Robotics: Robotics is the branch of technology that deals with the design, construction, operation, and application of robots.

Space 2.0: Space 2.0 is the new age of space technology in which businesses are developing technologies for NASA and commercial use simultaneously.

Digitalization and Big Data: Digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities. It is the process of moving to a digital business. Big data refers to extremely large data sets that may be analysed computationally to reveal patterns, trends, and associations.

Forewords

International Telecommunication Union (ITU)

A digital revolution is sweeping across the world, driven by the emergence of frontier technologies ranging from artificial intelligence to the Internet of Things and 5G. Whether we are dealing with rising sea levels, biodiversity loss, water shortages, air quality or food security, these technologies hold great potential for addressing the root causes and already devastating effects of the climate crisis.

This timely report examines the implications and applications of frontier technologies, including their impact on the environment. It takes us inside the United Nations system and beyond to explore how these innovative technologies are being used in areas as diverse and critical as smart cities, earth monitoring, natural disaster risk reduction, e-waste and water and electricity management.

ITU is at the forefront of this digital revolution. We harmonize the use of the radio-frequency spectrum and satellite orbits, broker international standards and help ensure coherent policy and regulatory frameworks for these fast-changing technologies. With influential platforms like the Green Standards Week, ITU brings public and private actors together to identify Internet of Things and artificial intelligence applications that can improve the quality and sustainability of life on the planet.

For the first time in history, more than half of the world's population is using the Internet. Inequalities in how frontier technologies are distributed and used risk creating new and evolving digital divides. At stake is the ability to bring the benefits of the digital revolution to everyone, including all those in developing countries, least developed countries and Small Island Developing States who are on the frontline of climate change.

The UN family has a key role to play in building a global digital ecosystem for the environment. This report is a call to action, an open invitation for governments, civil society, academia, the scientific community and the technology industry to join UN agencies in their effort to leverage frontier technologies to tackle one of the defining issues of our time.

Houlin Zhao
Secretary-General of the International Telecommunication Union

UN Environment

At the Second Global Session of the UN Science Policy Business Forum and UN Environmental Assembly in March 2019, unprecedented initiatives were launched to unite global efforts to leverage frontier technologies to monitor the state of the world environment. The four key outcomes will lay the foundation for building a global digital ecosystem for the planet.

Firstly, ministers from 193 countries pledged to support UN Environment to develop a global environmental data strategy by 2025, while simultaneously improving national environmental monitoring systems and technologies. They also committed to promoting the use of data-analysis models to develop environment foresights, support evidence-based decision making and improve national and local preparedness and responses to mitigate environmental degradation and risks from disasters and conflicts, in line with the 2030 Agenda for Sustainable Development.

Secondly, a paper entitled 'The case for a digital ecosystem for the environment: bringing together data, algorithms and insights for sustainable development[31]was adopted by the Working Group of the UN Science Policy Business Forum. This represents a collective intelligence process involving more than 200 stakeholders, including a variety of trendsetting technology companies. The report makes a clear call to action. Now is a pivotal moment in history when we can reimagine and supercharge environmental governance and public-private partnerships by using big data, frontier technologies and data analytics to target our action and investments. The working group was mandated to develop an implementation plan for the digital ecosystem to be presented to in March 2020.

Thirdly, a vision for the World Environment Situation Room was launched. This groundbreaking initiative aims to promote transparent access and sharing of statistical and geospatial environmental data supporting policy and action for sustainable development, peacebuilding and humanitarian action at the global, regional and national levels. The Situation Room supports 'Environmental Foresight' for the analysis of data, mapping trends, creating scenarios and identifying emerging issues on a permanent basis, at the frontier of environmental knowledge. The situation room will be powered by environmental spatial data from MapX.[32]

Finally, the European Commission's Joint Research Centre (JRC), Google Earth Engine and UN Environment teamed up to develop a global water explorer application to help monitor SDG 6.6.1.[33] It shows changes from 1984 to 2018 through interactive maps, graphs and full-data downloads and provides critical statistics for every country's annual surface water (such as lakes and rivers). The new app aims to make this water data open, free and easily accessible.

Inger Andersen
Under-Secretary-General of the United Nations and Executive Director of the UN Environment Programme

United Nations Educational, Scientific and Cultural Organization (UNESCO)

Under the motto 'Changing Minds, Not the Climate', UNESCO is mobilizing its full set of competencies in an integrated approach through education, sciences, culture, communication and information in support of Member States efforts to address the climate crises. The role of new technologies is paramount in this context. The 2018 IPCC special report on the impacts of global warming of 1.5 °C and the 2019 IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, made it crystal clear that science, technology and innovation are central to reaching the targets under the Paris Agreement.

The urgency of the climate and biodiversity crises should not blind us from the fact that past advancements in science and technology, and their applications, have contributed to aggravating a number of environmental and climate challenges that the world is now facing. This calls for a sober assessment of benefits and risks in the advancement and implementation of increasingly powerful technological and artificial intelligence systems devised to help address them. UNESCO, such as through its World Commission on the Ethics of Scientific Knowledge and Technology, is, therefore, putting a premium on ethical frameworks, as manifested in the UNESCO Declaration of Ethical Principles in Relation to Climate Change adopted by its UNESCO General Conference in 2017.

As implied under the pledge to 'leave no one behind' in the context of the 2030 Agenda for Sustainable Development, UNESCO is also a stern advocate of seeking to ensure that frontier technologies benefit those most in need and that they promote rather than compromise gender equality. A good example of this is the ITU-UNESCO Broadband Commission that advocates for the development of broadband infrastructure in developing countries and marginalized communities.

Ranging from work on climate modelling, ocean science and monitoring, hydrology and water management, science policy, basic sciences, disaster risk reduction and biodiversity conservation, several references are given in the present publication on how UNESCO, and its unique number of centres and institutes, such as the UNESCO Abdus Salam International Centre for Theoretical Physics (ICTP), promote the application of such technologies to address environmental and climate issues.

While supporting sound advanced technologies and their applications, UNESCO is also well aware of the fact that they are not a panacea, and that sustainability and sustainable development are a function of technology working in harmony with nature-based solutions and with traditional and indigenous knowledge. UNESCO has several tools and programmes in place for this purpose, including the networks of almost 2000 UNESCO designated sites around the world that strive to enhance the protection and sustainable use of our cultural and natural resources with and for local people and the international community at large. By designating World Heritage Sites, Biosphere Reserves and Global Geoparks, UNESCO provide excellent frameworks as observatories for implementing, assessing and sharing technology and sustainability solutions to address climate change and environmental concerns at local, regional and global scales. As such, they are also the ideal venues for UN interagency collaboration and international cooperation in pursuit of the Sustainable Development Goals in harmony with nature.

Audrey Azoulay
Director-General of the United Nations Educational, Scientific and Cultural Organization (UNESCO)

United Nations Framework Convention on Climate Change (UNFCCC)

Climate change is an existential crisis and represents the greatest challenge facing this generation. It is clear that business as usual is simply not good enough anymore. We need deep, transformational and systemic change throughout society if we are to truly build a low-emissions, highly-resilient and more sustainable future. Technological innovations have a critical role to play in this process, including enhancing and accelerating the implementation of Nationally-Determined Contributions, National Adaptation Plans and both long and medium-term climate change strategies. Specifically, technological innovation in adaptation and mitigation has received increased attention, thereby providing opportunities to accelerate climate action on all fronts.

Frontier technologies present even greater potential in our fight against climate change. In the energy and renewables sector, innovations such as smart grids, through the Internet of Things (IoT), may substantially lower global emissions, helping to drive their necessary peak and decline. In the area of climate resilience, technologies such as satellite 2.0 and artificial intelligence offer enormous opportunities when it comes to identifying and addressing climate risks and their impacts, as well as promoting climate-resilient development.

While the potential of these new technologies is extraordinary, as the United Nations family, it is our responsibility to not only promote the transfer and diffusion of new technologies, but also to ensure that their benefits are available to all people. For example, we must ensure that autonomous systems are free of biases and discrimination and we must also ensure they consider the interests of the most vulnerable.

Technology, if harnessed correctly, offers enormous potential in our efforts to address climate change. It can not only offer unique opportunities—including economic—but it can have an immediate and significant impact and put countries on the path to low-carbon and climate-resilient development.

Patricia Espinosa
United Nations Climate Change Executive Secretary

United Nations Global Compact (UNGC)

Technology is responsible for some of the greatest strides ever made in the areas of medicine, research, agriculture and — of course — communications. Technology has saved millions of lives and given a voice to the voiceless. It has helped topple dictators, improved food security, given people access to clean drinking water, and made cities around the world safer and more livable. Technology is also our greatest hope of combating, and possibly solving, humanity's gravest threat — climate change.

At the same time, alongside globalization, technology is often blamed as a factor contributing to rising levels of inequality. Advancements in robotics, artificial intelligence, and other 'frontier technologies' are perceived as mortal enemies of traditional labour markets, threatening to displace workers and make entire industries obsolete. Likewise, there is mounting concern over the lingering 'digital divide', which has far-reaching implications for people in developed and developing countries alike.

The Sustainable Development Goals (SDGs) provide a roadmap to overcome these concerns and broaden access to the benefits technological advancements bring. They offer a framework for ensuring a just transition to a digital age as new technologies transform our societies. For companies and investors, there is a huge potential in localizing and materializing the opportunities presented by the SDGs — for example, through their foreign direct investments, companies can make significant capital allocations in frontier technologies that promote and translate local innovations into globally accessible climate solutions. Businesses can also focus more on leveraging technological advancements to develop local talent and create jobs, especially for young people who are challenged to find professional opportunities. In the food and agriculture, cities, energy, and health sectors alone, the SDGs could unlock an estimated $12 trillion in market opportunities by 2030 and create up to 380 million jobs. But these opportunities must go hand-in-hand with changing internal business practices. A growing number of UN Global Compact participants are responding by setting science-based targets aligned with limiting global temperature rise to 1.5°C above pre-industrial levels.

Climate change is the biggest transformation challenge the world has ever faced. Frontier technologies may provide the breakthrough innovations we need to stabilize global temperatures and avert disaster, but all sectors of the economy must do their part. All industries must transform to ensure a sustainable future. There is no other choice.

Lise Kingo
CEO & Executive Director, United Nations Global Compact

United Nations Industrial Development Organization (UNIDO)

As leaps in technology are profoundly reshaping the global economy, a new chapter of industrial development is unfolding. Frontier technologies, such as artificial intelligence, additive manufacturing, automation, the Internet of Things, big data, and other innovations including clean renewable energy are driving this transformation.

UNIDO embraces innovations that help the world navigate our greatest global challenges, such as poverty, inequalities and climate change. From reduced air pollution to water savings, we can already see the benefits of data-driven decision-making in cities and industries across the world.

Providing the right solutions for the benefit of people, while protecting the planet, is a challenge. No one should be left behind. We need to take a human-centred approach, particularly when considering the future of work. We need strong leadership and partnerships to ensure inclusive and sustainable development. The adequate and appropriate deployment of frontier technologies can help us to meet this goal.

UNIDO remains committed to working with partners in the UN family and beyond to further explore and seize the potential of frontier technologies. The tools to combat climate change, achieve a circular economy and improve the daily lives of people across the world are within our reach. We must seek to collectively maximize this opportunity.

LI Yong
Director General of the United Nations Industrial Development Organization (**UNIDO**)

United Nations Human Settlements Programme (UN-Habitat)

Information and communications technologies, data and the new digital economy are all around us and transform society. More than 50 per cent of the world´s population – 3.9 billion people – are now connected to the internet, and since 2018 there have been more mobile phone subscriptions in the world than people. This explosion in the use of digital technologies is playing a major role in shaping cities – from the internet of things and sensor networks, to digital platforms and tools for urban management and service delivery and the coming age of electric and autonomous mobility. Well-managed use of these technologies can contribute to sustainable development and promoting human rights by reducing carbon emissions from transport, increasing access to information for persons with disabilities, facilitating participation in public affairs for young people, and ensuring comprehensive access to services for communities at risk of marginalization. The New Urban Agenda calls for the adoption of a "a smart-city approach that makes use of opportunities from digitalization, clean energy and technologies".

As access to digital technology is becoming increasingly necessary to access services, the labour market and urban life, a persistent digital divide remains. While 50 per cent of us have access to the internet, the other half do not. The digital divide within countries is nearly as high as that between countries. Worldwide, about 21 per cent of households in the bottom 40 per cent of their countries' income distribution do not have access to a mobile phone and 71 per cent do not have access to the internet. Women are less likely than men to use digital technologies and groups already at risk of marginalization are particularly negatively impacted, for example older people.

While technology has demonstrated the potential to increase efficiency and productivity and create value, it also creates risks of asymmetries among actors at all levels. It holds great promise for sustainably increasing the quality of life but must be carefully directed and managed. Our challenge is to set a new direction that favours the inclusive, resilient and sustainable use of technologies in cities. Considering the importance of this, the Secretary General made "reducing digital inequality, building digital capacity and ensuring that new technologies ...are a force for good" one of his top five priorities.

By bringing its unique global urban perspective to the smart cities field, UN-Habitat can ensure that potentially highly disruptive technology is used effectively for sustainable urban development. UN-Habitat's multisectoral approach to urban development and deep knowledge of urban fundamentals provides a good opportunity to move the discussion about smart cities beyond technology and link it to the implementation of the urban dimension of the Sustainable Development Goals, specifically SDG 11 and the New Urban Agenda. Critically, sustainability in cities will not be primarily be about tech-filled buildings, cars and tools, but people, communities, mixed walkable neighbourhoods and interconnectivity. Our aim is to make the urban digital transformation work for the benefits of all, driving sustainability, inclusivity and prosperity and the realization of human rights in cities and human settlements.

In order to do this successfully, UN-Habitat and our partners will ensure that voices from marginalized groups, including children, youth and older people, women in vulnerable situations and people with disabilities as well as cities with less resources are more strongly heard. We support national and local governments with digital transition, helping them build skills and capacity to develop, procure and effectively use appropriate technologies to make sure that no one is left behind, including using technologies effectively to understand the needs of underserved populations. UN-Habitat will take an approach that is based on real challenges and priories coming from citizens and urban residents, while seriously respecting human rights. It is critical that smart city planning focuses on solving specific sustainability problems and key missions such as battling climate change and reducing poverty, rather than following a technology-driven, industry-driven approach. We welcome our partnership with ITU and the rest of the UN family in achieving these goals.

This publication is a valuable new contribution to knowledge in the field and we hope that it will contribute to further collaboration in future.

Maimunah Mohd Sharif
Executive Director of the United Nations Human Settlements Programme (UN-Habitat)

UN Women

Innovation and technology seldom benefit women and men equally. This has to change; there must be no further growth in the gender divide. Women and girls must have equal opportunities to use their originality and creativity to shape the frontier technology products and policies that impact their lives and those in their communities. And designs must not use algorithms and data sets that reflect and reproduce historical gender biases.

The dramatic changes possible through innovation can be a vital force for good in women's lives. We need that power to bring significant, positive opportunities and action in the biggest challenges to sustainable development, such as climate change, and to arrive at effective and creative solutions to systemic social and economic issues that are preventing progress in protecting the environment.

Phumzile Mlambo-Ngcuka
United Nations Under-Secretary-General and Executive Director of UN Women

United Nations Economic Commission for Europe (UNECE)

The UNECE region faces a wide range of environmental, social and economic challenges. As environmental pressures persist, sustainable economic development requires further advances in connectivity and the smart use of technologies across the region. In the wake of climate change and more extreme weather events, disasters triggered by natural and man-made/technological hazards are expected to occur more often and have more severe impacts. Natural hazard-triggered technological accidents are on the rise. Industrial production and transportation cause emissions of air pollutants and greenhouse gases, with detrimental effects on human health and the environment. Poor, disadvantaged and vulnerable populations, including young people, older people, women and migrants, are especially affected by climate change and environmental degradation. The application of relevant innovative technologies can help to address the climate change-related challenges and ensure that no-one is left behind.

UNECE has extensive experience in supporting countries in the UNECE region in their efforts to address the consequences of climate change through the application of tools in land management, land use and spatial planning, urban mobility, housing, risk-based and standards-based regulatory systems, environmental stewardship (including air pollution abatement), integrated water resources management, water supply and sanitation, environmental assessments, industrial safety, disaster risk reduction, energy management and efficiency, access to information and public participation, population, innovation/competitiveness and public-private partnerships.

UNECE also promotes climate mitigation and sustainable development through its conventions and other instruments such as international standards, national and regional policy reviews, information portals, policy advice, awareness-raising, advocacy and capacity development/assistance for the transition towards a smarter and more sustainable world for all.

Across all policy domains, UNECE uses the power of innovation to help countries enhance information exchange and cooperation across borders, to improve, the alignment and coherence of regional standards and approaches and effective policies for more inclusive sustainable development and achieving the SDGs.

Olga Algayerova
United Nations Under-Secretary-General Executive Secretary of the United Nations Economic Commission for Europe

1. Introduction

Frontier technologies are new, cutting-edge and innovative technologies. Frontier technologies fundamentally change the way we operate. They constantly collect data and information to create a shorter feedback loop that could, in theory, enable better decision-making overtime.[34] This report explores the vast potential of frontier technologies to help assess, mitigate and adapt to climate change. Leveraging these technologies to address climate change represents a significant opportunity to accelerate efforts to achieve the Sustainable Development Goals – in particular, SDG 13: 'Take urgent action to combat climate change and its impacts.'

Frontier technologies are helping to address climate change, drive sustainability and environmental resilience, and empower citizens all over the globe. New technologies are already enhancing the well-being of many by allowing, for instance, greater access to medicine, improving communication and connectivity through the proliferation of mobile technologies, and making financial services more inclusive and accessible to millions in developing countries through innovative digital financial mechanisms.[35] This report explores the applications of frontier technologies within the context of climate change and response.

The applicability of frontier technologies is examined at the city or local level and – where possible- through the lens of smart sustainable cities. Local experiences and outcomes can often serve as use cases for solutions that can, subsequently, be scaled up to regional, national and international levels. Each city's case study focuses on a particular frontier technology and its successful implementation within the city, in order to provide for a thorough exploration of each frontier technology highlighted. Since cities and urban areas are the biggest drivers of, and most affected by, climate change, it is appropriate to emphasize the role of frontier technologies in cities.

Some observers have noted that the use of technology and data have the potential to reinforce inequalities, which is further compounded by climate change.[36] Aspects related to the affordability of and access to frontier technologies remain of particular concern[37] and will be explored briefly in the report.

It is hoped that the report and its conclusions will serve to further explore the application of frontier technologies to combat climate change at the local level. The authors also aim to highlight specific literature, frameworks, standards and programmes developed by UN bodies that aim to foster successful achievement of the Sustainable Development Goals (SDGs). These highlights will be interwoven within the following sections.

2. The United Nations Sustainable Development Goals (SDGs)

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs) – as seen in Figure 1 – which are an urgent call for action by all countries – developed and developing – in a global partnership. They recognize that ending poverty and other deprivations must go together with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests.[38, 39]

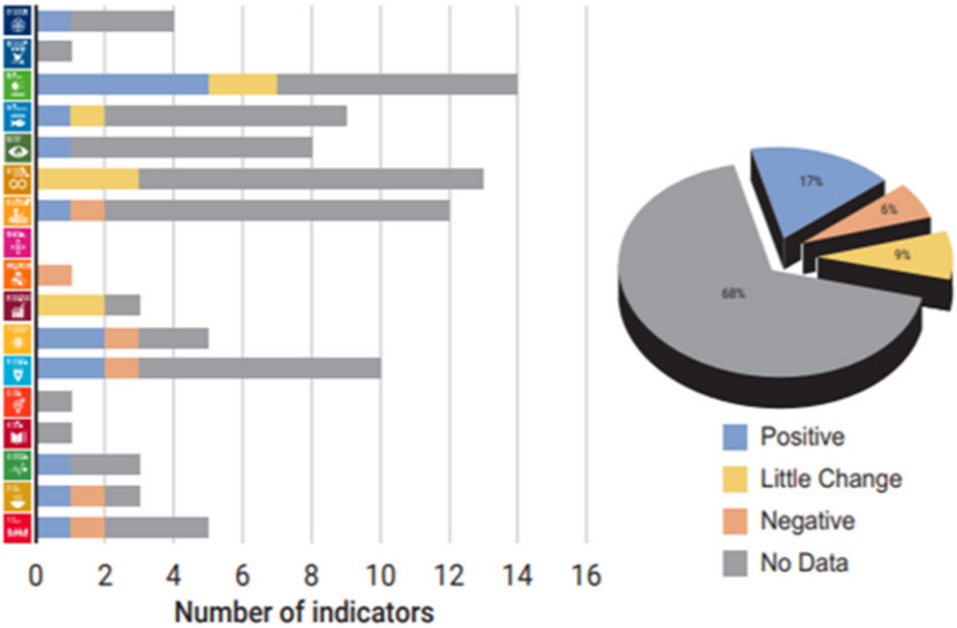
Figure 1: The United Nations Sustainable Development Goals [i]

The 2030 Agenda identifies climate change as 'one of the greatest challenges of our time,' a belief that mirrors the scientific community's concern that climate change now constitutes an 'existential threat' to humankind.[40, 41] It further elaborates that climate change and 'its adverse impacts undermine the ability of all countries to achieve the SDGs. Rising global temperature, sea-level rise, ocean acidification and other climate change impacts are seriously affecting coastal areas and low-lying coastal countries, including many least developed countries (LDCs) and small island developing states (SIDS). The survival of many societies, and of the biological support systems of the planet, is at risk.'[42]

The Agenda acknowledges that 'the spread of information and communications technology and global interconnectedness has great potential to accelerate human progress, to bridge the digital divide and to develop knowledge societies, as does scientific and technological innovation across areas as diverse as medicine and energy.' It also envisages a world 'in which development and the application of technology are climate sensitive, respect biodiversity and are resilient.'[43]

However, it must be noted that despite their universal support from world leaders, according to a recent UN Environment report, 68 per cent of the 93 indicators covering the environmental dimensions of the SDGs cannot be measured due to a lack of global data[44] (as seen in Figure 2). Of these, there are 17 environment-related indicators that must be underpinned by geospatial data – and yet no public system for storing or sharing geospatial data exists on a global scale. Without knowing the precise location of certain environmental drivers and their evolution over time, it is impossible to understand the challenges facing specific ecosystems and human settlements or the relationships between the people, the planet and peace.

