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Innovation for the Earth

Harnessing technological breakthroughs for people and the planet

In this report

pwc

Foreword

The World Economic Forum (WEF) has called the current explosion in technological innovations the 4th Industrial Revolution (4IR). It is underpinned by innovations ranging from rapid advances in artificial intelligence and robotics to the internet of things, nanotechnology, and quantum computing. These breakthroughs have the potential to transform business models and industries globally. But how can 4IR technologies have an equally transformational impact on people and the planet?

The challenge to Earth: there is mounting scientific consensus that Earth systems are under unprecedented stress. Our model of human and economic development, developed during past industrial revolutions, has largely come at the expense of the planet. The Earth's climate, water, air, biodiversity, forests and oceans are under increasing strain.

Making the 4IR a sustainable revolution is the opportunity of this generation. The systems change required to deliver a clean, resource-secure and inclusive economy can be enabled by technology and supported by public policy and investment. But these same technological advances could also have unintended consequences in accelerating risks to the Earth and society if they are not designed and scaled in a smart and sustainable way. Setting the course for a responsible 4IR now will be key to tackling our planet's urgent environmental, social, and economic challenges.

Companies are still in the early stages of grappling with the 4IR and what it means for their business, but CEOs are under no illusions as to its importance. In this year's PwC Annual CEO Survey[1], innovation is ranked as the top business priority to strengthen, with 71% of CEOs also concerned at the speed of technological change for their growth prospects.

As companies, entrepreneurs and investors across sectors look at how the technologies of the 4IR can create strategic advantage, this report takes a look at the opportunity for technology to be a means to deliver much broader economic, social and environmental benefit. We look at how innovators can harness 4IR advances to help solve Earth challenges, while creating commercial advantage. This report focuses in particular on the challenge of climate change. In future, we will examine broader global challenges linked to the 4IR.

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[1] PwC's 20th CEO Survey. http://www.pwc.com/gx/en/ceo-agenda/ceosurvey/20th-anniversary.html

Introduction: 4IR for the Earth
The challenge and opportunity

Backdrop

The events of 2016 underscore the combination of social, environmental and economic challenges confronting large segments of the world's population. From climate stresses to job losses, to automation and mounting economic inequality. The purpose of this report is to examine, in the specific domain of one of the stresses, climate change, to what extent technology can provide transformational solutions. What's coming on stream, in terms of technologies? What are their sustainable applications? What, finally, are the recommendations for accelerating their deployment at scale?

The challenge

We are living in a world facing unprecedented global challenges. The Earth has been in a state of relative stability for the last 10,000 years, enabling civilisations to thrive. In a short space of time, however, this stability has been put at risk. Scientists at the Stockholm Environment Institute have identified that four out of the Earth's nine 'Planetary Boundaries' have been crossed, namely climate, biodiversity, land-system change and biogeochemical cycles[2]. Risks will only heighten as population swells to a projected 9 billion by 2050 increasing food, materials and energy needs.

The opportunity

We are also witnessing an era of unprecedented technological change – the so-called 4th Industrial Revolution (4IR) as defined by the World Economic Forum – which offers unparalleled opportunities to tackle these challenges[3]. There are two key attributes that differentiate the 4IR from the industrial revolutions that preceded it, and these create a remarkable opportunity for innovation to secure the sustainability of our planet:

1. **The 4IR is much more connected and global.** Building on the innovations of the 3rd industrial revolution – the rise of digital technology, computing and the internet – the 4IR has become the most rapid period of innovation, ever. 4IR technologies driven by zero-cost digital distribution can penetrate the mainstream, impact many sectors, and rapidly 'go global' in a matter of years.
2. **The 4IR is smarter.** 4IR technologies have the ability to deliver a unit of output with fewer units of energy. The digital economy underpinning the 4IR is intrinsically connected, making it possible to increase global and local optimisation, and to become more efficient (e.g. energy efficiency enabled by smart home meters, 'eco-driving' and route optimisation of self-driving cars, local production enabled by 3D printing).

4IR technologies for the Earth

This report shines the spotlight on ten 4IR technologies that we contend will be the most influential over the coming decade. Their influence will not only be in shaping industry and businesses worldwide, but in helping, if proactively harnessed to do so, to safeguard the planet's sustainability. We focus here specifically on environmental sustainability, but acknowledge that there are broader social challenges of the 21st century that must equally be addressed.

Focusing on the urgent challenge of addressing climate change, this report sketches out how these ten 4IR technologies for the Earth could be used to address our five climate solution levers: clean power, smart transport systems, sustainable production and consumption, sustainable land use, and smart cities and homes.

Solution types range from entirely new business models that could disrupt traditional industries and sectors, to optimising existing products and services, for example around energy efficiency, waste, and performance. We then identify five key game-changers where multiple 4IR technologies could scale climate solutions in a meaningful way in the short to mid-term. We conclude by proposing practical steps for businesses, investors, governments and research institutions to take to maximise the opportunity.