Figure 2: SDG Tree [ii]



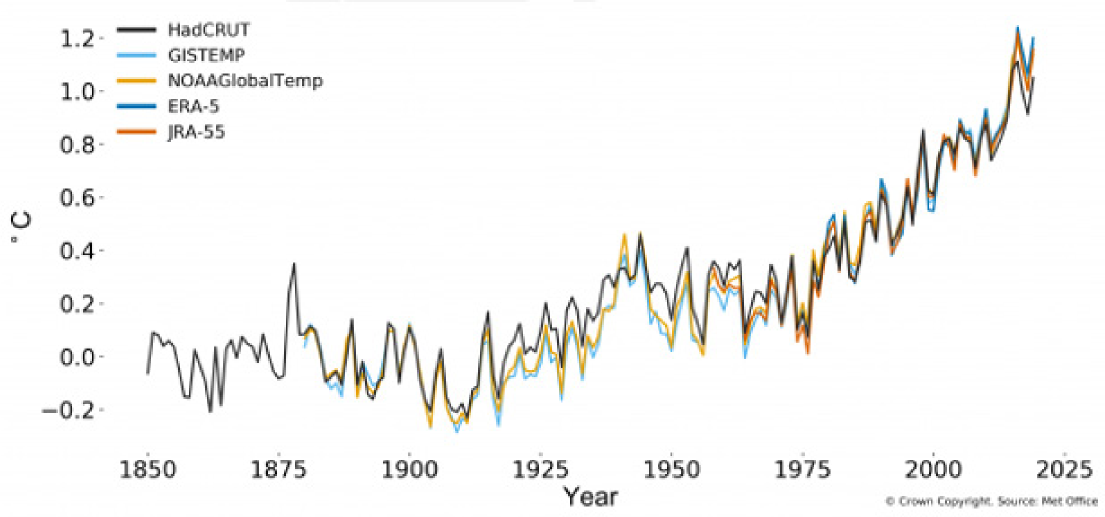
3. Climate change and SDG 13

According to the Intergovernmental Panel on Climate Change (IPCC), climate change refers to 'change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.'[45, 46, 47, 48]

Several causes of climate change exist and are leading to a warming of the planet as a result of the release of greenhouse gases (GHGs) – primarily in the form of carbon-based emissions that contribute to the greenhouse effect by retaining more heat from the sun. The average global temperatures increased by 0.85°C between 1880 and 2012.[49]

In light of this, the IPCC has issued its starkest warning yet on the consequences of climate inaction and the importance of limiting global warming to 1.5°C.[50] It has confirmed that the Earth is now (on average) already 1°C above pre-industrial levels.[51] 2016 was the warmest year on record, with 2019 confirmed by the World Meteorological Organization (WMO) to be the second warmest year on record after 2016.[52] Figure 3 from WMO shows the rapid long-term warming trend since the 1980s, after which each decade has been warmer than the previous one, with average temperatures for the five-year (2015-2019) and ten-year (2010-2019) periods being the highest on record.[53]

Figure 3: Global mean temperature difference from 1850 – 1900 (°C) [iii]



January 2020 has already been the warmest on record in many places – including in Antarctica where record high temperatures are leading to large-scale ice melt and glacier fracturing, which will contribute to global sea level rise. Meanwhile, smoke and pollutants from the extensive fires in Australia are permeating the globe, spiking CO_2 emissions.[54]

Essentially , the world is experiencing increasingly frequent and severe weather-related phenomena such as heat waves, droughts, floods, wildfires, hurricanes, tropical cyclones and heavy rain and snowfall, a selection of which from 2019 are seen in Figure 4 published by the WMO based on data from the WMO and the National Oceanic and Atmospheric Administration (NOAA). Already vulnerable and poor population groups are likely to be the most affected by such events.[55] The WMO Statement on the State of the Global Climate in 2019 devotes an extensive section to weather and climate impacts on human health, food security, migration, ecosystems and marine life.[56]

Figure 4: Selected significant climate anomalies and events in 2019 [iv]

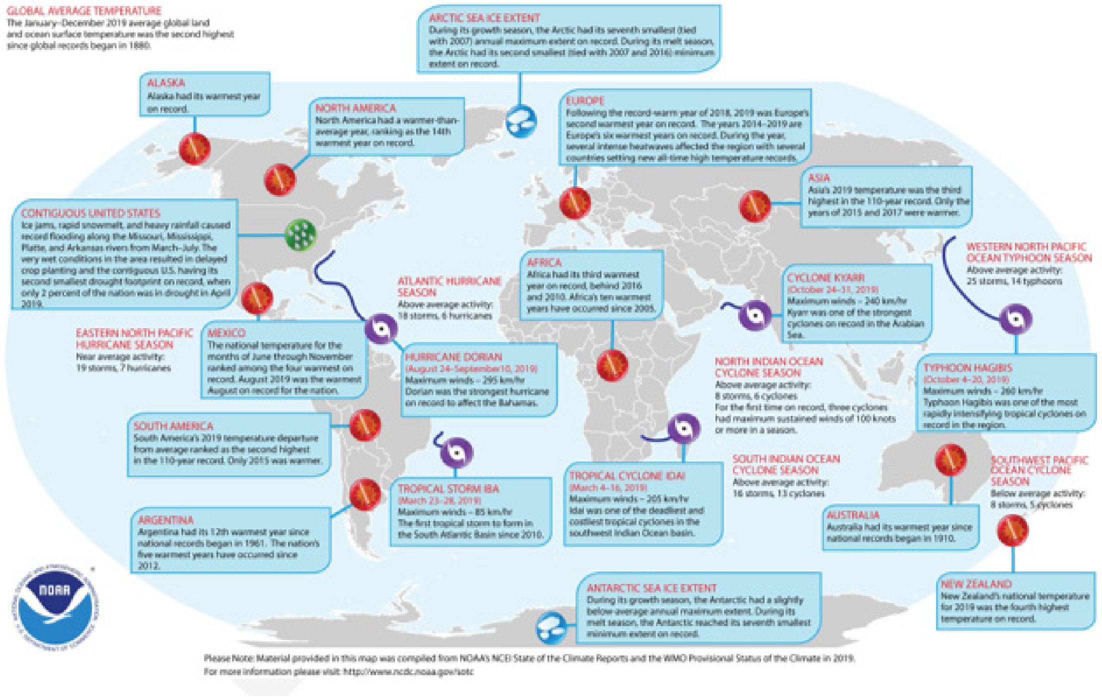
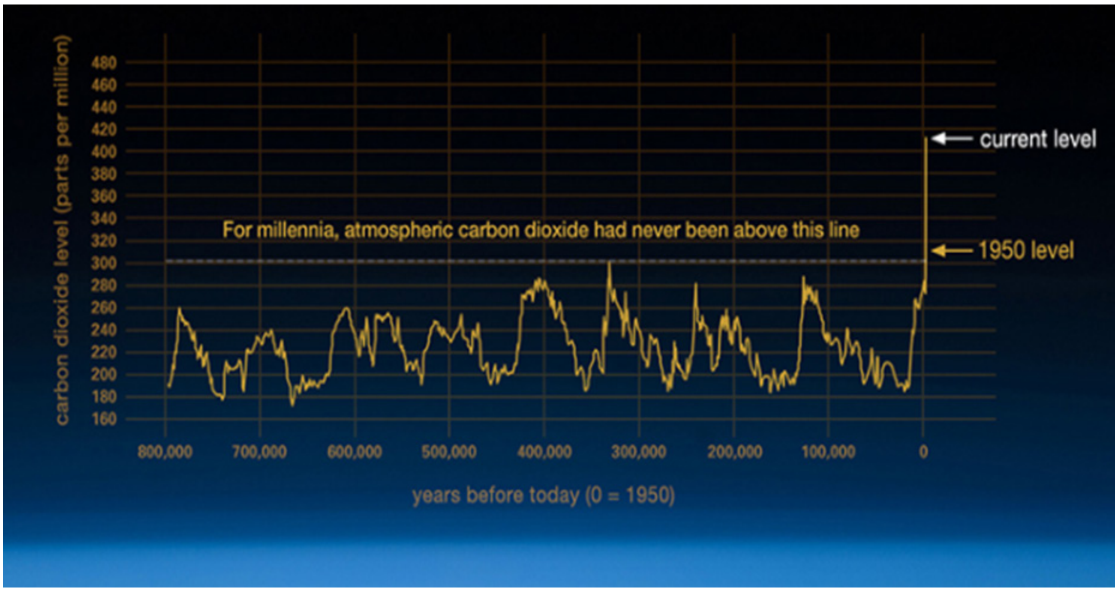


Figure 5 from NASA graphs the increase in atmospheric carbon over time. NASA has echoed that the current warming trend that corresponds to this increase is 'proceeding at a rate that is unprecedented over decades to millennia.'[57]

Figure 5: Increase in atmospheric carbon with time [v]



Adding to the aforementioned concerns is the fact that while momentum to view the environmental and climate challenges as part of the overall global economic architecture gained ground after the 2008 to 2009 global financial crisis[58] – as seen in the formulation of the Paris Agreement (detailed in Box 3) – a decade later, there is still not enough that has been done economically or politically to shift the balance toward sustainability, even though the deteriorating environmental conditions increasingly threaten humanity itself.[59] In a strange paradox, despite worsening climate conditions the political and economic will to fight climate change appears to be fading, according to the UN Secretary-General Antonio Guterres in early 2019.[60]

The evidence for this is clear: despite having made promises to make their operations more sustainable, the world's biggest companies have continued to rely on fossil fuels to meet their energy demands. Research shows that the carbon footprint of the global tech giants is growing particularly fast.[61] This is partly explained by the exponential growth of data centres worldwide.[62] While investment is being made to ensure that the manufacturing and operations of these new data centres may be as environmentally sustainable as possible (e.g. through water efficiency measures, the use of renewable energy and sustainability certifications),[63] it is still unclear what impacts the continued operation or dismantling of the old data centres will have on the environment and climate. The fact remains that data centres are consuming vast amounts of electricity and are leaving significant environmental footprints.[64] Unless these data centres begin to move towards utilizing renewable energy sources in their operations, they will remain responsible for a significant portion of global emissions.[65]

In light of this, at the briefing to Member States on the 26th session of the Conference of the Parties (COP26), the Secretary-General set the following four main priorities:

1. 'First, national climate plans – the NDCs – must show that countries are working to implement the Paris Agreement, and each new NDC should show more ambition than the previous one. The newly revised NDCs must set clear targets for 2025 or 2030 that will help stick to the 1.5-degree limit.'[66]
2. 'The second priority is to establish a common direction of travel, with all nations adopting strategies to reach net zero emissions by 2050. So far, 70 nations have announced that they are committed to achieving carbon neutrality by 2050. Many other constituencies are doing the same, such as cities; banks and businesses. But this still only represents less than one quarter of global emissions.'[67]
3. 'The third priority is for a robust package of programmes, projects and initiatives that will help communities and nations adapt to climate disruption and build resilience against the impacts to come.'[68]
4. 'The fourth priority is finance. By COP26, developed countries must deliver on the commitment they took to mobilize 100 billion dollars a year by 2020 with both public and private investments.'[69]

The need to mobilize long-term finance is to 'align with net-zero emission commitments by 2050, and incorporate climate risk and carbon pricing in investments.'[70] The cycle of climate change will never cease unless 'it is widely understood that it is no longer profitable to invest in the gray or brown economy.'[71]

The ramifications of climate change are, moreover, likely to be exacerbated by the growing pressure of urbanization. Today, more than 4 billion people (over half the global population) live in cities and urban areas; and this number is expected to grow over the coming years.[72,73] Over 70 per cent of energy-related CO_2 emissions can be traced back to cities,[74] which are responsible for about 60-80 per cent of all energy consumption.[75]

Cities are more and more at risk from the direct and indirect impacts of climate change, which means that most of the global costs of adaptation to climate change are likely to be incurred by, and within, cities.[76 77] These costs will increasingly include those associated with negative health outcomes resulting directly from air pollution in urban areas; approximately 7 million people around the world die every year from exposure to air pollution alone.[78]

Longer, hotter periods will continue to become the norm in many cities, making city life very taxing. The 'heat island effect' will be exacerbated by concrete surfaces and the lack of greenery in many cities. Air conditioning systems will contribute more to greenhouse gas emissions[79], making it urgent to find alternative ways of cooling buildings, including by taking inspiration from traditional architectural designs.[80]

Temperature, however, is just one indicator of climate change; changes in the global distribution of rainfall are also having major impact around the world. Rising sea levels – largely due to the thermal expansion of sea water and melting of the largest glaciers, like in Greenland and Antarctica – are another impact of climate change of deep concern for those living in low-lying urban coastal areas.[81] The global mean sea level reportedly rose 3.7 mm higher in 2018 than the previous year.[82] This is exposing coastal areas and islands to a greater risk of flooding and submersion. The resulting risks to transportation, especially in the case of coastal transport infrastructure, pose significant threats to global trade and development. International maritime transport carries over 80 per cent of the volume of world trade and provides access to global markets for all countries, including those that are landlocked.[83]

For Small Island Developing States, which are already exposed to major natural hazards, the outlook is particularly alarming. Their critical reliance on coastal transport infrastructure, in particular: seaports and airports, worsens their susceptibility to climate change impacts such as rising sea-level and extreme weather events. These impacts threaten trade and disaster relief efforts, as well as international tourism, which is the crown jewel of economic development in SIDS that requires secure and reliable international transport connections. Yet SIDS, and other developing countries, have limited capacity to adapt and build the resilience of their transport infrastructure to cope with climate change.[84] The Least Developed Countries are similarly affected and the UN Office for Disaster Risk Reduction estimates that the average annual losses in the LDCs in 2017 due to disasters were 8.5 per cent of their GDP.[85]

Also at risk are the planet's life-supporting eco-systems themselves.[86] A comprehensive UN study has found that 'nearly one million species are at risk of becoming extinct within decades, while current efforts to conserve the Earth's resources will likely fail without radical action. Although the planet already has specially designed ecosystems to heal itself, there is an urgent need to define how to rapidly identify where the areas of highest concern are, and where the greatest opportunities for restoration lie.'[87]

All this evidence shows that catastrophic global climate change is not an event waiting to happen sometime in the future. It is the reality that the entire world is facing right now. It is, therefore, imperative that countries take urgent and immediate action to address climate change. That is why the decade starting 2020 has been called the 'Decade of Action to deliver the Sustainable Development Goals' by the UN Secretary General – one which 'will be crucial for achieving a fair globalization, boosting economic growth and building peaceful societies. And it will strive to generate the ambition, innovation, financing and solutions needed to usher in an era of low-emission sustainable development. Climate action will be both a priority and a driver of the Decade.'[88]

The only way this can be achieved is by following the agreed-upon conventions and protocols of international instruments such as the 2018 Kigali Amendment to the UNFCCC's Montreal Protocol and the Paris Agreement, the latter being the UN-coordinated response of Member States to the issue of climate change. Any interventions that may help lessen the impact of this crisis must be utilized, including the use of innovative digital technologies as part of countries' climate change response strategies. Boxes 2 and 3 provide further information on the Kigali Amendment and the Paris Agreement.

There is also increased need for cities to invest in the development and implementation of vulnerability and risk assessments for potential disaster mitigation, as part of local disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015-2030.[89] The risks and vulnerabilities assessed and planned for need not stem only from unforeseen or sudden natural disaster events. Future inadequacy and/or unsuitability of water for human consumption is one example of a gradually escalating vulnerability as identified under the implementation of the Sendai Framework. The framework requires the following elements to be implemented in cities:[90-91]

a) city infrastructures and systems available for resilience;

b) risk and vulnerability assessments;

c) financial (capital and operational) plans to address the risks and vulnerabilities; and

d) technical systems to implement the plans.

Box 2: Synopsis of The Kigali Amendment [91]

Synopsis of the Kigali Amendment

The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer entered into force on 1 January 2019, following ratification by 65 countries. UN Environment announced its entry into force and noted that it will help reduce the production and consumption of hydrofluorocarbons (HFCs), potent greenhouse gases (GHGs), and thus avoid global warming by up to 0.4°C this century.

The need for the Amendment emerged from the 1987 Montreal Protocol process, which controls ozone-depleting substances. With HFCs' use as an alternative to ozone-depleting substances in cooling equipment, their role in warming the atmosphere became a greater concern. In 2016, the Parties to the Montreal Protocol adopted the agreement on HFCs at the close of the 28th Meeting of the Parties (MOP 28) in Kigali, Rwanda.

Under the Amendment, all countries will gradually phase down HFCs by more than 80 per cent over the next 30 years and replace them with more environmentally friendly alternatives. A specified group of developed countries will begin the phase-down in 2019. Several developing countries will freeze HFC consumption levels in 2024, followed by additional countries in 2028. The Amendment also includes agreements on technologies to destroy HFCs, data-reporting requirements, and provisions for capacity building for developing countries.

Box 3: Synopsis of The Paris Agreement[92]

Synopsis of the Paris Agreement

At COP 21 in Paris, on 12 December 2015, Parties to the UNFCCC reached a landmark agreement to combat climate change and accelerate and intensify the actions and investments needed for a sustainable, low-carbon future. The Paris Agreement builds upon the Convention and, for the first time, united all signatory nations in a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so.

The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century to below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (Art. 2). Additionally, the agreement aims to increase the ability of countries to deal with the impacts of climate change, and to make finance flows consistent with a low-GHG-emission and climate-resilient pathway. To achieve these ambitious goals, appropriate mobilization and provision of financial resources, a new technology framework and enhanced capacity-building is to be put in place, thus supporting climate action by developing countries and the most vulnerable countries, in line with their own national objectives.

The Agreement also provides for an enhanced transparency framework for action and support. The Paris Agreement requires all Parties to put forward their best efforts through 'nationally determined contributions' (NDCs) and to strengthen these efforts in the years ahead. This includes requirements that all Parties report regularly on their emissions and their implementation efforts. There will also be a global stocktake every five years to assess the collective progress towards achieving the purpose of the agreement and to inform further individual actions by the Parties.

The Paris Agreement, adopted through Decision 1/CP.21, addresses crucial areas necessary to combat climate change. Some of the key aspects of the Agreement are set out below:

- ***Global peaking and 'climate neutrality'*** (Art. 4) – To achieve this temperature goal, Parties aim to reach global peaking of greenhouse gas emissions (GHGs) as soon as possible, recognizing that peaking will take longer for developing-country Parties, in order to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century.
- ***Mitigation*** (Art. 4) – The Paris Agreement establishes binding commitments by all Parties to prepare, communicate and maintain a nationally determined contribution (NDC) and to pursue domestic measures to achieve them. It also prescribes that Parties shall communicate their NDCs every five years and provide information necessary for clarity and transparency. To set a firm foundation for higher ambition, each successive NDC will represent a progression beyond the previous one and reflect the highest possible ambition.
- ***Sinks and reservoirs*** (Art.5) – The Paris Agreement also encourages Parties to conserve and enhance, as appropriate, sinks and reservoirs of GHGs as referred to in Article 4, paragraph 1(d) of the Convention, including forests.

- ***Voluntary cooperation/Market and non-market-based approaches*** (Art. 6) – The Paris Agreement recognizes the possibility of voluntary cooperation among Parties to allow for higher ambition and sets out principles – including environmental integrity, transparency and robust accounting – for any cooperation that involves internationally transferal of mitigation outcomes. It establishes a mechanism to contribute to the mitigation of GHG emissions and support sustainable development and defines a framework for non-market approaches to sustainable development.
- ***Adaptation*** (Art. 7) – The Paris Agreement establishes a global goal on adaptation – of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in the context of the temperature goal of the Agreement. It aims to significantly strengthen national adaptation efforts, including through support and international cooperation. It recognizes that adaptation is a global challenge faced by everyone. All Parties should engage in adaptation, including by formulating and implementing National Adaptation Plans, and should submit and periodically update an adaptation communication describing their priorities, needs, plans and actions. The adaptation efforts of developing countries should be recognized.
- ***Loss and damage*** (Art. 8) – The Paris Agreement recognizes the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow-onset events, and the role of sustainable development in reducing the risk of loss and damage. Parties are to enhance understanding, action and support, including through the Warsaw International Mechanism, on a cooperative and facilitative basis with respect to loss and damage associated with the adverse effects of climate change.
- ***Finance, technology and capacity-building support*** (Art. 9, 10 and 11) – The Paris Agreement reaffirms the obligations of developed countries to support the efforts of developing country Parties to build clean, climate-resilient futures, while for the first time encouraging voluntary contributions by other Parties. Provision of resources should also aim to achieve a balance between adaptation and mitigation. In addition to reporting on finance already provided, developed country Parties commit to submitting indicative information on future support every two years, including projected levels of public finance. The agreement also provides that the Financial Mechanism of the Convention, including the Green Climate Fund (GCF), shall serve the Agreement. International cooperation on climate-safe technology development and transfer and building capacity in the developing world are also strengthened.

  A technology framework is established under the Agreement and capacity-building activities will be strengthened through, inter alia, enhanced support for capacity building actions in developing country Parties and appropriate institutional arrangements. Climate change education, training as well as public awareness, participation and access to information (Art. 12) are also to be enhanced under the Agreement.
- ***Transparency*** (Art. 13), ***implementation and compliance*** (Art. 15) – The Paris Agreement relies on a robust transparency and accounting system to provide clarity on action and support by Parties, with flexibility for their differing capabilities of Parties. In addition to reporting information on mitigation, adaptation and support, the Agreement requires that the information submitted by each Party undergoes international technical expert review. The Agreement also includes a mechanism that will facilitate implementation and promote compliance in a non-adversarial and non-punitive manner and will report annually to the CMA.

- ***Global Stocktake*** (Art. 14) – A 'global stocktake', to take place in 2023 and every five years thereafter, will assess collective progress towards achieving the purpose of the Agreement in a comprehensive and facilitative manner. Its outcome will inform Parties in updating and enhancing their actions and support and enhancing international cooperation on climate action.

Sustainable Development Goal 13: 'Take urgent action to combat climate change and its impacts'[93] was developed to guide and ensure a comprehensive response to the many facets of climate change. The goal is accompanied by the following environment-related targets:[94]

Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

Target 13.2: Integrate climate change measures into national policies, strategies and planning (including urban planning).

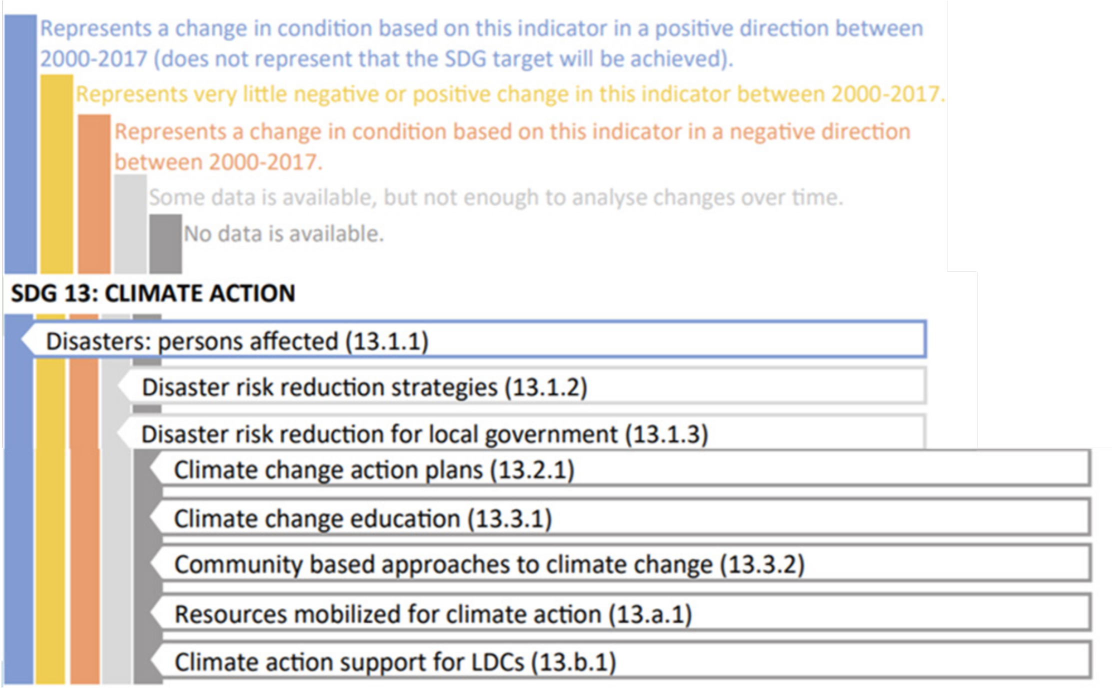
Target 13.3: Improve education, awareness raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.

Target 13.a: Implement the commitment undertaken by developed-country Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to a goal of mobilizing jointly USD 100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation, and fully operationalize the Green Climate Fund (GCF) through its capitalization as soon as possible.

Target 13.b: Promote mechanisms for raising capacity for effective climate change-related planning and management in Least Developed Countries and Small Island Developing States, including focusing on women, youth and local and marginalized communities.

As mentioned previously, global progress towards each of these targets is so far inconsistent, as summarized in Figure 6.

Figure 6: Global progress in achieving climate action targets [vi]



The remainder of this report will focus on the role and potential of frontier technologies in combatting the impacts of climate change to achieve SDG 13.

4. The role of frontier technologies in addressing climate change

Frontier technologies are new, cutting edge, innovative, and (often) disruptive technologies, including: artificial intelligence (AI), the Internet of Things (IoT), 5G, clean energy technology, digital twins, robotics, Space 2.0 technologies, and digitalization and Big Data.[95]

The World Economic and Social Survey 2018 published by the United Nations Department of Economic and Social Affairs (UN-DESA) concluded that new renewable energy technologies and efficient energy storage systems are 'already enhancing environmental sustainability' within certain regions.[96] Frontier technologies are enhancing the well-being of many people around the globe by allowing, for instance, greater access to medicine, improving communication and connectivity through the proliferation of mobile technologies, and making financial services accessible to millions in developing countries through innovative digital financial mechanisms.[97] These technologies can be key enablers of smartness, sustainability and environmental resilience – offering important opportunities to help assess, mitigate and adapt to climate change.

The UN, scientific community and academia have been leading global efforts to encourage the use of frontier technologies in tackling climate change. Leveraging these technologies to engineer new solutions to address climate change represents a significant opportunity to accelerate efforts to achieve SDG 13.

It is important to keep in mind that frontier technologies could also be seen as a double-edged sword that may bring unintended consequences to the detriment of the environment and societies. For instance, information communication technologies (ICTs) are one of the key enablers of frontier technologies that can drive innovation and climate actions. At the same time, the environmental aspect of ICTs is often being overlooked. From issues related to energy efficiency of ICT equipment to generating increasing amount of e-waste, without adopting a sustainable approach to the utilization of these technologies, their environmental impacts would offset the benefits that they may bring. To that end, International Telecommunication Union (ITU)'s Study Group 5 on "Environment, climate change and circular economy" has been working closely with policy makers, industry leaders, and the academia to develop international standards (also called ITU-T Recommendations) that support the sustainable use of ICTs. The group is responsible for developing international standards, guidelines and methodologies for evaluating the environmental impacts of ICT facilities and equipment, as well as aligning the environmental performance of the ICT sector to the SDGs. For example, one of these standards is Recommendation ITU-T L.1470 "GHG emissions trajectories for the ICT sector compatible with the UNFCCC Paris Agreement", and its associated Guidance which was developed together with GSMA, GESI and SBTi. The standard sets concrete guidelines for ICT industry to reduce GHG emissions by 45% from 2020 to 2030, aligned with science targets necessary to achieve the Paris Agreement. In order to fully realize the transformative potential of frontier technologies, ITU has also created the Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies (FG-AI4EE) to identify the standardization needs to develop a sustainable approach to AI and frontier technologies. The box below provides further information on this Focus Group.

Focus Group on Environmental Efficiency for Artificial Intelligence and other Emerging Technologies (FG-AI4EE)

In May 2019, the International Telecommunication Union (ITU)'s Study Group 5 on "Environment, climate change and circular economy" (SG5) took the initiative to create one of the first global platforms dedicated to studying the standardization needs for adopting a sustainable approach to frontier technologies. The group recognizes that artificial intelligence, 5G, blockchain, cloud computing, augmented and virtual realties, among other emerging technologies, play a key role in driving innovative solutions that would tackle some of the most pressing global challenges including climate change. Yet, the environmental aspect of developing and operating these technologies have been largely missing in the global discourse. This is particularly true in the case of blockchain as blockchain-related activities such as mining have been regarded as one of the most energy intensive activities in the world. This has posed significant adaptability and scalability challenges that are preventing blockchain from scaling up effectively and realizing its full potential to drive climate actions. Hence, this Focus Group provides an open platform for engaging in global dialogues related to the environmental performance of frontier technologies and to produce result-oriented deliverables that will provide guidance on how to operate these technologies in an environmentally conscious manner. Currently, this Focus Group has three distinct working groups. They are; Working Group 1 on "Requirements of AI and other Emerging Technologies to Ensure Environmental Efficient"; Working Group 2 on "Assessment and Measurement of the Environmental Efficiency of AI and Emerging Technologies"; and Working Group 3 on "Implementation Guidelines of AI and Emerging Technologies for Environmental Efficiency". The work of this Focus Group is open to all interested stakeholders and is expected to contribute significant to the progress towards the SDGs.

The successful applications of eight specific frontier technologies within the context of climate change & response and environmental protection will be explored in the following sections. Each section presents an overview of a frontier technology and some specific impacts of climate change that it can be used to address, followed by a brief city or urban agglomeration case study that highlights the technology in practice and concludes with key findings or takeaways from that example.

a. Artificial Intelligence (AI) to help reduce air pollution, reduce hydrological risk, and environmentally consciously manage e-waste

An International Telecommunication Union (ITU) flagship publication series, the ITU News Magazine, devoted its January 2018 edition to artificial intelligence (AI) systems that can solve complex problems autonomously. In this edition, titled 'Artificial intelligence for global good', ITU identified several applications of AI that address climate change, including those related to topics such as biodiversity and conservation, ocean health, water security, clean air and disaster risk.[98] Many of these applications are relevant and applicable at the city or urban agglomeration/regional level.

ITU also hosts the annual AI for Good Global Summit[99], which is 'the leading United Nations Platform for dialogue on beneficial AI,' according to Dr Chaesub Lee, Director of the ITU Telecommunication Standardization Bureau (ITU-T). Box 4 provides highlights of the summit series.

Box 4: The AI for Good Global Summit Series[100]

The AI for Good Global Summit

The AI for Good Global Summit, organized in partnership with the XPRIZE Foundation, the Association for Computing Machinery (ACM) and more than 26 UN agencies, was the first event to initiate global dialogue on AI's potential to act as a force for good. The 2017 summit sparked the first-ever inclusive global dialogue on beneficial AI, which was followed by 2018's action-oriented summit that focused on impactful artificial intelligence solutions able to yield long-term benefits by identifying applications of AI capable of improving the quality and sustainability of life on Earth. The summit also formulated supporting strategies to ensure trusted, safe and inclusive development of AI technologies and equitable access to their benefits. The 2019 summit took place from 28–31 May, 2019 in Geneva, Switzerland with the following goals as seen in Figure 7.

Figure 7: Goals of the 2019 AI for Good Global Summit [vii]

AI provides unprecedented opportunities to eradicate hunger, end poverty and reverse the degradation of our natural environment. The *AI for Good* series aims to inspire innovation by highlighting the extraordinary possibilities soon to be within reach thanks to AI, and to ensure that AI accelerates progress towards the United Nations Sustainable Development Goals (SDGs). The United Nations could convene all AI stakeholders in an impartial debate. Only with strong dialogue and partnership among governments, international organizations, the private sector and academia will AI fulfill its great potential to act as a force for good.

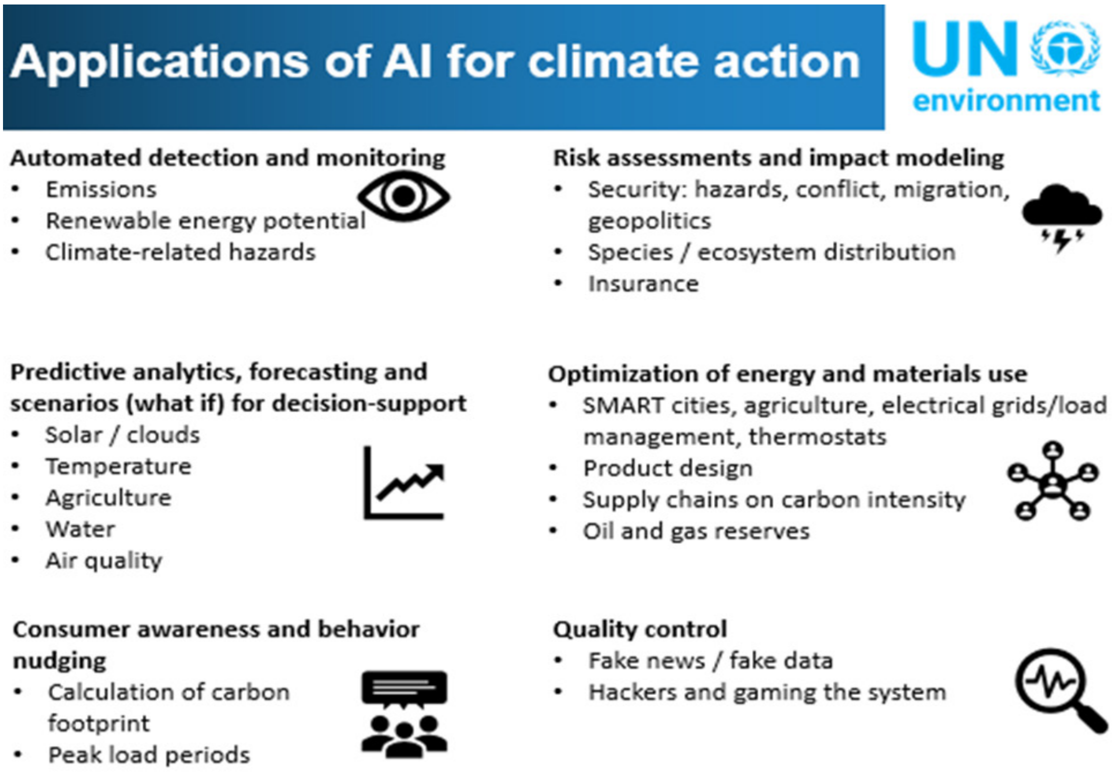
Discussion on the UN platform will build a common understanding of the capabilities of emerging AI technologies. This will create cohesion in policy approaches to AI and encourage the international community to rally around applications of AI with the potential to address the greatest challenges facing humanity.

Artificial intelligence (AI) is arguably one of the most important and rapidly developing new technologies to emerge in past decades. While the world is only just beginning to grasp all its possibilities, AI is already a big part of people's everyday lives and can also help address some of the world's most pressing challenges, including that of climate change.

AI and machine-learning algorithms will increasingly help to mitigate and manage climate change-related risk in the future, including catastrophic weather events such as tornadoes, hurricanes and thunderstorms, by improving the accuracy of global climate models and climate forecasts. Clouds are the single biggest source of uncertainty in global climate models. New studies suggest that AI and artificial neural networks can successfully resolve more complicated and smaller-scale atmospheric processes like the ones involved in convective cloud formation and, thus, reduce the uncertainties inherent to current climate models.[101]

UN Environment has identified six major categories where artificial intelligence can contribute to climate action (as seen in Figure 8).

Figure 8: Applications of AI for climate action [viii]



Reducing air pollution through AI

One of the foremost issues facing many cities, irrespective of size, is traffic congestion.[102] There is a direct correlation between traffic volumes and average levels of air pollution, with the prevalence of motor vehicles being a major contributor of air pollution worldwide. The negative effect of traffic on an urban region's air quality is further exacerbated by the fact that slower moving traffic, i.e. congested or jammed traffic, has been observed to emit more pollution compared to free-flowing traffic that moves between 45 and 65 miles per hour (mph).[103] Although the two are different, UN Environment has called air pollution and climate change two sides of the same coin.[104]

The World Health Organization (WHO) is the custodial agency for three air pollution-related SDG indicators: 3.9.1: 'Mortality from air pollution', 7.1.2: 'Access to clean fuels and technologies', and 11.6.2: 'Air quality in cities'.[105] The WHO defines the major components of air pollution and sets guidelines for acceptable levels. Meeting these levels is imperative in the fight against climate change and for the overall health of a region's residents.

Even so, close to 92 per cent of the world's population live in areas that fail to meet WHO's air quality guidelines.[106, 107, 108] As seen in Figure 9, the WHO has also reported that around 7 million people die annually from exposure to air pollution, which equates to one death out of every eight globally.[109]

Figure 9: The WHO's infographic on annual global deaths caused by air pollution [ix]

Furthermore, air pollution is not an isolated local problem. As transboundary sources are often major contributors to urban pollution, many cities will be unable to meet WHO guideline levels for air pollutants through local action alone. Even national and regional action may not be enough in some cases. Transboundary cooperation such as that under the UNECE Convention on Long-range Transboundary Air Pollution, is, therefore, key.[110]

To improve air quality, UNECE Member States must continue to work to reduce air pollution in the region. The Convention has been extended by eight protocols that identify specific measures to be taken by Parties to cut their emissions. The Convention provides access to emission measurement and modelling data, and information on the effects of air pollution on ecosystems, health, crops and materials. In doing so, it has substantially contributed to the development of international environmental law and has created the essential framework for controlling and reducing the damage to human health and the environment caused by transboundary air pollution.[111]

As explained previously, carbon dioxide (CO_2) contributes to the greenhouse effect by insulating more heat from the sun. Ozone (O_3) is a major factor in asthma morbidity and mortality, while nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) play a role in asthma, bronchial symptoms, lung inflammation and reduced lung function. Sulfur dioxide also leads to acid rain.[112] Methane gas also retains heat very well – it is 34 times as powerful a greenhouse-gas warming blanket as carbon dioxide over the timescale of a century, and when judged on the timescale of two decades, it is actually 86 times as powerful.[113] Small particulate matter ($PM_{2.5}$) is another pollutant that affects people by increasing mortality and morbidity (both daily and over decades). The WHO has estimated that emissions of $PM_{2.5}$ from idling car exhaust and other sources kill more than 3 million people annually worldwide.[114]

An integrated approach to climate change and air pollution is needed, therefore, to reduce the risks of applying climate change measures with significant negative impacts on air quality.[115]

Recent studies have aimed to quantify the costs associated with negative health outcomes resulting directly from traffic congestion in urban areas. A 2010 Harvard University-led paper that studied the effects of small particulate matter ($PM_{2.5}$) concluded: 'The public health impacts of congestion may be significant enough in magnitude, at least in some urban areas, to be considered in future evaluations of the benefits of policies to mitigate congestion.'[116]

Another study conducted jointly by the University of Texas and University of Michigan in 2013 focused on the effects of nitrogen dioxide on public health. It found that while NO_2 exposures and associated health risks were not proportional to traffic volumes, traffic congestion and additional traffic volumes can significantly increase exposures and risks.[117]

The Global Burden of Diseases Study 2015, which was conducted over a 25-year period, echoed these concerns by concluding: 'Ambient air pollution contributed substantially to the global burden of disease in 2015, which increased over the past 25 years, due to the population ageing, changes in non-communicable disease (NCD) rates, and increasing air pollution in low-income and middle-income countries (LMICs).'[118]

There is significant potential to realize substantial greenhouse gas and air pollution reductions by utilizing AI for route and traffic optimization (to reduce idling times, to introduce local traffic restrictions or to enable better active traffic flows), for facilitation of autonomous and ride-sharing services (to decrease the overall number of vehicles on roads) and for increasing driver compliance with environmental regulations, as seen in the case of Moscow, Russian Federation, in Box 5, below.

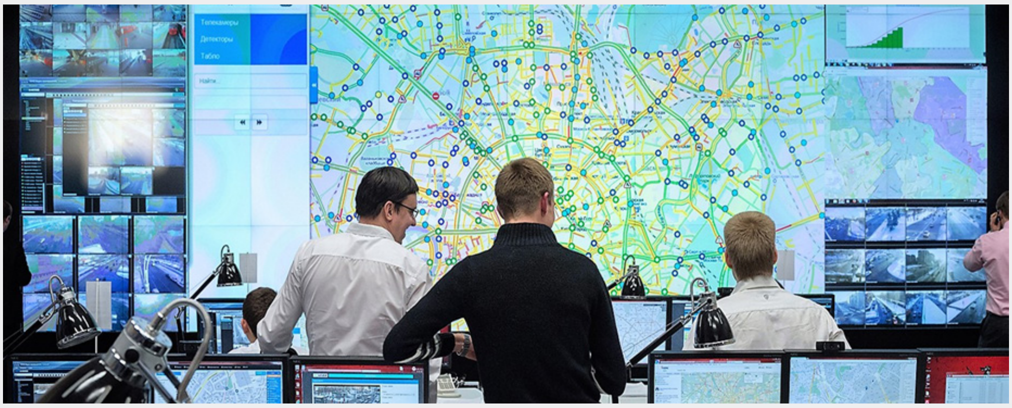
Box 5: Moscow's use of AI for smart traffic management[119, 120, 121, 122]

Moscow was recently the subject of a comprehensive case study, in which the rapid evolution and success of its smart and sustainable city journey were mapped in detail. Its increasing use of AI-powered intelligent traffic control systems is an important element in its response to the challenge of traffic congestion. Moscow's Intelligent Transport System (ITS) was developed as a joint project between the federal government and city officials looking to reduce the city's infamous traffic jams. It includes more than 2 000 smart traffic lights, 3 500 TrafiCam x-stream vehicle presence sensors and 2 000 CCTV cameras that feed into FLIR Systems that monitor the city's traffic.

Moscow's smart intersections are essentially controlled in real time using AI-powered technology. Four TrafiCam x-stream sensor units (i.e. intelligent, all-in-one cameras) per intersection detect waiting and approaching vehicles in order to alter and optimize traffic signal timings. By doing this, FLIR's TrafiCam x-stream sensors help reduce waiting times at traffic lights. Based on the information from the TrafiCam x-stream sensors, the ITS can alter entire traffic signal cycles in real time to respond to changing traffic conditions.

Data from these smart devices are also transferred to the city's Traffic Management Centre situation room (as seen in Figure 10), where they are analysed and used to develop targeted traffic management and mobility strategies. Real-time data is also automatically sent to electronic displays on Moscow's highways. These then show commuters real-time information about highway traffic conditions, weather or pollution conditions, and estimated travel times – thus empowering citizens with an improved traffic experience in the busy megacity.

Figure 10: Moscow's Traffic Management Centre [x]



As a result of its AI and other complementary, ICT-based traffic mitigation efforts, drivers in Moscow now spend less time idling at traffic lights or driving around to find a parking spot. According to the Moscow City Government, average traffic speed within the city centre has increased by 10–15 per cent from a baseline of 19 kph (11.8 mph). In addition, implementation of the ITS has reduced search times for available parking spaces by 65 per cent, on average.

The resulting improvement in traffic flow around the typically busy Belorussky Railway Station area is seen in Figure 11.

Figure 11: Improved flow of traffic in the Tverskaya Zastava Square - Belorussky Railway Station [xi]

Moscow is endeavouring to reduce traffic volumes even further by making alternative travel and commuting methods more attractive and accessible. One example is Moscow's encouragement of its citizens to take advantage of car-sharing programmes, which utilize AI-based algorithms to map shared routes, by offering shared vehicles and free or low-cost parking at various locations around the city, as well as by incentivizing the development of smart parking applications.

Recognizing that public transport is one of the most efficient ways to relieve traffic congestion, Moscow has also invested significantly in improving the city's public transport system. As a result, Moscow's public transport system has become one of the world's largest and most efficient. Its Metro system is now ranked number 1 in the Western Hemisphere in terms of passenger volume (2.5 billion passengers), and number 1 on minimal headways maintained at all lines during all peak hours (1.5 minutes).

Managing this high volume of passengers is possible only with the implementation of ICT-based tracking and AI-based signaling controls. Furthermore, Moscow has plans to launch driverless trains, powered by AI, on the Koltsevaya metro line within the next five years.

Self-driving cars could also play a role in improving future traffic flows in Moscow by automatically following the most optimized routes, recalculating routes in real time, based on updated traffic information, and eliminating errors of human decision making through reliance on AI. Moscow recently hosted the world's best engineering students at an event labelled 'the world's first hackathon for driverless cars'. And it is leveraging the relatively tougher conditions that exist for use of autonomous cars within the city into solutions that can more creatively drive self-driving cars forward.

Moscow's phased introduction and implementation of AI components within its 'ITS' offer an example for other cities looking to integrate advanced frontier technologies such as AI into their existing or planned traffic and transport management systems. Another key takeaway from Moscow's experience has been the pivotal role that public and private partnerships have played in the deployment of its smart technologies. Several uses of disruptive technologies are being developed by Moscow's private sector and are being incentivized by the city's government. There exists, therefore, a tremendous opportunity to accelerate the refinement and proliferation of AI-based technologies through partnerships and projects among technologists, scientists, industry and governments.

Quantum computing and AI

Such acceleration will also be achieved partly through further development of complementary frontier technologies such as quantum computing.[123] As quantum computing becomes more mainstream over the next few decades, it is expected that the enablement and use of AI-based systems will escalate in conjunction. Quantum computing promises a future of unprecedented computing speed.

UNESCO's Abdus Salam International Centre for Theoretical Physics (ICTP) inaugurated the Trieste Institute for Theoretical Quantum Technologies (TQT) in March 2019. The institute provides a hub for the study of the future of AI on quantum devices, offering, in parallel, a convenient link to private actors such as Google and IBM. The ICTP provides hundreds of scientists from developing countries with advanced training and research opportunities each year.[124]

Natural risk reduction using AI

Another burgeoning application of AI is in natural disaster risk reduction. While many ideas and prototypes have already been tested, so far, they have tended to focus on the response and rescue phase. For example, Sendai City in Japan has tested a prototype with private companies for a tsunami alert using AI, whereby the AI system can automatically launch a drone, sending an alert through mobile phones and radios and using facial recognition software to identify victims.[125] The automatic analysis of social media tweets by means of ML algorithms and advanced semantic technique can also make it possible to pinpoint ongoing floods and provide real-time data to enhance situational awareness; such information can be useful to citizens and to first responders faced with natural hazard.

It is expected that future applications of AI will focus not only on disaster response but also on the prevention phase. In the field of earthquake risk reduction, for example, there are sensors available that can provide about 10 seconds' advance warning of an impending earthquake. However, seismology is not yet capable of predicting an earthquake hours, days or weeks in advance.[126]

Another example is the number of new modelling systems that are being tested for their ability to forecast drought events with precision: Artificial Neural Networks (ANN), Adaptive Neural-based Fuzzy Inference Systems (ANFIS), Genetic Programming (GP) and Support Vector Machines. The current drawback in using AI for drought management, however, is the lack of 'Big Data" necessary to produce models that can provide accurate forecasting. The G-Wadi Geoserver aims to tackle this problem (as seen in Box 6).

Box 6: UNESCO: Using AI to reduce hydrological risk[127, 128]

The UNESCO G-WADI Geoserver application (Water and Development Information for Arid Lands – a Global Network) is using an artificial neural network (ANN) to estimate real-time precipitation worldwide. This product is called the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks – Cloud Classification System (G-WADI PERSIANN-CCS). The G-WADI PERSIANN-CCS GeoServer has been under development since 2005, through a close working relationship between the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine, and UNESCO's International Hydrological Programme. The core algorithm of this system, supported by NASA and NOAA, extracts local and regional cloud features (coldness, geometric structure and texture) from the international constellation of GEO satellites capturing infrared imagery and estimates of rainfall every 30 minutes. Information from LEO satellites is then used to adjust the initial precipitation estimation from the ANN algorithm.

The G-WADI PERSIANN-CCS geoserver is also being used to inform emergency planning and management of hydrological risks, such as floods, droughts and other extreme weather events. For example, the Namibian Drought Hydrological Services uses it to prepare daily bulletins with up-to-date information on flood and drought conditions for local communities. The geoserver is also being widely used to track storms globally, as in the case of the Haiyan Super Typhoon.

The G-WADI PERSIANN-CCS system is now available through the iRain mobile application, devoted to facilitating people's involvement in collecting local data for global precipitation monitoring. iRain allows users to visualize real-time global satellite precipitation observations, track extreme precipitation events worldwide and report local rainfall information using a crowd-sourcing functionality to supplement the data. This provides an opportunity to improve remotely sensed estimations of precipitation. Moreover, the use of a crowdsourcing functionality in iRain to supplement the data opens opportunities for engaging citizen scientists.

Waste optimization using AI

Waste prevention, recycling and resource recovery are also areas in which the application of AI within the waste sector can significantly contribute to climate change mitigation. Reuse and repair are the first waste management options that extend the life of products, improving material efficiency and reducing GHG emissions.[129] This can be illustrated via the example of one of the fastest growing hazardous waste streams: Waste Electrical and Electronic Equipment (WEEE), as detailed in Box 7.

Box 7: Using AI to manage waste and e-waste [130] [131] [132] [133] [134] [135]

ITU, UNU and ISWA estimated that in 2050, the world will generate about 50 Mton of WEEE. In the same study, it was estimated that currently, only 20 per cent of the WEEE produced is being collected formally and 80 per cent is either recycled informally or dumped, generating a loss of value and a negative impact on climate change. The concept of embodied energy helps to measure the impact of waste management on climate change. To understand this concept, it is necessary to examine, for example, how climate benefits related to e-waste recycling come from looking at the whole life cycle of electrical and electronic goods. For example, 'It takes 539 lbs (245 kg) of fossil fuel, 48 lbs (22 kg) of chemicals, and 1.5 tons (1 524 kg) of water to manufacture one computer and monitor.'

An important part of the energy consumption in the life cycle of electrical and electronic goods is in the extraction and refinement of raw materials and the production phase. The embodied energy is the sum of energy consumed by each of the processes associated with extraction and production, from the mining and processing of natural resources to manufacturing, transport and product delivery. It is the 'upstream' or 'cradle-to-gate' component of the life cycle. Furthermore, advanced digital technology is energy-hungry in the production phase: a handful of microchips can have as much embodied energy as a car. A study from Norway (2008) shows that the end-of-life carbon footprint of all e-waste is small, although its share is expected to increase as e-waste volume increases. The production and use phases are where most emissions occur.

E-waste that is sent straight to landfill – or is hoarded and unused – loses its embodied energy. It is important to remember that e-waste is a resource that continues to have value throughout its life cycle. Recycling has positive climate impacts not only for the materials that are recovered, but also for saving the energy that was used to make them. (E-waste challenge MOOC, 2016)

Automating the processes of waste sorting and disposal, by switching to AI for smart recycling and waste management, is expected to bring in better disposal methods to recycle sustainably. In Finland, for example, AI was employed for smart recycling by managing waste using a robotic waste sorter. Combining computer vision, ML and AI, the robots ran synchronized trials to sort and pick recycled materials from moving conveyor belts. Since then, leveraging technology in the field of waste management has come a long way, refining itself over the years.

The Intelligent Trash Can, which is equipped with AI programs and Internet of Things (IoT)-enabled sensors, is another revolutionary concept in the waste management sector. The sensors on these trash cans measure the waste stream levels of the waste thrown inside them and send these data, via intermediate servers, to the main disposal system for processing. The system categorizes the data into the type of waste, the quantity of each type of waste, and the respective waste disposal method. This entire system can also refine itself over time by studying historical records to improve its efficiency.

AI-powered smart recycling equipment is also being utilized in smart bins, e.g. in the city of Dubai. These smart bins can think for themselves while sorting and sending waste (trash). All a person has to do is put the waste in the bin. The bin then uses its sensors to study and compare the waste recovered with previous waste records, and then decides on what needs to be done with the waste. Depending on the decision, the bin itself sends the waste to an appropriate disposal system, be it a dumping ground or a recycling factory.

AI is also being used to optimize WEEE mobile collection for take-back schemes in Poland. Mobile, on-demand collection schemes require that waste is taken back from household residents, at their request. This type of waste equipment collection is comfortable for residents as they can indicate day and time windows for the take-back. Collection companies are interested in lowering operational costs required for the service. This lowering includes selecting enough vehicles and employees, and then minimizing the routes' length in order to achieve savings in fuel consumption, and the lowering of emissions.

The move toward responsible and environmentally conscious handling of waste and hazardous materials has been a special focus of the Basel Convention. Box 8 below provides some detail on the Convention's activities in this regard.

Box 8: The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal[136]

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal is the most comprehensive global environmental treaty on hazardous and other wastes. It has 187 member countries (Parties) as of July 2019 and aims to protect human health and the environment against the adverse effects resulting from the generation, management, transboundary movements and disposal of hazardous and other wastes.

Firstly, the Basel Convention regulates the transboundary movements of hazardous and other wastes applying the 'Prior Informed Consent' procedure (i.e. shipments made without consent are illegal). Shipments to and from non-Parties are illegal unless there is a special agreement. Each Party is required to introduce appropriate national or domestic legislation to prevent and punish illegal traffic in hazardous and other wastes, thereby, making illegal traffic criminal.

Secondly, the Convention obliges its Parties to ensure that hazardous and other wastes are managed and disposed of in an environmentally sound manner (ESM). To this end, Parties are expected to minimize the quantities that are moved across borders, to treat and dispose of waste as close as possible to their place of generation and to prevent or minimize the generation of waste at source. Strict controls must be applied from the moment of generation of a hazardous waste to its storage, transport, treatment, reuse, recycling, recovery and final disposal.

Some waste streams that the Basel Convention is focusing on are:

- Electronic and electrical waste ('e-waste or WEEE') such as mobile phones and computers
- Mercury and asbestos wastes
- Plastic wastes
- Illegal dumping of hazardous and other wastes

The limitations of AI

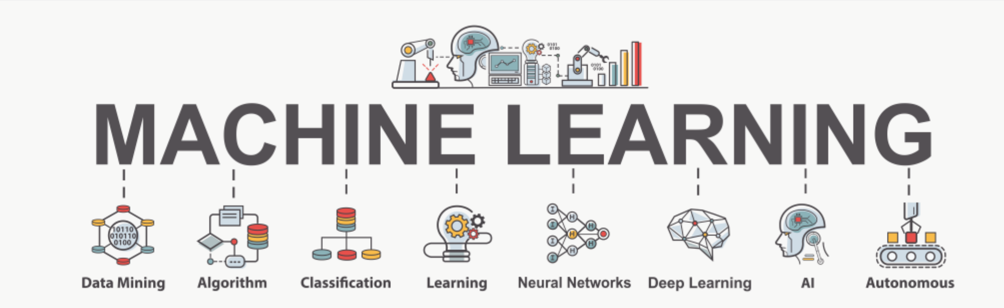
While AI offers vast potential in the fight against climate change, as per the above examples, it must also be noted that there are certain limitations and downsides pertaining to its carbon footprint. These are explored in Box 9.

Box 9: The carbon footprint of AI and machine learning (ML)[137, 138, 139, 140]

The carbon cost of AI and ML

Artificial Intelligence (AI) and machine learning (ML), like most technology, have the potential to help in the fight against climate change. They can make systems more efficient (e.g. prevent electricity loss during transmission), enable remote sensing and automatic monitoring (e.g. pinpoint deforestation, gather data on buildings, and track personal energy use), provide fast approximations to time-intensive simulations (e.g. climate models and energy scheduling models), and has the potential to lead to the development of interpretable or causal models (e.g. for understanding weather patterns, informing policy makers, and planning for disasters). Figure 12 shows some of the applications of ML.

Figure 12: Applications of machine learning [xii]



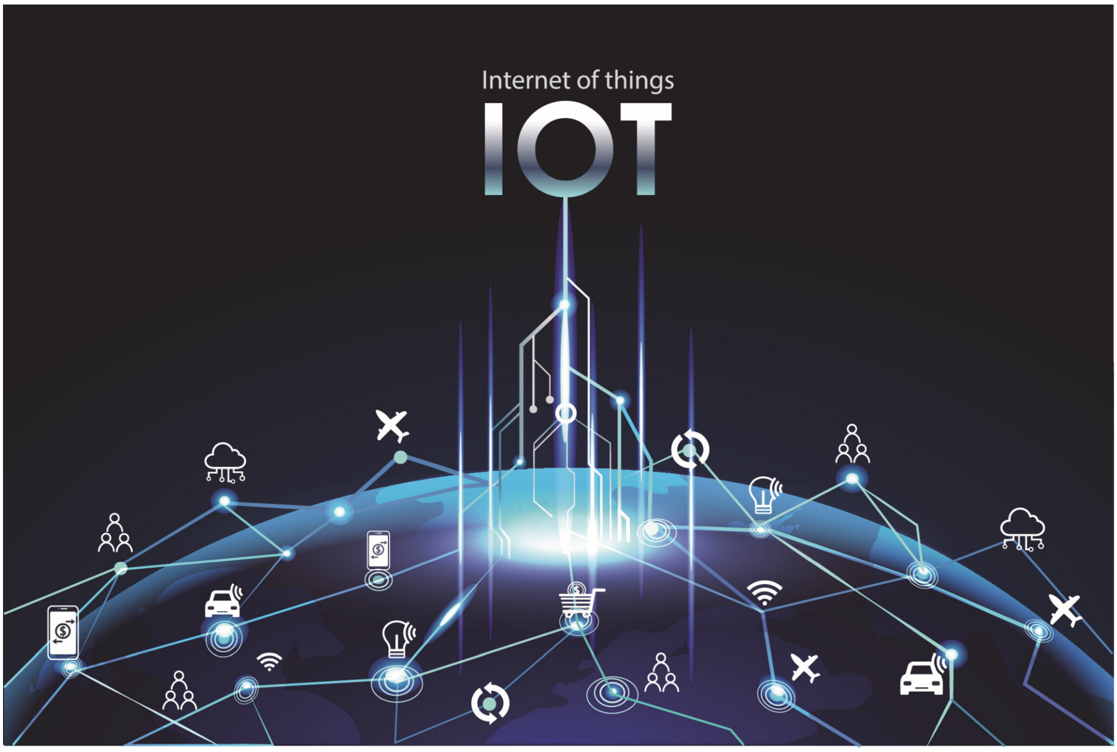
It has been estimated, for instance, that 'using AI for environmental applications could boost the global economy by up to USD 5.2 trillion in 2030, a 4.4 per cent increase on the business-as-usual scenario, while reducing GHG emissions worldwide by 4 per cent, equivalent to the 2030 annual emissions of Australia, Canada and Japan combined.'

The efficacy of ML and AI will, however, rely on bringing together several factors, including ensuring their effective integration into other technologies and – because they require large amounts of computing power – decarbonization of the energy system to ensure that AI and ML can fulfil their sustainability potential. This is imperative as new studies are showing that typical current ML processes can 'emit more than 626 000 pounds of carbon dioxide equivalent (CO_2e) – nearly five times the lifetime emissions of the average American car (and this includes manufacture of the car itself)'.

The significance of this finding is immense, and until the issue of efficiency can be addressed, AI research within academia may even be impacted due to lack of necessary computational resources.

b. Internet of Things (IoT) for smart energy infrastructure management to help reduce carbon dioxide and greenhouse gas emissions

ITU has defined the Internet of Things (IoT) as 'a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies' (Recommendation ITU-T Y.2060/4000). The concept of IoT encompasses M2M (i.e. communication directly between machines and devices), M2P (i.e. communication directly between machines and people), as well as other technologies related to ambient intelligence and smart environments. Big Data is also an organic byproduct of IoT due to the ability of machines to generate, process and analyse large volumes of data at high speeds.[141]



The Broadband Commission for Sustainable Development was established by UNESCO and ITU in 2010. Its recent report on 'Harnessing the Internet of Things for Global Development' highlighted two main factors[142] contributing to the rapid mobilization of IoT systems:

1) the exponential increase in IoT-enabled devices; and
2) the decrease in the cost of computing.

The corresponding rise in wireless technologies is also considered a symbiotic factor in the rapid and evolving proliferation of IoT as a distinct frontier technology. It has been reported that the IoT industry could add USD 14 trillion in global economic value by 2030,[143] and that 84 per cent of IoT deployment has the potential to successfully address the SDGs.[144] The cost affordability of IoT-enabled devices and IoT-based systems has particularly benefitted developing countries over recent years by opening up new opportunities.

IoT can help scientists from developing countries to bridge the so-called scientific divide. If we define the digital divide as being the gap between those with access to digital technologies and those without, the scientific divide can be defined as the gap between those with access to scientific data and those without. Today, scientific data is collected mainly using a limited range of expensive equipment that uses wired infrastructure, particularly when it comes to environmental applications. Data collection has been a costly, difficult task restricted to a relatively small number of fixed, sparsely distributed locations and maintained by organizations with large budgets. As a result, the data gathered are often incomplete, especially in developing countries and remote areas. IoT could radically change the situation; this low-cost, low-power technology does not require any pre-existing infrastructure to operate and can be deployed in most remote areas. The vast range of sensors that can be connected to the nodes support many different scientific applications.

IoT's use in optimizing services and systems to increase accountability toward and combatting climate change is one of the ways that it is being deployed by cities at the forefront of smartness and sustainability. Dubai, UAE, is an example, as seen in the Box 10.

Box 10: Dubai's use of IoT for smart management of its electricity grid [145, 146, 147, 148, 149]

Dubai is another city with a smart sustainable city initiative that was recently studied in detail by ITU via a case study. The high-tech global centre has increasingly leveraged IoT in recent years as part of its evolving digital ecosystem, which now includes the city's integrated energy infrastructure and services. IoT initiatives are expected to generate close to USD 14 billion in Dubai by 2021.

Towards the end of 2017, Dubai announced that Silver Spring Networks, the US-based global provider of smart grid products that it had contracted with for implementing its city-wide IoT network, had successfully implemented a multi-application IPv6 network canopy at the Dubai Electricity and Water Authority (DEWA), which is the Emirate of Dubai's integrated public services infrastructure company for water and electricity. DEWA leverages ICTs routinely as part of its mission to improve service provision and engage Dubai's citizens to save energy and water.

The IoT technology that DEWA acquired from Silver Spring is the latest Gen5 technology that boasts high performance, reliability, security and, most importantly, scalability. The technology has been integrated backward into more than 200 000 existing smart meter devices in Dubai and will be functional for the remaining devices that will be installed by 2020, covering the whole Emirate of Dubai and replacing all mechanical and electromechanical meters. This will connect all electricity customers to the new IoT canopy under the city's Smart Meters and Grids initiative, which is part of the U.A.E. Vision 2021 and the Smart Dubai Plan 2021.

Figure 13: Dubai and U.A.E. water and electricity consumption facts [xiii]

The use of IoT to promote sustainability, increase resilience and reduce its impact on the climate is timely for Dubai given the region's increasing consumption of water and electricity (as shown in Figure 13 from DEWA's promotional material on electricity and water conservation) and the city's commitment to make progress toward achieving the aims of the Dubai Clean Energy Strategy 2050.

Furthermore, the IoT network deployment for its electrical grid is accompanied by the city's latest conservation initiative, Green Dubai, which according to HE Saeed Mohammed Al Tayer, Managing Director and Chief Executive Officer of DEWA, 'supports the Demand Side Management Strategy to reduce electricity and water use by 30% by 2030, generating clean solar energy, and encouraging the use of eco-friendly electric vehicles.'

The tri-fold aim of the initiative is seen in Figure 14.

Figure 14: Green Dubai [xiv]

Infrastructure modernization efforts overall have been a key priority for DEWA in recent years. The ITU case study found that, among its working relationships, DEWA 'works with U.A.E.'s Supreme Council on Energy (DSCE) to define policies and measurement frameworks for energy, GHG emissions and climate change targets in the country. Dubai's energy integration and carbon reduction policies are designed to drive energy efficiency across its transportation, building, energy and water sectors'.

The case study also reported that 'DEWA's infrastructure supplies buildings, households, industries and the service sector. The Dubai Carbon Abatement Strategy 2021 has specific greenhouse gas reduction targets for each sub-sector.

For example, power and savings in the built-up environment contribute to the overall carbon emission targets for the energy and water sector through demand-side management programmes. These targets then contribute to Dubai's yearly city targets. Another example is the reduction realized through operational efficiency programmes in power and other plants. Many of these improvements are the result of enhancing controls and deploying smarter and more efficient infrastructure within these plants.'

Furthermore, Dubai's experience shows that its IoT initiatives in this area often intersect with its other smart sustainable city initiatives. The progressive stage of its IoT deployment, implementation and adoption has made it easy for the city to roll up all IoT-related initiatives (existing and planned) into a dedicated Dubai IoT Strategy. Having a distinct IoT-related strategy will further ensure that IoT technologies are fully leveraged and utilized. The likelihood of this is evident in the IoT strategic plan that is being implemented in four phases until this year, 2020. Phase one saw government departments working to implement IoT policies, which are being standardized in the second phase. The third, or 'optimization' phase, will see government entities fully implement the overall IoT strategy in order to realize returns in six 'strategic domains' (i.e. functions): governance, management, acceleration, deployment, monetization and security.

Such innovative use of technologies to curb global warming is important because anthropogenic emissions of CO_2 and other greenhouse gases, as contributed to by the global electric power sector, are well-known drivers of climate change. Global energy demand grew at its fastest pace in the last decade, increasing CO_2 emissions to a record high, according to the International Energy Agency (IEA)'s latest 'Global Energy & CO_2 Status Report'[150]. To achieve the UNFCCC's goal of regulating the average global temperature increase to below 2°C degrees, and as close as possible to 1.5°C above pre-industrial levels, each city must evaluate and modernize its energy, water, transport, industry, agriculture and other systems to ensure that cumulative net emissions do not surpass one trillion tonnes of cumulative carbon.[151] Even so, with today's greenhouse gas levels being the highest in 3 million years and levels of carbon in the atmosphere being the highest in 12 million years, even if current Paris Agreement pledges are kept, there is risk that global average temperatures in the year 2100 may still end up being at least 3°C above pre-industrial levels, which is well above the targets to avoid the worst impacts of climate change.[152]

In taking a planned, integrative approach to reducing its carbon and greenhouse gas emissions, Dubai has ensured that it is making tangible progress toward its city and national carbon targets – and that it is also in a position to evaluate its progress against any other targets stipulated within the Paris Agreement, Sustainable Development Goal (SDG) 13 and the Connect 2020 Agenda. The transition to a fully energy-efficient economy is an immediate priority for all cities but will take time. This transition can entail fundamental changes in a city's economy structure and in its technical infrastructure, as well as changes in the regulatory framework, in the mobilization and coordination of all federal and regional executive authorities, in the consumption structure, and in behavioural stereotypes.[153]

c. 5G for smart water supply management to help reduce water loss and inefficiencies

5G technology refers to the fifth generation of cellular networking technology that is expected to offer faster speeds, less latency and more coverage, in addition to longer battery life, larger data transfer capabilities, greater potential for cloud processing and improved overall reliability. While existing 4G networks typically allow for 1 000 devices to be connected per square kilometer (km^2), 5G networks and technologies are expected to connect some one million devices per km^2. 5G devices will include not only smartphones, but various vehicles, appliances, and other technologies that are all part of the emerging Internet of Things (IoT).[154, 155, 156]

5G technology is expected to be more directional and efficient than current technologies, resulting in less energy and power being wasted. Preliminary findings suggest that large-scale 5G adoption may help cities save up to 70 per cent in overall energy usage for networks in areas of public health, safety, transit, and utilities management.[157] For example, 5G can enable the adoption of more driverless cars, seamlessly operate public cameras, and provide high connectivity speeds to magnetometers that track traffic flows and volumes in real-time. Water availability, air quality, and energy efficiency in a city can all be improved by a network of 5G-enabled sensors and corresponding computers analysing data in real time. Positive outcomes and cost savings can be realized for overall public health and environmental conservation by reducing waste using 5G technologies.[158]

This section will focus on water availability, efficiency and conservation as potentially facilitated by 5G technologies. Continuing waste of water and diminishing freshwater supplies are complex yet urgent issues within the context of climate change. UN-Water has summarized the key relationship between climate change trends and water security and potability, as follows: 'Water is the primary medium through which we will feel the effects of climate change. Water availability is becoming less predictable in many places, and increased incidences of flooding threaten to destroy water points and sanitation facilities and contaminate water sources. In some regions, droughts are exacerbating water scarcity and thereby negatively impacting people's health and productivity. Ensuring that everyone has access to sustainable water and sanitation services is a critical climate change response strategy for the years ahead.[159]

The Environmental Protection Agency (EPA) estimates that in the United States (U.S.) alone, water leaks within households account for 1 trillion gallons (approx. 3.8 trillion litres) of usable water lost annually, enough to fill 1.5 million Olympic-sized swimming pools.[160] This figure is especially stark when viewed in conjunction with the intensive water demand of the agricultural activities in the US, which account for over 80 per cent of the Nation's consumptive water use[161] – a level that is fairly typical for the agricultural and livestock farming sectors all over the world. The demand for more power to fuel economic growth also necessitates harnessing more water for hydropower dams and nuclear plants. Combined with the constraints on water supplies due to unpredictable weather events, water shortages have already become a reality in several cities around the world (including in recent years, water crises in Cape Town, South Africa, and New Delhi, India). The ramifications of water crisis patterns are far-reaching as water shortage affects not only the agricultural output and food security in the areas affected, but also leads to rising conflict and the suspension of vital services (such as medical surgeries, as seen during New Delhi's period of water crisis a few years ago).[162]

Moreover, only 3 per cent of all water worldwide is actual freshwater, of which 30 per cent lies underground as groundwater. [163, 164] A 2015 study at the University of Victoria in B.C., Canada, found that while groundwater (in aquifers and wells that millions of people rely on globally) is usually considered a renewable resource due to its three times larger volume than other fresh water contained in the Earth's lakes and rivers, in reality, groundwater is largely non-renewable due to its slow rate of replenishment and renewal, which is estimated to be only 6 per cent within a 50-year span.[165] Therefore, as pollution and climate change affect the global water cycle, the world may fall 40 per cent short of the amount of freshwater needed to support the global economy by the year 2030.[166, 167, 168]

The United Nations General Assembly had designated March 22nd as the annual international World Water Day[169] in 1993 in order to focus attention on the importance of water as the foremost natural resource and to advocate for sustainable management of global freshwater resources. Recognition of water scarcity became even more important over the following decades when research into, and observation of, climate change impacts was conducted cohesively under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC) that was formally adopted on 21 March 1994. In its Fourth Assessment Report 'Climate Change 2007' under the UNFCCC, the Intergovernmental Panel on Climate Change (IPCC)'s Working Group II (on climate change impacts, adaptation and vulnerability) included water resources and their management as one of the key areas projected to be impacted by climate change. Its projections included the following conclusions:[170]

- Run-off and water availability are projected to increase at high latitudes and in some wet tropics and decrease over much of the mid-latitudes and dry tropics, some of which are already water-stressed areas.
- The extent of drought-affected areas will probably increase, and extreme precipitation events are likely to increase in frequency and intensity, and augment flood risk.
- Hundreds of millions of people are projected to be exposed to increased water stress.

These projections paint an especially disquieting picture when viewed in the context of the existing water-consumption trends compiled by UN-Water and other UN bodies (as seen in Box 11). Working closely with UN-Water, UNESCO has been producing the World Water Development Report series, the annual flagship publication of the United Nations that offers a comprehensive assessment of the overall state, use and management of the world's freshwater resources. This fact-based publication looks at the current and imminent freshwater-related challenges from a thematic perspective (with a focus on water and climate change in its 2020 edition and valuing water in its 2021 edition) and reports on the progress being made towards achieving SDG 6 targets on clean water and sanitation.

Box 11: Facts and figures related to water consumption[171]

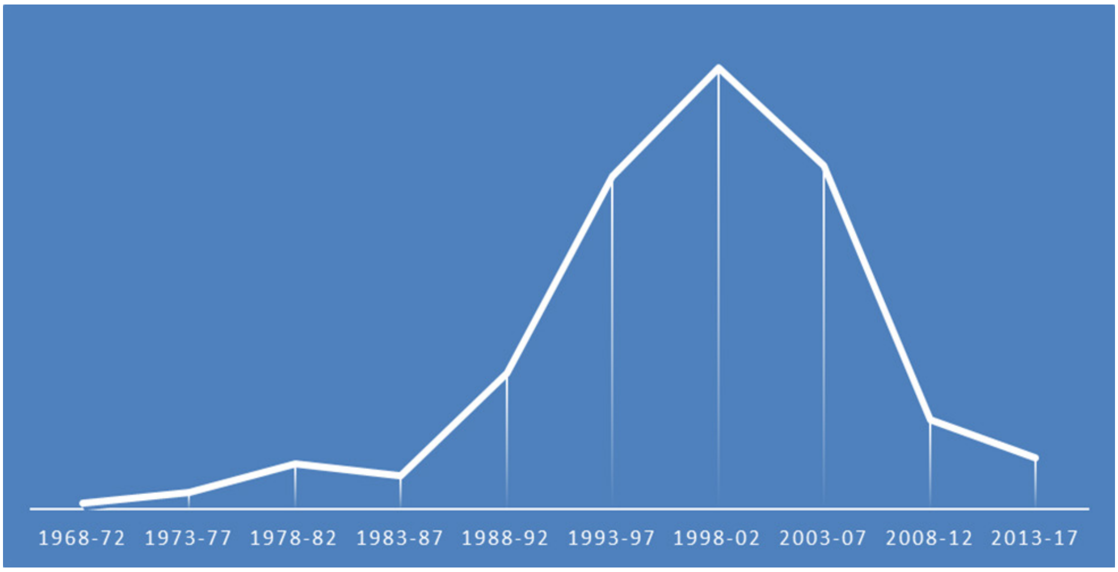
Water consumption: Facts and figures

- Around 4 billion people – nearly two-thirds of the world's population – experience severe water scarcity during at least one month of the year.
- 700 million people worldwide could be displaced by intense water scarcity by 2030.
- 2.1 billion people live without safe water at home.
- One in four primary schools have no drinking water service, with pupils using unprotected sources or going thirsty.
- More than 700 children under five years of age die every day from diarrhea linked to unsafe water and poor sanitation.
- Globally, 80 per cent of the people who use unsafe and unprotected water sources live in rural areas.
- Women and girls are responsible for water collection in eight out of ten households with water off-premises.
- For the 68.5 million people who have been forced to flee their homes, accessing safe water services is highly problematic.
- Around 159 million people collect their drinking water from less safe surface water, such as ponds and streams.

To ensure tangible global progress to mitigate this issue, there are increased calls for smart, real-time monitoring of urban water supply systems and further decreases in apparent water losses (i.e. those occurring through customer meter errors, billing data inaccuracies or unauthorized consumption), as well as in real water losses (those occurring through water leakage and storage overflows). To this end, the UNECE- WHO/Europe Protocol on Water and Health was adopted in 1999 and entered into force in 2005. The Protocol aims to protect human health and well-being through better water management, including the protection of water ecosystems, and by preventing, controlling and reducing water-related diseases. It is the first international agreement of its kind adopted specifically to attain an adequate supply of safe drinking water and adequate sanitation for everyone, and to seek to protect water used as a source of drinking water.

To illustrate that smart monitoring and management of water supplies does work, Figure 15 shows the significant global rise in agricultural water withdrawal as a percentage of total renewable water resources over the last few decades, prior to the more widespread introduction of smart water management and water saving schemes.

Figure 15: The global trend in agricultural water withdrawals as a percentage of total renewable water resources [xv]



Smart sustainable cities are investing in sensor systems and advanced metering infrastructure to upgrade treatment plants and underground pipes so that municipal water management authorities can monitor when and where leaks take place and assess water losses en route to end-users. Proactive monitoring and active management of water supplies are especially vital for cities that have aging infrastructures, including many that still employ on-line monitoring and analysis capabilities only at inlets to the water system. The drive to reduce leakages, wastage and other operational inefficiencies (such as power consumption) becomes even more imperative considering the increasing expectations of transparency and accountability for publicly funded functions. [172] [173]

Singapore – another urban body that was recently explored in a detailed smart sustainable city (SSC) case study[174] – is a high-tech, highly connected city that has prioritized the smart management of water supply as part of its smart sustainable city (SSC) goals. Singapore's suitability and readiness for potential integration of 5G connectivity into its smart water management systems are explored in Box 12.

Box 12: The readiness of Singapore's smart water management system for 5G connectivity [175, 176, 177, 178, 179, 180]

Singapore currently employs a smart water grid and supply management system called WaterWiSe in cooperation with the Public Utilities Board of Singapore (PUB). WaterWiSe provides PUB's water supply network operations and planning teams with decision-support services, including event detection (leaks, bursts, etc.), hydraulic and other system modelling, operational/valve simulation and as a test bed to support further ongoing research into leak and burst detection. It achieves this by using hundreds of sensors, feeding data into data-analytic tools, that are deployed island-wide to not only detect pipe leaks, but to also monitor the water pressure, flow and quality in the network.

The benefits for the city-state are that the system enables real-time remote sensing, ensures faster response times, minimizes disruption to flows, reduces unaccounted water loss, and supports planning and operations through accurate demand prediction and cost savings via energy optimization. The sensors can be seen in Figure 16, along with a few of their deployment destinations and part of the monitoring mechanism in the following Figure 17.

Figure 16: The WaterWiSe multi-sensor probe [xvi]

Figure 17: Deployment of the WaterWiSe multi-sensor probe [xvii]

As the network of WaterWiSe sensors continue to expand, the systems' operators will need to be equipped with the necessary data and tools for timely incident management and continual improvement of response times in order to serve customers optimally. WaterWiSe relies on a generic wireless sensor network for online monitoring of the city's entire water distribution system. The network is linked to PUB's Supervisory Control and Data Acquisition (SCADA) system to exchange sensor data. Real-time telemetry is a powerful tool for a city or utility to employ, which is why a scalable sensor network needs a stronger, more reliable platform for cellular connectivity as it expands.

This is where 5G technology can best be leveraged, offering value for integrated platforms such as WaterWiSe that are built to monitor in real-time and to generate and mine vast datasets for predictive and actionable insights. Traditional 4G speeds could potentially result in connectivity issues, which would mean that true real-time is not achievable, including due to the power requirements, large batteries, etc. needed to transmit data in real or even near real time.

Singapore is on the cusp of rolling out 5G mobile network technology for wide-scale commercial use this year in 2020, with the early adoption phase already started. Since 2017, its three incumbent network operators – Singtel, StarHub and M1 – have been conducting 5G trials with industry partners such as Ericsson. Singapore's Minister for Communications and Information, H.E.S. Iswaran, confirmed the possible use of 5G connectivity for nationwide sensor networks. Singapore's example also shows that populous regions or cities with 'fast-growing, increasingly digital economies that have a desire for speed and connectivity' are optimal test beds for frontier technologies, such as 5G, and their applications. Projections by Frost & Sullivan show that there will be 280 million 5G subscriptions in the Asia-Pacific (APAC) region by 2022, with 5G service revenues reaching USD 4.5 billion.

The drive for continual innovation is reflected in Singapore's commitment to smart improvement of its utilities' infrastructure, which has seen the city-state apply its expertise from the smart water grid project to a new pilot project to create an energy-efficient wastewater treatment process using smart monitoring and advanced control strategies. This work is backed by financial support provided by the Singapore Economic Development Board (SEDB), which has encouraged water companies to use Singapore as a 'living laboratory' and transform the city into a global 'hydro hub'. Singapore's Public Utilities Board (PUB) will collaborate with SUEZ Environnement, a French resources management company, to develop innovative solutions, before scaling the solutions city-wide.[181]

d. Clean energy technology for renewable electricity generation to help reduce fossil fuel consumption

The term 'Clean energy technologies' is often used synonymously with renewable energy technologies that enable the creation of electricity, heat and fuel from renewable sources, such as solar, wind, hydro, wave and tidal power, heat-exchange/geothermal and bioenergy. The British Columbia (BC) Sustainable Energy Association in Canada succinctly conveys the importance of these technologies in the context of climate change as follows: 'These technologies allow us to heat and cool our buildings, generate electricity, and to travel by land, sea, and potentially also by air without generating dangerous greenhouse gases and other forms of pollution.'[182]

The role of renewable and clean energies has also been explored in detail in the UN Intergovernmental Panel on Climate Change (IPCC)'s 2011 special report on 'Renewable Energy Sources and Climate Change Mitigation.' The report builds on the coverage of renewable energy from IPCC's 2007 climate change assessment report and highlights cost savings in comparison to non-renewable energy by concluding: 'Renewable energy can contribute to social and economic development, energy access, secure energy supply, climate change mitigation, and the reduction of negative environmental and health impacts.'[183]

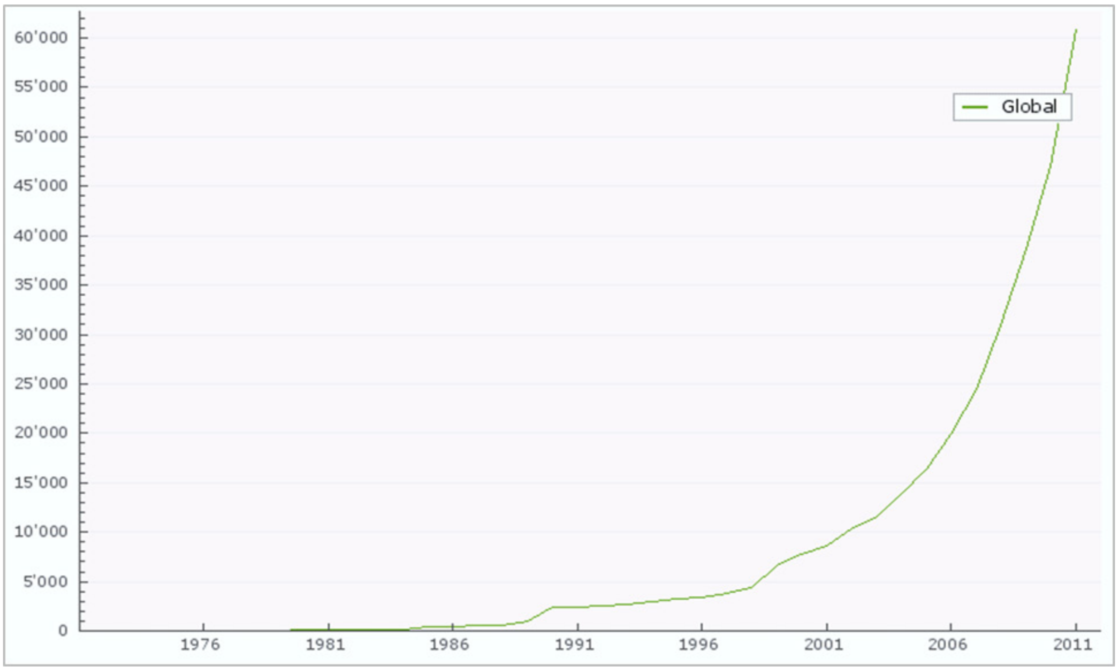
Progress in clean energy technologies is particularly important considering the existing energy consumption trends compiled by the United Nations Development Programme (UNDP) and other UN bodies (as seen in Box 13).

While clean and renewable energy technologies have existed for a long time, their design and efficacy have evolved over the decades. Solar energy, wind energy, and battery energy storage technologies, in particular, have seen some measure of success across the world.[184, 185] The International Renewable Energy Agency (IRENA) in its Renewable Capacity Statistics 2019 report found that 'Strong gains in solar and wind energy... have pushed renewable energy to... account for a third of global power capacity' with these two sources alone accounting for 84 per cent of the growth in 2018.[186]

Similarly, the International Energy Agency (IEA) Energy Technology Perspectives 2017 report also concluded that three clean technologies of solar, wind and battery power, are the only ones being deployed rapidly enough to address climate change effectively. Solar and wind power are fast becoming more affordable than electricity generated from fossil fuel sources. Clean battery technology is being employed in electric vehicles as well as in grid-scale electricity storage projects.[187]

The global rise in renewable energy supply over the last few decades can be seen in Figure 18.

Figure 18: Total primary global renewable energy supply (thousand tons of oil equivalent) [KTOE] [xviii]



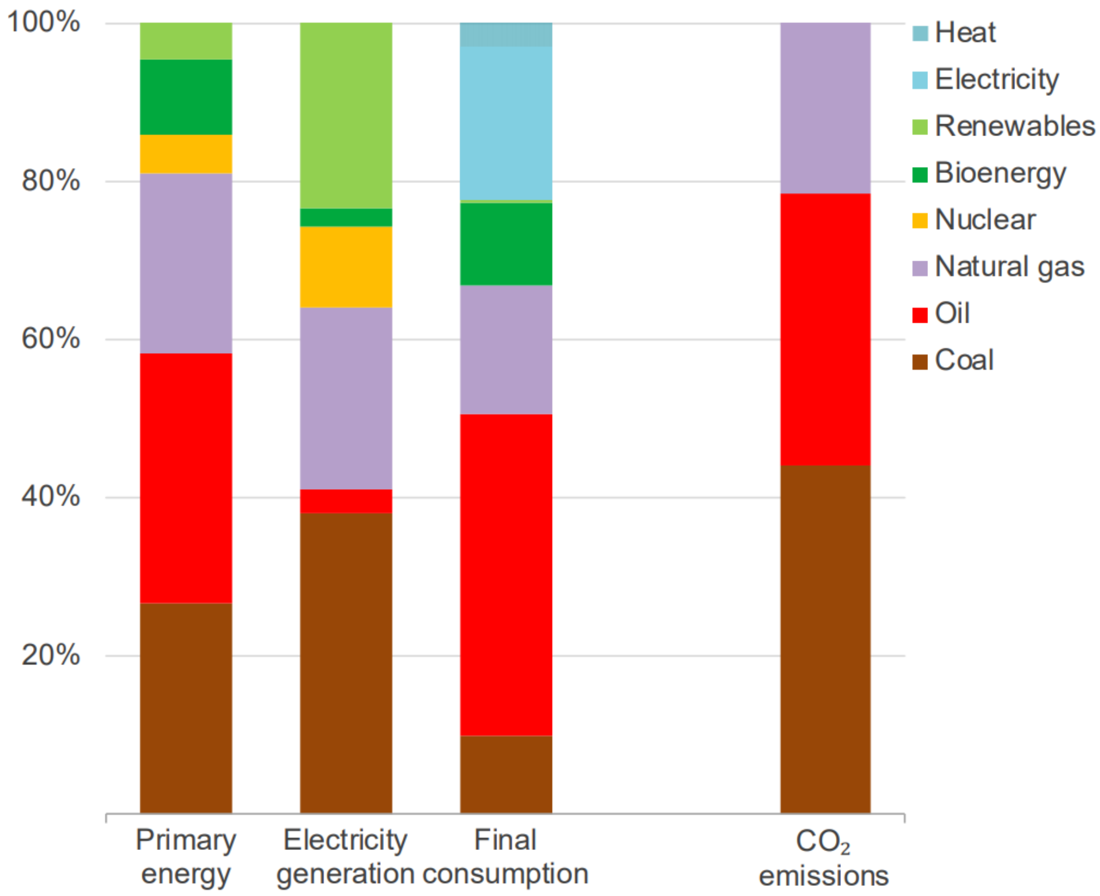
Box 13: Facts and figures related to energy consumption[188]

Energy consumption: Facts and figures

- 13% of the global population – just under 1 billion people – still lack access to modern electricity.
- 16 out of 20 countries with the largest deficits in electricity access are in Africa.
- 3 billion people rely on wood, coal, charcoal or animal waste for cooking and heating.
- Energy is the dominant contributor to climate change, accounting for around 60% of total global greenhouse gas emissions.
- The health and well-being of some 3 billion people are being impacted adversely by the lack of clean cooking fuels; the fuel being used, such as wood, charcoal, dung and coal, cause indoor air pollution.
- Indoor air pollution from using combustible fuels for household energy caused 4.3 million deaths in 2012, with women and girls accounting for 6 out of every 10 of these.
- The share of renewable energy in final energy consumption reached 17.5% in 2015.
- The world needs to triple its investment in sustainable energy infrastructure per year, from around USD 400 billion to USD 1.25 trillion by 2030.

Even so, global reliance on traditional fossil fuels (such as coal, petroleum, natural gas, oil shale, bitumen, tar sand, and heavy oil) remains pervasive to the point that it still exceeds the volume of clean energy technologies deployed. Despite the fact that, according to the IEA, '30 per cent of global electricity can be produced from wind and solar PV in the long term, without adding to the total cost of reaching a low-carbon future,' 47 per cent of global new electricity demand since 1900 has been fueled by coal,[189, 190] with 'too many national energy plans dependent on coal and new coal plants being planned'.[191] There is no end to subsidies for fossil fuel, with subsidies even increasing in 2019.[192] And while almost two-thirds of new power generation capacity added the year prior in 2018 came from renewables, non-renewable generation capacity also increased in pace globally. This is because since 2010, non-renewable capacity decreases in Europe, North America, and Oceania have been offset globally by equivalent gains in Asia and the Middle East.[193, 194] Figure 19 illustrates the global energy makeup in 2018.

Figure 19: Overview of the global energy system in 2018 [xix]



Indeed, the IEA found that with global energy demand increased 2.3 per cent in 2018, emissions also reached a record high in correlation due to increased demand for fuels, with natural gas accounting for 45 per cent of the rise in energy consumption.[195, 196] IEA believes, therefore, that 'the world needs a clean energy revolution in order to break dependence on fossil fuels. Such a revolution would enhance global energy security, promote enduring economic growth and tackle environmental challenges such as climate change. It would break the long-standing link between economic growth and carbon dioxide (CO_2) emissions. But to succeed, it must also be truly global in scope.'[197, 198]

The World Economic Forum (WEF) has echoed this sentiment and underscored 'the need for speed in energy transition,' reasoning that renewable energy growth is still not occurring swiftly enough.[199] IRENA also notes: 'While the growth of renewables has been impressive, the transition to low-carbon energy production will require that more countries and regions not only switch to expanding renewable capacity, but also start to retire or convert more of their existing fossil fuel power plants.'[200]

Moreover, during this transition to renewable energies, comprehensive assessments of the potential impacts of energy facilities throughout their life cycle (construction, operation and decommissioning) and adequate monitoring are important. The UNECE Convention on Environmental Assessment in a Transboundary Context (Espoo Convention) and its Protocol on Strategic Environmental Assessment (Protocol on SEA) promote key tools for assessing and managing the impacts of infrastructure or technologies (e.g. energy infrastructure) – for example, environmental impact assessments (EIA) for individual energy development projects and strategic environmental assessments (SEA) for energy policies, plans and legislation.

A practical approach is to pilot and implement frontier technologies at the city level and then scale up to regional/provincial level and then to national level. This can only be achieved through public private partnerships. Due to the economic dominance (partly through subsidization) and influence of the global fossil fuel industries, the next generation of technologies in solar, wind and energy storage, as well as other emerging clean technologies, may attract less private investment in the absence of public and governmental support. A recent paper made the case for continued innovation in solar, wind, and energy storage and recommended: 'Well-designed policies would spread public funding across a diverse range of technologies and phase out that support as technologies mature, ensuring maximal return on public investments in innovation.'[201]

There is certainly an economic case to be made for the research, prototyping, development and deployment of clean energy technologies. In his 2017 policy paper 'The irreversible momentum of clean energy', former U.S. President Barack H. Obama made the case for the 'decoupling' of energy sector emissions and economic growth by concluding: 'We have long known, on the basis of a massive scientific record, that the urgency of acting to mitigate climate change is real and cannot be ignored. In recent years, we have also seen that the economic case for action – and against inaction – is just as clear, the business case for clean energy is growing, and the trend toward a cleaner power sector can be sustained regardless of near-term federal policies.'[202] Previous research has established the case for clean energy technologies on the basis of observed improved health outcomes through the active mitigation of the existing environmental consequences of climate change.[203]

Adoption of emerging clean energy technologies is already being made possible by innovation-driven regional and international public and private partnerships. There is increasing interest in offshore wind farming as an abundant energy resource that can be located close to major coastal load centres, i.e. those that typically have high energy needs. While wind farming has existed for some time, the U.S. Bureau of Ocean Energy Management (BOEM) elaborates that new offshore wind farms provide 'an efficient alternative to long-distance transmission or development of electricity generation in these land-constrained regions. Offshore wind facility design and engineering depend on site-specific conditions, particularly water depth, seabed geology, and wave loading.'[204]

Offshore winds tend to flow harder, faster and more steadily than those over land. Relatively small increases in wind speed can yield high increases in energy production; offshore wind farms in a 15-mph (24.1 km/h) wind can generate twice as much energy as land-based wind farms in a 12-mph (19.3 km/h) wind. Offshore wind farms also offer the same advantages as land-based wind farms. Once operational, they do not consume water or emit any environmental pollutants or greenhouse gases. They do provide a nearby domestic energy source (so cutting down the costs of the energy) and create jobs in local communities. These factors and advantages, when combined with innovative developments in wind turbine materials and technology, make offshore wind farms one of the most effective cutting-edge ways to help maximize efficiency and increase the production of electricity.[205]

A recent example of successful wind farm deployment is the operationalization of the world's largest offshore wind farm in the county of Cumbria, UK, which is expected to surpass the London Array in terms of megawatt (MW) output,[206] as detailed in Box 14.

Box 14: Successful acquisition of clean renewable energy via large-scale operation of wind farms by Cumbria [207, 208, 209]

The 659 MW Walney Extension project in Cumbria covers an area of 145 square kilometres (km^2) in the Irish Sea and uses eighty-seven (87) wind turbines that are capable of generating enough green energy to power over half a million homes in the U.K. Combined with previously existing capacity out of the Cumbrian district of Barrow-in-Furness, the Extension would help generate up to a combined 1.5 gigawatts (GW), which is enough to power more than 1.2 million homes in the UK. The project was spearheaded by the Danish company Ørsted, and its partners PKA and PFA. Figures 20 and 21 show the offshore wind farm installation at Cumbria.

Figure 20: Cumbria offshore wind farm turbines [xx]

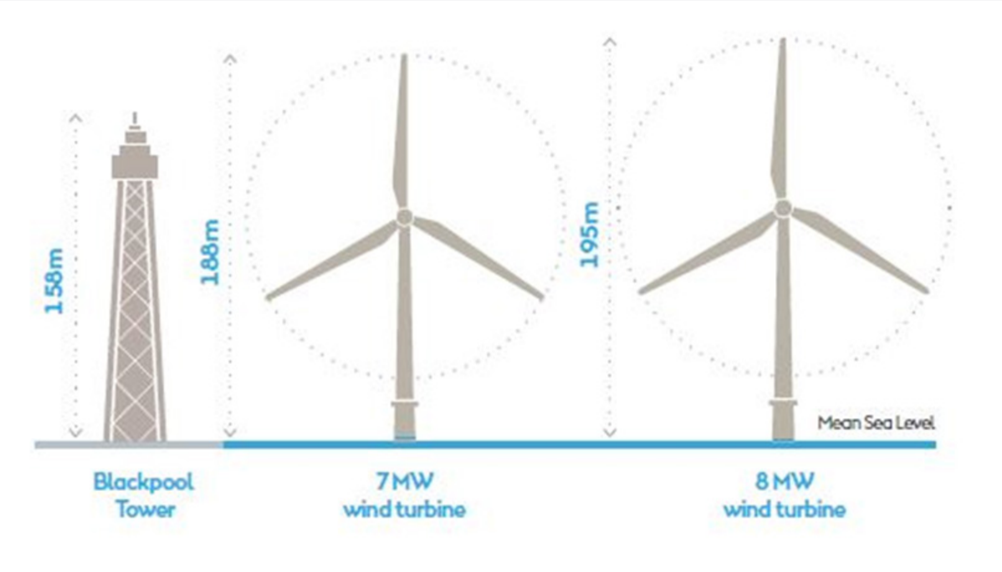
Wind farm technology is at a pivotal stage of innovation, wherein 'subsidies are needed now to fuel the innovations that will lead to cost reductions and subsidy-free renewable energy later,' as explained by the De Oude Bibliotheek Academy from Delft, Netherlands. It advocates deep-water, offshore floating wind turbines, as they will 'greatly expand the potential of the offshore wind market as it will open up previously unavailable waters for offshore construction. This will lead to more investment, more innovation and thus a cost reduction for offshore energy.'

Figure 21: The relative location and size of the Walney extension [xxi]

The De Oude Bibliotheek Academy has also found that innovation in wind turbine size is paramount, as 'increasing turbine size is key to cost reductions in offshore wind. At present, the largest offshore turbines commissioned are 8 MW, but this is forecast to increase to 11 MW or even more in 2030, these are turbines with a rotor diameter of approximately 190 meters. Wind speed increases with elevation, larger wind turbines can therefore catch higher wind speeds, and due to their larger blades generate more power.' Moreover, 'costs of investment, installation and maintenance will decrease when fewer turbines are needed. Turbines sizes are expected to increase until the challenge of installing enormous structures outweighs the gain in energy production, maintenance and construction costs.'

Utilizing the latest current technology from two of the world's leading turbine manufacturers, the Walney Extension features 47 MHI Vestas 8 MW turbines and a further 40 Siemens Gamesa 7 MW turbines (the comparative sizes of which are seen in Figure 22), with blades manufactured in Hull and the Isle of Wight, UK.

Figure 22: MHI-Vestas 8.25 MW turbines and Siemens Gamesa 7 MW turbines relative to Blackpool Tower in size [xxii]



In fact, local sourcing and focus were key success factors in the realization of this project, as the project entailed buy-in from, and benefits to, the local Cumbrian communities and involved use of more than 50 local UK suppliers during construction, supporting the growth of offshore wind 'clusters' around the entire country.

Furthermore, construction of the Walney Extension was coordinated from Ørsted's West Coast Hub, which also services three other wind farms (Barrow, Walney and West of Duddon Sands). The Hub, located in Barrow, now hosts the project's operations and maintenance teams, whose ongoing activities mean support for more than 250 direct jobs in Cumbrian regions. The far-reaching network effects of the project's success are evident in the £15 million Walney Extension community fund that Ørsted has set up to support local projects and organizations, including an annual £100 000 allowance for a skills fund to promote education, support local students and increase uptake of STEM subjects.

The example of Cumbria also shows that political support and economic incentives by national governments are needed to make the offshore wind sector a success story. The U.K.'s commitment to furthering this sector saw offshore wind's share of annual U.K. generation increase from 0.8 per cent in 2010 to 6.2 per cent in 2017, and it is expected to reach around 10 per cent in 2020. To facilitate continual growth and to capitalize on projections that building up to 30 GW of offshore wind by 2030 could account for over £40 billion of infrastructure spending in the next decade, the U.K. has signed an Offshore Wind Sector Deal as part of its Industrial Strategy. This deal also seeks to increase representation of women in the country's offshore wind workforce to at least one-third by 2030.[210]

Cumbria's project, therefore, not only demonstrates the innovativeness, survivability, high potential, reliability and cost-competitiveness of offshore wind technology, it also underscores that decarbonizing electricity supply is possible and must be prioritized for combatting climate change. To this end, further exploration of the potential of clean energy technologies is vital for any city or region looking to tackle climate change.

e. Digital twin for disaster risk planning to help increase environmental resilience

A digital twin is a virtual model, replica or representation of a physical object, product, service, process, system or geographic location. It essentially builds a bridge between the virtual and physical worlds that allows the analysis of data to identify, avoid or mitigate problems before they even occur, and then to identify new opportunities and develop plans for the future by simulating how a physical object, product, service, process, system or geographic location will be affected by chosen variables, i.e. inputs. Subsets within the digital twin concept include a predictive twin, process twin and product twin, among others. While the concept itself is not new, technological progression is now at a point where connectivity levels and machine intelligence are advanced enough to apply and demonstrate the large-scale advantages of digital twins. The technology behind digital twins has extended to include entire systems such as organizations and even cities.[211, 212, 213]

When it comes to digitizing a highly multi-faceted, complex and dynamic entity such as a city, a digital twin project will always be a large-scale, cross-collaborative undertaking (across sectors and industries) that brings together all the data on the city's areas, buildings, infrastructure, flows, environment, and the way the city is used into either a federation of composite sets of models or all models under an overarching framework of an integrated city model. As the digital twin technology matures, more than one twin may be commissioned, with some cities employing digital quintuplets or more, each of which will interact with the physical twin (triplet, etc.) and with each other, while focusing on solutions to its own assigned problem.[214, 215]

Figure 23 illustrates a digital twin rendering for a city.

Figure 23: Sample view of a city's digital twin [xxiii]

Within the context of climate change and response, digital twins are an attractive proposition, particularly for cities that are growing rapidly in population, size and energy consumption and that need efficient management and maintenance of all their systems. The increasing unpredictability of weather events due to climate change are a prime example of the kind of challenge for which cities need prevention, mitigation or adaptation strategies, including the design of resilient infrastructures and systems.

In practice, real-time data generated within a city would feed the relevant set of digital twin models to analyse the impacts of such weather events in order to develop and test a set of appropriate action plans. This could, for example, involve placing sensors in the city's transport network that would automatically feed real-time data into the digital twin model(s), which would then simulate alternative routes for the network paths likely to be affected by extreme weather events.[216]

Weather and disaster resilience are a particularly appropriate area for using digital twins. Extreme weather events are increasing in frequency and severity around the globe. WEF's 2018 report on 'Harnessing Artificial Intelligence for the Earth' reported: 'In 2016 (alone), the world suffered 772 geophysical, meteorological, hydrological and climatological 'natural loss events' – triple the number in suffered in 1980.'[217] Its Global Risks Report has also repeatedly identified failure of climate change-mitigation, extreme weather and natural disasters as the gravest threats for global business and industry,[218] as seen in Figure 24.

Figure 24: WEF Global Risks Report's top 10 risks by likelihood of occurrence [xxiv]

1	Extreme weather events (e.g. floods, storms, etc.)	
	Failure of climate-change mitigation and adaptation	2
3	Major natural disasters (e.g. earthquake, tsunami, volcanic eruption, geomagnetic storms)	
	Massive incident of data fraud/theft	4
5	Large-scale cyberattacks	
	Man-made environmental damage and disasters (e.g. oil spills, radioactive contamination, etc.)	6
7	Large-scale involuntary migration	
	Major biodiversity loss and ecosystem collapse (terrestrial or marine)	8
9	Water crises	
	Asset bubbles in a major economy	10

Cities face a growing number of climatic disasters and risks. Two global frameworks address natural and human-induced disasters, namely the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Office for Disaster Risk Reduction (UNDRR) Sendai Framework. Under both frameworks, vulnerability to heat, drought, flooding, earthquakes, typhoon, tsunami and other natural hazards are to be investigated as part of disaster management planning. This is especially important given the adverse effects extreme and variable weather can have on food security, as well as biodiversity.

In addition to these global frameworks, the United Nations Economic Commission for Europe (UNECE) Convention on the Transboundary Effects of Industrial Accidents (Industrial Accidents Convention) is an important multilateral environmental agreement and legal instrument for disaster risk reduction. It assists countries in establishing and improving their policies and measures for the prevention, preparedness and response to major industrial accidents triggered by natural disasters. UNECE promotes transboundary and interinstitutional cooperation to improve risk management and disaster planning, both within and across borders.

The city of Newcastle, UK, has undertaken such disaster management planning efforts by developing a digital twin to facilitate predictive disaster risk management. Its experience is documented in Box 15 and may serve as a basis for potential national roll-out in the future.[219]

Box 15: Strategic deployment of digital twin technology by Newcastle to combat extreme weather events[220, 221]

Newcastle experienced an extreme rainstorm in 2012 that was dubbed locally the 'Toon Monsoon'. An entire month's worth of rain fell in two hours during an evening commute rush, causing the city's drainage systems to be overwhelmed and costing £8 million worth of damage. The aftermath of the storm can be seen in Figures 25 and 26.

Figure 25: Rescue amid flooding after Newcastle's 2012 extreme storm [xxv]

Figure 26: Submerged cars after the 2012 flooding in Newcastle [xxvi]

This extreme weather event served as the city's impetus for building a digital version of itself in order to better predict and mitigate future associated risks through resilience testing. Risk management is, in fact, expected to be a major focus of most cities adopting digital twins, as climate change is creating rapid new challenges and risks globally. Newcastle can now prepare for future floods by simulating which buildings will be flooded, which infrastructure will have to be closed, which hospitals may be affected operationally, and so on.

Newcastle's digital twin project is jointly spearheaded by Newcastle University and the utility firm Northumbrian Water, with most of the data coming from the university's Urban Observatory project. This project has sensors all over the city monitoring pollution, water quality and biodiversity, among other indicators (as seen in Figure 27) and can use these data to test hypothetical emergencies to assess how Newcastle may fare in the event of flooding and extreme weather, as well as to evaluate how the city may cope with issues such as significant population growth. Simulated changes may be seen immediately, from visualizing what would happen if the River Tyne rose by a few metres to what the city would look like if the population aged over a certain period. The twin may also be used to model human behaviour by, for example, determining the most likely routes people would use in the event of another extreme flood. The Urban Observatory has already collected over half a billion data points and this information is now starting to shed light on the way different systems interact across the city and provide a baseline for Newcastle's integrated digital twin data platform.

Figure 27: One of the Urban Observatory's AQMesh sensors being positioned [xxvii]

While this project has made Newcastle a frontrunner in the use of digital twin technology to recreate the entire city digitally in order to help planners stress-test the city's infrastructure, commercial off-the-shelf style software offerings are expected to emerge to lower the costs of this technology. In order to best leverage this technology to its full potential, cities will still need to define their approach, establish how the project will be managed end to end, facilitate widespread adoption of the end results and engage in activities to help combat climate change.

f. Robotics for monitoring underwater climate change impacts and the observation of marine life to help protect biodiversity

Rapid advances in robotics are the key driver behind several technological innovations within the forthcoming 4th Industrial Revolution (4IR). Robotics is a branch of technology that deals with robots, which are programmable machines built with the ability to carry out a series of actions autonomously or semi-autonomously. There are three important factors that distinguish a robot from similar technologies:[222]

- Robots interact with the physical world via sensors and actuators.
- Robots are programmable.
- Robots are usually autonomous or semi-autonomous.

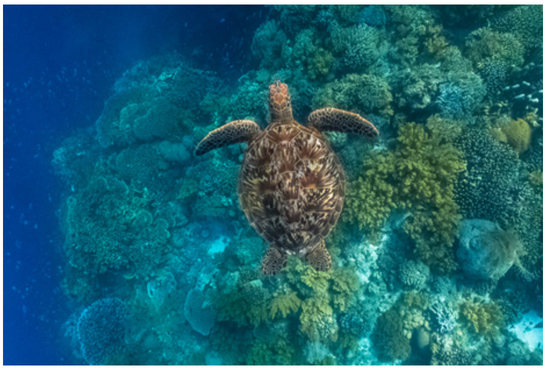
Furthermore, artificially intelligent robots can be controlled by AI programs, thereby acting as the bridge between the disciplines of robotics and AI. These and other emerging breakthroughs within the field of robotics have the potential to transform entire industries and existing business models.

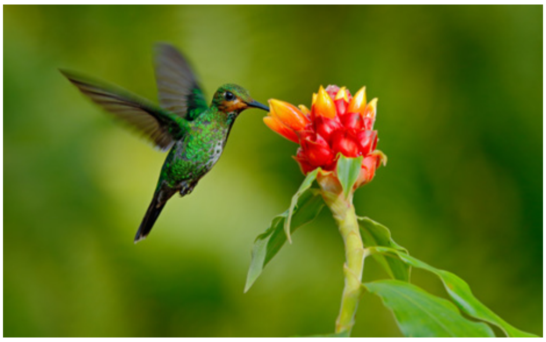
In the context of climate change, robotics can provide several tangible benefits[223] such as:

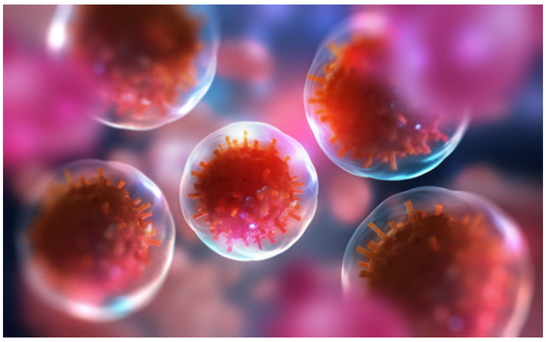
- prevention of pollution and reduction of emissions through monitoring and preventing the release of harmful greenhouse gases;
- optimization of precision manufacturing processes, thereby reducing energy consumption;
- increase in precision strength robots that minimize the need for larger, less-efficient machines; and
- eliminating product waste through more efficient use of raw materials.

Robots can also reach environments that are inaccessible to humans.[224] By swimming through coral reefs, for example, or by hovering above a rain forest canopy, the emerging generation of robots can yield powerful insights for scientists studying phenomena such as climate change and its impacts on biodiversity.

Biodiversity comprises of all fauna, flora and microbial life on Earth. It is the foundation for the health of the Earth's delicately balanced biosphere. The continued health of the Earth's biodiversity is also critical for the millions of vulnerable people in developing communities who depend directly on forests, rivers, lakes and oceans for their lives and livelihoods.

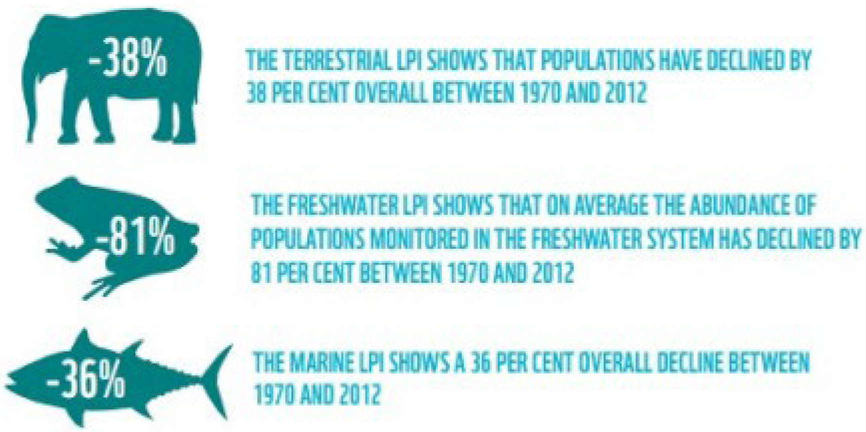




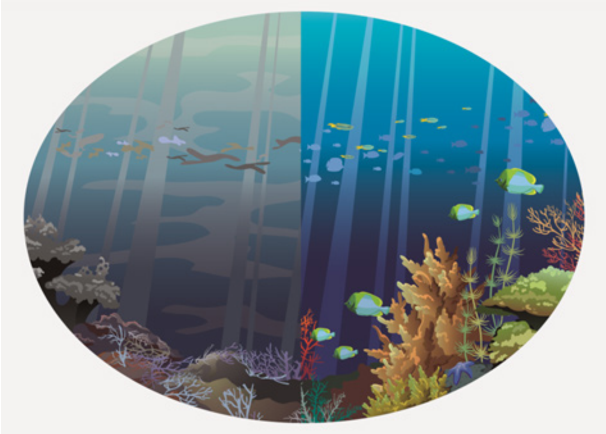


All over the world, however, biodiversity is diminishing at an accelerating rate.[225] The World Wide Fund for Nature (WWF)'s Living Planet Report 2018 shows a nearly 60 per cent decline in the abundance of wildlife populations on average across land, sea and freshwater in less than one generation since 1970. Figure 28 below summarizes this rapid decline. The report confirmed that 'the most common threat to declining populations is loss and/or degradation of natural habitat, but unsustainable exploitation, invasive species and pollution are also major threats.' Climate change, specifically, was identified as the common exacerbator for all these factors.

Figure 28: WWF's summary of global biodiversity loss [xxviii]



Marine biodiversity is particularly at risk. According to UNESCO's Facts and Figures on marine biodiversity, as seen in Box 16, by the year 2100, without major intervention, more than half of all marine species will be at risk of extinction. Over the last 30 years alone, there has been a 40 per cent loss of coral reefs in oceans across the globe.[226] Coral reefs are one of the foremost indicators of ocean health, but warming temperatures have accelerated global coral bleaching, depleting key reefs that support more species than any other marine environment. These are alarming trends, especially since the world's oceans contain the greatest diversity of life on Earth.[227] [228]



Box 16: UNESCO's Facts and figures on marine biodiversity[229]

Marine biodiversity: Facts and figures

- The ocean constitutes over 90% of the habitable space on the planet.
- The ocean has a much higher phylogenetic diversity: 30% of phyla are exclusively marine, whereas only one phylum is exclusively terrestrial.
- By the year 2100, without significant changes, more than half of the world's marine species may stand on the brink of extinction.
- Today, 60% of the world's major marine ecosystems that underpin livelihoods have been degraded or are being used unsustainably.
- Marine Protected Areas (MPAs) are essential to conserve the biodiversity of the oceans and to maintain productivity, especially of fish stocks. World Heritage marine sites represent, in surface area, one third of all marine protected areas.
- Approximately 12% of land area is protected, compared with roughly 1% of the world's ocean and adjacent seas.
- Tiny phyto-plankton provide 50% of the oxygen on Earth and form the basis of the ocean food chain up to fish and marine mammals, and ultimately human consumption.
- Ocean acidification may threaten plankton populations and diversity, which is key to the survival of larger fish.
- If the concentration of atmospheric CO_2 continues to increase at the current rate, the ocean will become corrosive to the shells of many marine organisms by the end of this century. How or if marine organisms may adapt is not known.
- Ocean acidification may render most regions of the ocean inhospitable to coral reefs, affecting tourism, food security, shoreline protection, and biodiversity.

- Coral reefs are the nurseries of the oceans, they are biodiversity hot spots. On some tropical coral reefs, for example, there can be 1 000 species per m^2.
- Today, fisheries provide over 15% of the human dietary intake of animal protein for communities around the world.
- Commercial overexploitation of the world's fish stocks is so severe that it has been estimated that up to 13 % of global fisheries have 'collapsed', with a much higher proportion under threat.
- Agricultural practices, coastal tourism, port and harbour developments, damming of rivers, urban development and construction, mining, fisheries, aquaculture, and manufacturing, among others, are all sources of marine pollution threatening coastal and marine habitats.
- Excessive nutrients from sewage outfalls and agricultural run-off have contributed to an increase in the number of low-oxygen (hypoxic) areas known as 'dead zones', where most marine life cannot survive, resulting in the collapse of some ecosystems.
- There are now close to 500 dead zones covering more than 245 000 km^2 globally, equivalent to the surface of the United Kingdom.
- Coastal systems such as such as mangroves, salt marshes and seagrass meadows can absorb, or sequester, carbon at rates up to 50 times those of the same area of tropical forest.
- Total carbon deposits in these coastal systems may be up to five times the carbon stored in tropical forests.
- Between 1980 and 2005, 35 000 square kilometers of mangroves were removed globally.
- Between 30 and 35 percent of the total global extent of critical marine habitats such as seagrasses, mangroves and coral reefs are estimated to have been destroyed.
- Technological change and the emergence of new economic opportunities such as deep-sea mining, more intensive fishing, and deeper oil and gas drilling increase risks to areas that historically were not under threat.

While oceans are global and not limited to a particular city or urban area, certain cities are supporting the use of emerging robotics to monitor marine pollution and measure its impacts on marine bio-life. Venice, Italy, was the launch site of such a pilot project a few years ago, as detailed in Box 17.

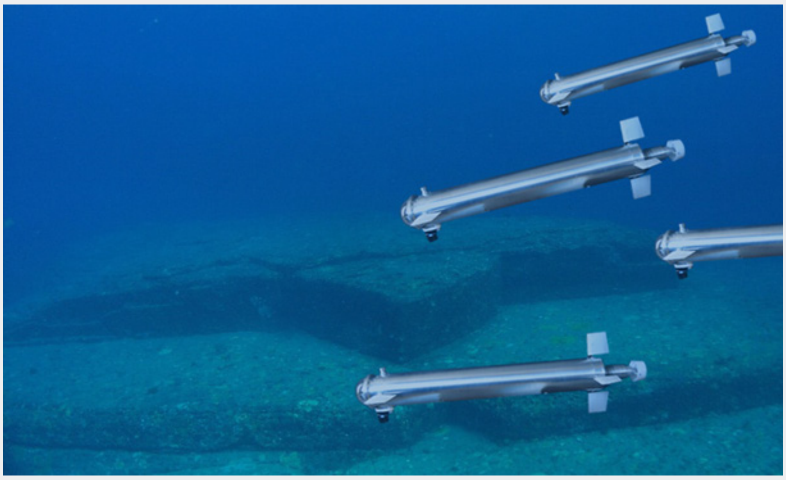
Box 17: ENEA's use of robotic fish in Venice, Italy[230, 231]

In 2015, an Italian team from ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, and Rome's University of Tor Vergata, presented, a new system of robotic fish that could be used to monitor a host of different marine factors and protect Venice from high tides. This system of 'bio-inspired' robots was called the 'Venus Swarm'.

The Venus Swarm was composed of several cooperative and coordinated robotic vehicles. The line of research that resulted in the technology focused particularly on imitating aggregation patterns in animals and their group intelligence. 'Venus Swarm is a swarm of robots that, in very close contact, act like network nodes and make up a submarine wireless system that uses sound and light to communicate. In clean waters, the optical system makes it possible to transmit a large quantity of information, whereas the sound system, redesigned specifically for this system, can be mainly used in dirty waters,' according to ENEA at the time.

While piloted initially to be used in the surveillance of MOSE, the bulkhead system that is in place to defend the Venetian Lagoon from the high tide, the Venus Swarm technology has great potential for application in environmental exploration and monitoring large marine areas underwater. These robotic fish could be used to map the seabed for sensitive data on acidification, salinity, temperature, speed and direction of marine currents, as well as on flooding and coastal erosion. The robots, which could be employed in swarms of dozens, may be used, for example, to monitor oil platforms, pipelines and ports, and also to manage migratory flows and protect marine biodiversity. The use of these robot swarms in the control and inspection of the seabed of coastal areas and ocean waters could offer greater advantages overall, compared to the use of single and sophisticated, but very expensive, robotic systems. Figure 29 shows the Venus Swarm in action.

Figure 29: The Venus Swarm [xxix]



Projects like the Venus Swarm can be used to implement the roadmap provided by policies and programmes aimed at reducing water pollution and protecting marine biodiversity, such as those in Box 18.

Box 18: Various UN programmes and policies to protect the marine climate and its biodiversity

UN Programmes and policies to protect the marine climate and its biodiversity

The United Nations has proclaimed a Decade of Ocean Science for Sustainable Development (2021-2030) to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that will ensure that ocean science can fully support countries in creating improved conditions for the sustainable development of the ocean. Scientific understanding of the ocean's responses to pressures and management action is fundamental for sustainable development. UNESCO's Harmful Algal Bloom Programme, for example, aims to foster the effective management of, and scientific research on, harmful algal blooms in order to understand their causes, predict their occurrences and mitigate their effects.

UNESCO's Intergovernmental Oceanographic Commission (IOC) coordinates the decade's preparatory process, inviting the global ocean community to plan for the next ten years in ocean science and technology. The IOC-UNESCO holds a universal mandate for marine science within the UN system and is working to improve responses to the unprecedented environmental changes and human impacts now occurring and to promote ocean health via marine sciences. The joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) is the UN advisory mechanism for collaboration and coordination, which conducts assessments and in-depth studies to evaluate the state of the marine environment and identify emerging issues. It is presently sponsored by 10 UN agencies.

UN Environment works with governments, businesses, universities and civil society groups around the world to promote the protection and sustainable management of marine and coastal environments. UN Environment hosts the secretariat for the Global Programme of Action (GPA) for the Protection of the Marine Environment from Land-based Activities. Since 2012, the work of the secretariat has been focused on establishing and strengthening voluntary, multi-stakeholder partnerships on nutrient pollution, marine litter and wastewater. Nutrients management, marine litter and wastewater have been highlighted as priority source categories to address, and the GPA secretariat has established and strengthened three global multi-stakeholder partnerships: The Global Partnership on Nutrient Management (GPNM); the Global Partnership on Marine Litter (GPML); and the Global Wastewater Initiative (GWI). The Regional Seas Programme, launched in 1974, is one of UN Environment's most significant achievements in the past four decades. Since its inception, the Regional Seas Programme has been aiming to address the accelerating degradation of the world's oceans and coastal areas through the sustainable management and use of the marine and coastal environment by engaging neighbouring countries in comprehensive and specific actions to protect their shared marine environment.

Keeping the world's oceans and seas under continuing review by leveraging robotic technology and integrating existing information from different disciplines will help to improve responses from national governments and the international community toward addressing the unprecedented environmental changes that are now occurring underwater. Data gathered by these technologies can be used to develop better models that can help predict the future of Earth's climate and help understand how its oceans will cope with higher temperatures, acidification and other climate shocks.

Combining the use of frontier technologies to achieve this will be particularly helpful. For example, AI and related technologies, such as IoT, are also expected to foster progress in most, if not all, areas of ecological and biodiversity research. AI can be used to analyse changes and threats to ecosystems and provide an understanding of the processes at play, while also facilitating a rapid response. A 2018 article by Norouzzade in the Proceedings of the National Academy of Sciences has shown that AI can automate animal identification for 99.3 per cent of the 3.2 million images in the Snapshot Serengeti dataset. Moreover, it can perform at the same level of accuracy (96.6 per cent) as crowdsourced teams of human volunteers. The authors of the article affirm that 'automatically, accurately, and inexpensively collecting such data could help catalyze the transformation of many fields of ecology, wildlife biology, zoology, conservation biology, and animal behavior into 'Big Data' sciences' (UNESCO, 2019). AI and IoT are, therefore, being combined with technologies such as robotics in UNESCO's World Network of Biosphere Reserves, which counts more than 700 sites in more than 120 countries, several of which are transboundary.

g. Space 2.0 Technologies for precise monitoring of ice sheets and ice caps to help accurately predict sea level rise and global weather patterns

Space 2.0 technologies are the successors to Space 1.0 (which is sometimes characterized as the first space age, which lasted approximately from 1957 until 2000). Space 1.0 resulted in essential technologies such as the Global Positioning System (GPS) that were eventually adopted for wider commercial use. Private space companies are now visible participants in the new space age, alongside traditional players such as the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA).[232]

Earth's climate does vary naturally, especially over prolonged periods of time. It is difficult to separate natural variability from changes caused by human activity, but this separation is important for confronting man-made climate change and its challenges. This speaks to the need for understanding the complexities of how the Earth functions as an entire system in the face of accelerating climate change. Hard evidence is vital for predicting future climate and weather patterns, and how best to mitigate and adapt to the realities posed by climate change.

Satellite technology has, over the decades, provided unequivocal evidence of the changes taking place on Earth due to climate change. Satellite measurements of the Earth's changing temperature, sea levels, atmospheric gases, declining ice and forest cover, for example, are some of the key ways of obtaining the scientific data needed to improve understanding of the Earth as a geological system and predict its climatological future.[233]

It is important that satellite measurements continue over long periods of time so that changes to geological features such as ice sheets can be monitored accurately. Climate change is eliminating significant portions of the polar ice caps and ice sheets so rapidly that the melt has already caused a significant contribution to overall sea level rise. Unfettered global warming will lead to the loss of further ice, further threatening coastal cities around the world. Indeed, by 2022, there may be little, or no permanent ice left in the Arctic.[234]

Significant sea level rises are of concern, as at least 40 per cent of the world's population lives in cities that are vulnerable to sea rise, including important economic centres such as New York, Miami, Los Angeles, Tokyo and Mumbai.[235] With glaciers starting to flow faster and breaking into icebergs that are moving into the ocean (a process known as 'calving'), a continuous increase in the rate of mass loss can be expected, resulting in an accelerating rate of sea level rise, that will continue to increase more rapidly every year.

Box 19 details the impact of climate change on ice sheets in Greenland, the world's largest island, with a national population of less than 57 000 that is most vulnerable to the effects of the territory's accelerating ice melt.[236]

Box 19: Use of Space 2.0 technologies to map Greenland's ice sheet[237, 238, 239]

While the acceleration of Greenland's ice loss has been established using satellite data such as the above, precise models for accurate future predictions need even more advanced satellite technologies.

To this end, in 2018, NASA launched a new cutting-edge satellite to map the loss of ice in Greenland precisely: The Ice, Cloud and land Elevation Satellite-2 (ICESat-2). ICESat-2's spacecraft provides power, propulsion, orbit, navigation, data storage and handling, and features precise knowledge of the satellite's position in space – which is critical for taking highly accurate measurements.

ICESat-2 follows a previous five-year mission, the ICESat, which concluded in 2009. The first ICESat helped demonstrate the way that ice cover has disappeared from coastal parts of both Greenland and Antarctica, as well as the thinning of sea ice. As its successor, ICESat-2 will provide additional information by examining how ice cover changes over the course of one year. It may help explain, for example, why the Tracy and Heilprin Glaciers, which flow side by side into Inglefield Gulf in northwest Greenland, are melting at radically different rates.

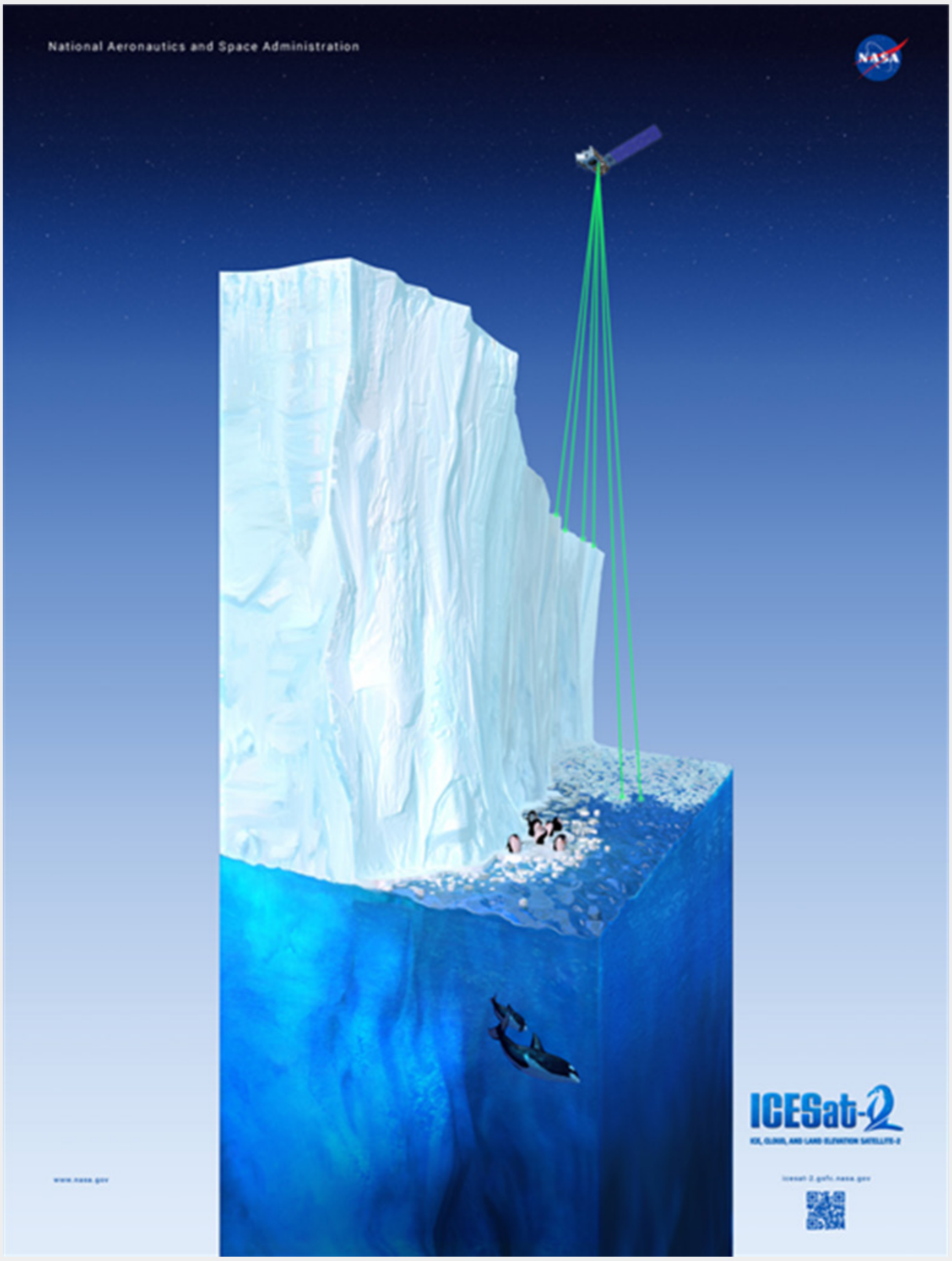
ICESat-2 is a spacecraft with a single major instrument, instead of the usual assortment of sensors and antennas. It deploys an industrial-size, hyper-precise altimeter: The Advanced Topographic Laser Altimeter System (ATLAS), which is a single, powerful green laser split into six beams (three pairs of two) that pass over the landscape in programmed patterns.

Next to the laser is a special telescope that monitors the beams' reflections, collecting a dozen photons from each laser pulse 10 000 times per second. With ICESat-2's altitude readings being accurate down to the inch, it should be able to tell whether an ice sheet has risen or fallen to the order of millimeters, and monitor ice sheet elevation and sea ice thickness.

The satellite's laser reference system controls where the laser is pointing, ensuring that it is aligned with the telescope. The laser reference system also tells the spacecraft where the telescope is pointing so that it can adjust if needed. The same space laser can also return measurements on land topography, vegetation characteristics, and clouds.

Figure 30 illustrates how ICESat-2's instrument takes measurements every 2.5 feet (85 cm) along its ground path – mapping dips and drop-offs in the ice.

Figure 30: NASA's illustration of ICESat-2's function [xxx]



Scientists hope that data from next-generation satellites will help improve uncertain forecasts for sea-level rise, as well as predict and help them understand global weather and climate patterns better. According to the IPCC, higher seas are already creating more dangerous storm surges, exacerbating flooding or coastal erosion from the US Gulf Coast to the Maldives to China. Some low-lying island nations, such as Fiji and Vanuatu, have already been forced to move certain coastal communities to higher ground. The future effect on communities in Greenland itself is uncertain, and, hence, of major concern.[240,241] The role of space technologies for monitoring, therefore, is becoming increasingly important.

h. Digitalization and Big Data for leapfrogging traditional pathways to help increase agricultural efficiency and food security

Digitalization (and the resulting Big Data) already form the basis for policymakers to build strategies for halting climate change. Digitalization of climate data, for example, preserves historical observations and provides the basis for understanding and assessing climate variability, predicting extreme climate events and designing adaptation and mitigation strategies. On the industry side, digitalization through platforms such as mobile and cloud computing not only enables financial growth and stability but can also help ensure sustainability in the social and environmental obligations of businesses.[242]

Small businesses and primary industries in the developing world can benefit significantly from the trend toward digitalization, as it can lead to new ways of doing business. Big Data analytics can enhance operational efficiencies at factory floors, while improving supply chain efficiencies. Small-scale, cost-effective digitalization projects can help inform local climate adaptation policies and result in significant positive impacts on livelihoods within local communities. Mobile apps can disseminate information regarding the weather and global warming trends or be used to track an individual or company's carbon footprint.[243] Figure 31 illustrates some key Big Data characteristics and considerations.

It is estimated that by this year, 2020, 40 zettabytes, i.e. 40 thousand billion billions of data will be generated around the world. Data pertaining to the Earth can be a valuable source of knowledge that can help inform the planet's collective future. Consolidating information from observations of the Earth with geographic, oceanographic and scientific data, and making data available to multiple players across industries, academia and governments will allow for newer services and create innovative new uses for Big Data.[244]

From agriculture to transport, all sectors can benefit from an increase in and accessibility to digitalization. By 2050, the world's population is expected to approach close to 10 billion people, as a median estimate.[245] Food security is already a major issue in many parts of the world and will become more so against a backdrop of increasingly scarce resources.

To increase agricultural production to adequate levels, digitalization of the agricultural sector is needed to ensure optimization of inputs such as water, while minimizing undesirable outputs such as CO_2 emissions. The information capital derived from Big Data on weather, soil moisture, mineral levels, maturity of plants, etc. and transmitted by connected mobile technologies will also alter jobs within agriculture and the food production chain.

Climate change has many implications for farming communities around the world and the global food security.[246] Box 20 contains facts and figures researched and published by the UN's Food and Agriculture Organization (FAO) on how change climate affects the ability to grow food and feed humanity.

Box 20: Food security Facts and figures from the FAO[247]

Food security: Facts and figures

- 75% of the world's poor and food-insecure people rely on agriculture and natural resources for their livelihoods.
- The FAO estimates that world food production must rise 60% to keep pace with demographic change. Climate change puts this at risk.
- Crop yield declines of 10 – 25% may be widespread by 2050 due to climate change.
- Rising temperatures will reduce catches of the world's main fish species by 40%.
- Although global emissions from deforestation have dropped, deforestation and forest degradation account for 10 – 11% of global greenhouse gas emissions. Emissions from forest degradation (logging and fires) increased from 0.4 to 1.0 gt CO_2 per year between 1990 and 2015.
- Livestock contributes nearly two-thirds of agriculture's greenhouse and 78% of its methane emissions.
- Climate change can transfer risks of food-borne diseases from one region to another, threatening public health in new ways.
- The FAO estimates that the potential to reduce emissions from livestock production (especially methane) is about 30% of baseline emissions.
- Currently, one-third of the food produced is either lost or wasted. The global costs of food wastage are roughly USD 2.6 trillion every year, including USD 700 billion of environmental costs and USD 900 billion of social costs.
- Global food loss and waste generate about 8% of humankind's annual GHG emissions.

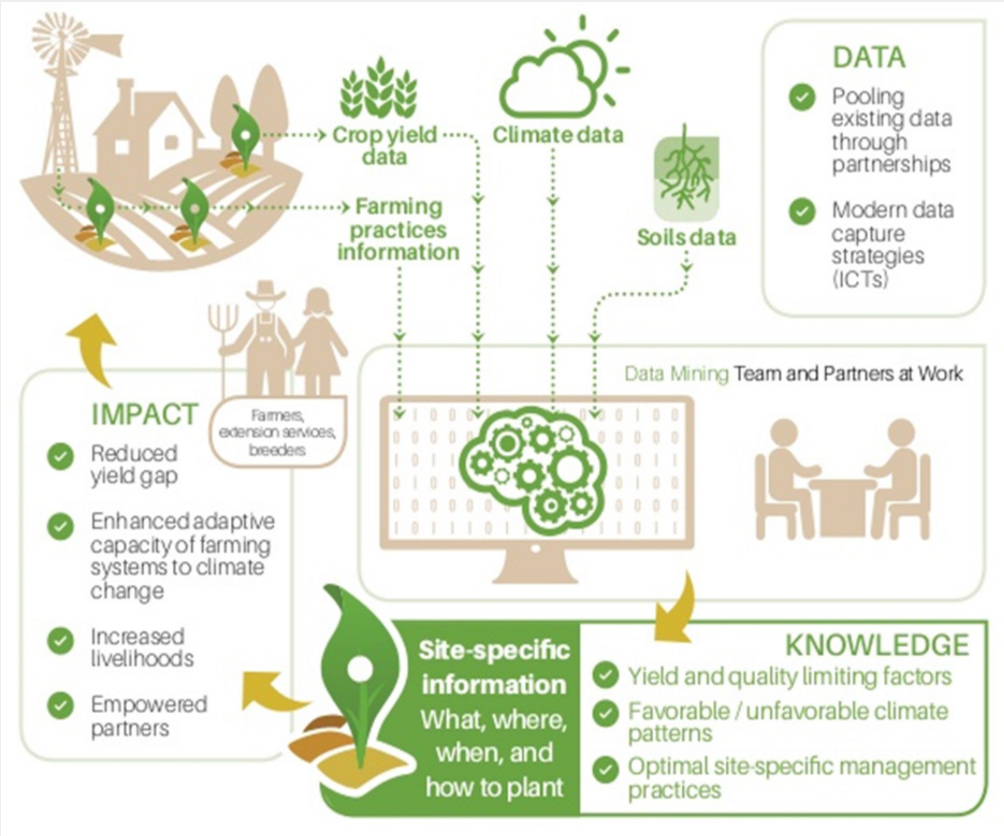
To summarize the above, climate change creates risks of more natural disasters and environmental problems, which can have the end effect of making it harder to grow food predictably. At the same time, agriculture is a major source of greenhouse gas emissions. As the world's population grows, societies need to adapt to the inevitable impacts of climate change by, for example, adjusting the sort of crops they grow and optimizing the ways in which they are grown. This can be achieved through the introduction of 'digital agriculture', which has been described as driving systemic change in the sector using a range of technologies, channels and analytic capabilities to make farming more precise, productive, and profitable.[248] Box 21 illustrates how digital agriculture has been used successfully and subsequently scaled in farming communities across Colombia.

Figure 31: Big Data characteristics and considerations [xxxi]

Box 21: Digitization of site-specific farming in Colombian communities[249, 250]

Figure 32 summarizes the inputs, outputs, and interaction between the tools and various stakeholders involved in Colombia's site-specific agriculture project.

Figure 32: Colombia's site-specific agriculture project [xxxii]



In September 2014, UN Global Pulse, a UN body exploring the uses of Big Data for sustainable development, named the climate-smart, site-specific agricultural decision-making tool one of two winners of the UN Big Data Climate Challenge. The CIAT-CCAFS team was invited to the UN Climate Summit, where their research was shared with heads of state, as well as global business leaders and civil society leaders.

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) reported that in 2014, 170 Colombian rice farmers avoided massive losses by taking the advice of their producers' federation, FEDEARROZ, not to plant in the first of the two annual growing seasons. The farmers who took the advice avoided economic losses estimated at USD 1.7 million. FEDEARROZ acted on a forecast by a team of young CCAFS scientists based at the International Center for Tropical Agriculture (CIAT). The scientists mined ten years of weather and crop data to understand how climatic variation impacts rice yields. The team then fed patterns in climate and yields into a computer model and predicted a drought in the Caribbean department of Córdoba, which led it to conclude that farmers in some regions could save themselves from crop failure by not planting at all.

The ability to analyse masses of crop and climate data to provide farmers with accurate, site-specific forecasts and advice has had huge implications, not only for rice, but also for cassava, beans and potato (the main crops in Colombia). In Colombia, rice production had fallen from around 6 tonnes a hectare to 5 tonnes since 2007. Variable weather from season to season meant that harvests could fluctuate by 30 to 40 per cent. Now, based on trends identified by the CIAT-CCAFS data team, FEDEARROZ and government extension services in three regions recommend the rice varieties that work best under specific weather conditions, and the best date to plant. By heeding forecasts and specific recommendations on what, when and how to plant rice in their area, the farmers can avoid losses of 1 to 2 tonnes per hectare. This matters, because farmers in Colombia already struggle to remain competitive in both domestic and export markets.

The CCAFS team recognized that more comprehensive data enable better and more accurate forecasts. To collect more data, the team developed a mobile phone app for farmers to capture and share information about their farms and their rice, maize and bean cultivation practices. This local knowledge and site-specific information, when fed into the computer model, enable scientists to refine their advice further. This advice gives farmers even more of an advantage: as weather conditions become more variable, they can increase production and so avoid catastrophic losses. The tools are now being scaled out throughout Colombia, Argentina, Nicaragua, Peru and Uruguay.

5. Key observations and considerations

A recurring observation in the cases presented above has been that buy-in from, and investment by, governments are critical to ensuring the progress and spread of frontier technologies. Also critical for ensuring relevance to city needs is a close working relationship between the public and private or business sectors, along with engagement of academia and citizen stakeholders. Governments can help ensure cooperation and spur innovation within private industry through economic and legislative incentives for research and development of frontier technologies.

The rapid furtherance of frontier technologies such as AI at the business level can be seen in the results of a 2017 Gartner survey, which showed that 59 per cent of organizations polled were actively gathering information to build their AI strategies, while over 40 per cent had already made progress in piloting or adopting AI solutions.[251] Therefore, the more prevalent the usage of these technologies becomes, the more scalable and cross-sector applicable they will be.

For frontier technologies to be successful in combatting climate change, it is essential that their carbon footprint be taken into consideration and that they are not used gratuitously despite their popularity, but as part of well-planned, integrative strategies that would see these technologies bring actual concrete results for both city operators and the city populations.

This is reflected in a new handbook, 'The Future of US Cities: How Cities are Innovating with Intention to Achieve Impact', which offers guidance on how technology can be deployed to benefit the whole of communities, especially vulnerable communities, and how to prevent aimless innovation. According to the Centre for Public Impact North America, 'When cities innovate with intention, they do so in a way that emphasizes legitimacy, equity, and agility.' The Aspen Institute's Centre for Urban Innovation adds: 'Cities are epicentres of innovation, opportunity, and delight. Especially in an age of smart cities, city leaders will need to continue innovating with an intentional focus on equity to ensure that all city residents are able to reap the benefits of new tools and technologies.'[252]

Dissimilar to the idea of aimless innovation is the 'leap-frogging' that some cities or countries may find themselves doing out of necessity. Leapfrogging has been described as 'the notion that areas which have poorly developed technology or economic bases can move themselves forward rapidly through the adoption of modern systems without going through intermediary steps.'[253] This has been seen in many African countries, where growing energy demand and slow response of governments in attracting or investing in traditional energy source infrastructure has seen Ethiopia, for example, move directly to hydropower to meet its future energy needs. Ethiopia is building the Grand Renaissance Dam on the Blue Nile River. Once completed, the dam would generate 6 000 MW of electricity, which is more than four times Ethiopia's capacity otherwise.[254] Although hydropower, like many other clean energy technologies is not a new technology, it could be a significant disruptor within Ethiopia's energy context, as well that of other countries nearby, and may help the country leapfrog over coal as a major traditional energy source, with potential implications for water supply as well.[255] [256]

Some cities or countries may find themselves leapfrogging even when they have limited capacities to access these technologies. This can be seen in the case of 'mini-grids', i.e. the local distribution networks of electrical generation systems that produce less than 10 MW, which are powered by renewable sources (such as solar power and biofuels) and are becoming increasingly popular in rural areas.[257] The International Energy Agency (IEA) predicts: '140 million people in rural areas will gain access to electricity via mini-grids by 2040.'[258]

Direct leapfrogging can have certain limitations, however, especially in the energy sector, which typically requires a certain amount of infrastructure investment, modernization of public utilities, development of regulations and institution of finance mechanisms. The development of technical literacy and skills through education is also necessary to ensure the required level of adoption that would make frontier technologies successful for the benefit of all, not just for some.

Similar observations were made during a 2017 study that mapped the national ICT infrastructure development journey of Azerbaijan. The study concluded: 'ICT development in Azerbaijan unfolded as a 'stage-skipping" variant of Technology Leapfrogging that consists of four stages: (1) Psyching, (2) Planting, (3) Propelling, and (4) Perpetuating. Analogous to the mechanics of a physical leapfrog, traversing the four stages enabled Azerbaijan to achieve an advanced state of ICT connectivity quickly and cost effectively in spite of its limited resources, which served to generate a variety of economic and social benefits for the country.'[259] Such variants of direct leapfrogging should be studied in more detail, a task which is particularly suitable for an organization such as the UN, which – through its many coordinated global activities – is encouraging and facilitating the strategic development, optimization, standardization and cohesiveness of the overall approach to frontier technology deployment.

The focus of this report on equitable deployment of innovative frontier technologies has been echoed by the UNFCCC especially in the context of climate change, where it has concluded: 'Climate change is the defining issue of our time, and while the world needs to move fast, the solutions must be fair. The world's most vulnerable people are suffering the worst effects of climate change, such as more intense storms, dangerous heat waves, more frequent and longer-lasting droughts, rising seas (and major technological disasters that have been triggered by these natural hazards), while contributing least to the problem'.

The interconnected Sustainable Development Goals, which include the standalone SDG 13 on Climate Action, provide the best framework for tackling the climate emergency in ways that help everyone, in particular, women, children, youth, older persons, persons with disabilities and those living in Small Island Developing States. This is even more important in light of the four demographic 'mega-trends' that are shaping the world in fundamental ways: population growth, population ageing, international migration and urbanization. These trends were highlighted recently during the annual Commission on Population and Development (which was held at the UN Headquarters in New York on 1 April 2019) as part of the discussion around the need to bring about a better and more sustainable future for all through achievement of the 2030 Agenda for Sustainable Development. The gender divide as explained by UN Women, in particular, is explored briefly in Box 22.

Box 22: UN Women's call to address the gender-environmental nexus

Using standards to ensure that frontier technologies address the gender-environmental nexus

Frontier technologies seldom benefit women and men equally. What is happening behind the scenes in machine learning (ML), robotics and digitization, to name a few, is incredibly complex and difficult. We see new tools emerging using algorithms and data sets which are picking up on historical and societal biases and further propagating them. When developing and using frontier technologies to protect the environment and tackle climate change, we need to have standards and systems in place to make sure women and girls have equal rights and access and are given opportunities to contribute to making real societal change.

Women's unique insights and perspectives can help shape the technology that impact their lives and those within their communities to respond appropriately to their needs and realities. Some 2.5 million new engineers are needed in Sub-Saharan Africa to achieve SDG6 (Water and Sanitation) and there will not be enough people to fill this need. Beyond increasing the proportion of diverse developers and experts, ensuring meaningful engagement with the affected communities is also needed to challenge the imposition of top-down technological solutions. This is not only a matter of justice and equality but is fundamental to ensuring that frontier technologies are able to deliver on their potential for all and not further enhance discrimination.

UN Women recommends adopting its newly launched Gender Innovation Principles, which point to the need to promote women as innovators, stakeholders and end-users throughout each of the phases of innovation (Global Innovation Coalition for Change, 2018). This is highly relevant for the world of frontier technology, which is filled with developers, enthusiasts and experts who are mostly men from developed economies that seem to outnumber not only women, but also other diverse populations. By adopting the Principles, public and private sector partners commit to:

- Champion diversity and inclusiveness in their innovation labs and management structures.
- Include women and gender experts at the design stage.
- Integrate women's needs and carefully select data sets during testing and piloting stages.
- Use sex-disaggregated data and gender impact assessments to monitor the results achieved using innovative technologies.
- Only scale the utilization of tools that provide gender-responsive and sustainable solutions.

This report noted at the start that the disruptive potential of frontier technologies can lead to certain downsides arising from inconsistency in affordability and access to these technologies, which can be particularly stark between developed and developing nations. These downsides can be minimized through the implementation of policies aimed at limiting the socio-economic costs of adjustment, at the city level, as well as at the national and regional levels. Effective regulatory environments and institutional infrastructures are required to promote the strategic innovation, balanced diffusion and appropriate use of frontier technologies. Fostering international cooperation for the exchange of technologies and innovation (particularly between developed countries and the rest of the world), reducing barriers posed by restrictive intellectual property rights mechanisms, and promoting ICT-related standards globally are some key specific ways in which frontier technologies can be leveraged for the benefit of all.[260]

6. Conclusions

Catastrophic global climate change is not an event waiting to happen sometime in the future. It is the reality that the entire world is facing right now. Climate change threatens to increase vulnerability, undermine economic gains, hinder social and economic development, and worsen access to basic services and the quality of life of people all over the world. Furthermore, its impacts could often turn into self-reinforcing cycles that affect the young, elderly and other vulnerable individuals (e.g. such as those without adequate shelter or access to cool environments) the most. These impacts also have the potential to further exacerbate inequalities and halt the social and economic progress of entire regions.

A recent discussion paper by UN Environment was issued and adopted in March 2019 in the margins of the fourth meeting of the UN Environmental Assembly. It was produced by members of the UN Science Policy Business Forum working group on Big Data, Analytics and Artificial Intelligence who were tasked to think through what a global digital ecosystem for the environment might look like. The paper perfectly summarizes key points discussed in this report and outlines some recommendations as to how this should be achieved – these are presented in Box 23.

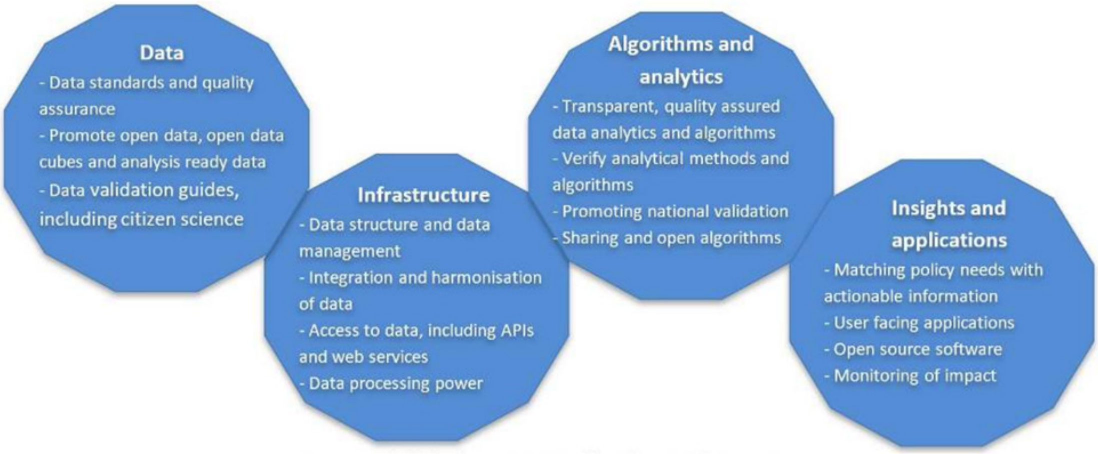
Box 23: UN Environment's key ways to pursue a digital ecosystem for the environment[261]

UN Environment's key recommendations to pursue a digital ecosystem for the environment

- Citizens must be engaged and empowered to use data and information to improve their own lives, communities and environment, while also holding leaders accountable. Citizen science initiatives need to be scaled and institutionalized in a manner where they become sustained, with trusted data streams.
- Countries must create a policy environment that promotes open data and a culture of data integration, use, innovation and governance in order to deliver tangible benefits to their citizens, as well as monitor their own progress towards the SDGs and multilateral environmental agreements.
- There is a need to move from awareness about Big Data and frontier technologies to understanding them and their practical applications that can be scaled by non-technical users and decision-makers. There is also a need to harness the power of data, AI and mobile apps to nudge consumer awareness and behavior towards sustainability.
- Public-private partnerships (PPPs) are needed in order to leverage private sector expertise and infrastructure in data science, cloud computing and AI, to share data and to promote the use of technology for global public goods.
- Environmental data custodians must make their data sets as open and interoperable as possible, allowing data to flow across digital ecosystems using web services and APIs. Environmental organizations should adopt common data strategies, assigning specific leadership rolls to different actors and agreeing on the core global public good data sets that are needed to monitor the health of the planet and progress against different global agreements.
- There is a need to curate and release global data analytics on environmental risks that have the power to influence global markets and investments towards more sustainable resource-management solutions.
- There is a need to build on, and leverage, existing partnerships and practitioner communities to ensure that the digital ecosystem for the environment is inclusive and does not overlap with, or duplicate, existing activities. Non-governmental organizations also need to increase their engagement on this topic and perform a critical watchdog function.
- The UN should take a leadership role and make a longer-term investment in convening stakeholders around a common vision for developing a global digital ecosystem for the environment, including new and innovative partnerships with all key actors. The UN should help broker partnerships that meet multiple criteria and demonstrate how data can be transformed into action, as well as global efforts to fill key data gaps. The UN also needs to take a more proactive role to promote open data, open source software, interoperability of data, and to provide guidance on which global data sets are the 'best available'.

Figure 33 further summarizes UN's Environment's proposed digital environment ecosystem for data, algorithms and insights.[262]

Figure 33: UN's Environment's proposed digital environment ecosystem [xxxiii]



As the above shows, frontier technologies offer significant potential to provide innovative ways to address and combat the drivers and impacts of climate change. Although still considered to be emerging, these technologies comprise innovative solutions to meet the needs of the world's population while addressing those of the planet. Cities and urban regions form the perfect backdrops to test bed frontier technologies to mitigate climate change. Continuing innovation, therefore, must be cultivated, nurtured and incentivized by local and national governments alike, in partnership with industry and academia.

Furthermore, many emerging technologies are inter-related, especially the Internet of Things (IoT), Artificial Intelligence (AI), 5G and Big Data. While the concepts of many of today's emerging technologies have been around for some time, it is now becoming feasible to implement IoT and scalable information systems on larger scales. Therefore, ensuring the affordable and wide-scale deployment of these 'enabler' and other connective technologies will assure further advancement and the adoption of other frontier technologies.

Even in instances where existing frontier technologies may not yet offer solutions to the complex challenges that faced at present or those that are expected to be faced in the future, the rapid advancement of overall technology trajectories will likely result in new or more effective frontier technology solutions in the future. Consequently, the assessment of emerging technology trends and scalable deployment of existing frontier solutions should play a part in any city's resilience strategy over the foreseeable term.

It must be noted, however, that these technologies can be a contributor to, and part of, the solution for climate change. They do have an environmental impact at each stage of their life cycle due to the energy consumed during their production, distribution and use, and the associated GHG emissions. However, if their double-edged nature is recognized and accounted for by policy makers, a balance can be achieved wherein their potential in helping to monitor, adapt to and mitigate climate change can be unlocked and optimally leveraged to ensure tangible, measurable progress.

Scaling frontier technologies is particularly vital for achieving widespread impact and lower deployment costs. As this report shows, most deployments vary significantly in the level of interest, investment, scale and complexity according to geography. Further research, processes and standardization efforts are needed to identify successful-use cases of frontier technologies in the context of climate change and response in order to eventually scale them nationally, regionally and – ultimately – globally.

Lastly, addressing climate change is everyone's responsibility, not just of the UN Member States but also of, as the UN Secretary-General remarked recently, 'the full constellation of partners, including cities, local officials, the private sector, finance institutions, the philanthropic community and civil society.' "Bottom up" ambition everywhere, therefore, is crucial.[263]

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