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[2] Steffen et al. (2015). 'Planetary boundaries: Guiding human development on a changing planet'. Science. 347 (6223)

[3] Klaus Schwab, 'The Fourth Industrial Revolution: what it means, how to respond,' World Economic Forum, 2016

Driving innovation

The role for governments and business

The instrumental role of governments

History has shown how government R&D investment programmes, coupled with access to government computing power, have played an instrumental role in catalysing innovation and private markets to create common goods, including big breakthroughs in space, pharmaceuticals, and technology. 20th century examples that touch everyday 21st century lifestyles include government-funded research in the systems that lie behind GPS, touch screens, and the internet.

Today, amidst the 4IR world, the private sector has unprecedented access to immense computing power, global connectivity, data and technology that can bring innovative concepts into the world faster than ever. But governments will play a critical role in ensuring 4IR innovations benefit both people and the planet.

Addressing market failures

Governments can address market failures in two key ways. The first is by identifying economic or environmental externalities that the market does not capture, and coming up with regulatory or market mechanisms to address this market failure. The second is by providing access to early-stage capital and underwriting risk to support breakthrough innovations and enable commercialisation.

Technological governance

In the context of the radical disruptions that the 4IR makes possible, there is increasing consensus that there is a third potential role for government providing technological governance. This mechanism that evaluates the overall societal impact of technological innovations, assessing and mitigating negative effects, and accelerating technology that delivers broader social, economic and environmental outcomes for society.

Accelerating investment

Whilst the UN Paris Agreement[4] provides a process for countries to ramp up their climate policy and investment ambition, and for businesses and investors to recognise the transition to a clean economy is real and underway, the current system is not going to change fast enough. The same threat applies for other global environmental challenges – from biodiversity and species loss to water security. The urgency of addressing Earth's environmental challenges, including climate change, will therefore require dramatically increased public and private sector investment. The resulting shift in investment flows would enable sustainable solutions to succeed over unsustainable ones in the market.

Staying the course

Growing geopolitical complexity, financial volatility, and strained global governance will make government cooperation on global environmental challenges tougher in the short-term. Following through on the political intent evidenced by, for example, the 22+ country strong 'Mission Innovation' initiative[5] to double government R&D funding on clean energy innovation over the next five years will be critical. Political ambition, cooperation and investment must continue to accelerate rapidly. But with geopolitical uncertainty and volatility, the imperative for market-driven sustainability solutions – harnessing leading entrepreneurs and investors – becomes stronger than ever.

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[4] http://unfccc.int/paris_agreement/items/9485.php

[5] http://mission-innovation.net/

The business imperative

To what extent does the current wave of technological innovation in the private sector address Earth's key challenges?

Companies across the world of every size, in every sector, feel the influence of technological breakthroughs of the 4IR. Responding to this, they increasingly have tech-savvy leadership teams, and corporate technology strategies and roadmaps. Our Digital IQ survey found that companies that are technology leaders in their industries are twice as likely to achieve rapid revenue and profit growth as the laggards[6]. Companies are investing in sustained innovation around 4IR technologies to harness potential market opportunities to sell more, make more, reduce costs and open up new revenue streams.

Entrepreneurs in start ups are pioneering 4IR solutions for both breakthrough and disruptive innovations to create radical new market-making solutions and displace existing market incumbents. Lower cost technology, global connectivity, the open-source movement, and increased access to capital has lowered barriers to entry and enabled start-ups to scale more quickly than ever.

Both groups are highly focused on how 4IR solutions can harness growth opportunities in the existing markets they know well and 'call home'.

Moon-shots, introduced by Silicon Valley pioneers, are innovations designed to propel humanity forward, funded by philanthropists and big companies (e.g. Google's X, Elon Musk's SpaceX, Mark Zuckerberg's Biohub). High-profile moon-shots include life extension; the production of 'true' artificial intelligence (AI); flying cars/ taxis; space elevators; and efforts for humans to land on (and perhaps colonise) Mars. They rarely focus on Earth's sustainability; or as it could be described – Earth-shots.

While each of these groups of innovators are focused on creating a new future powered by technological advances, the opportunity to harness 4IR innovations to develop breakthrough solutions to solve the most pressing challenges for the Earth itself is still largely untapped.

Motivations for investment

The motivation for investment in 4IR for sustainability is not simply to secure the Earth's future, but also the opportunity to make commercial returns. Sustainable products and services present a growth market, backed by the commitment of governments globally to a low-carbon economic transition by mid-century[7], the Sustainable Development Goals (SDGs), and to the resulting required reforms of market capitalism. Meaningful returns can also be realised in the short term, where novel technologies become cost competitive quickly (e.g. solar technologies), or sustainable goods and services simply provide a better user experience (e.g. home smart meters, or ride-share apps).

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[6] PwC, 2015 Global Digital IQ Survey: Lessons from digital leaders – 10 attributes driving stronger performance, 2015.

[7] The UN Paris Climate Agreement – https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf

The innovation landscape of the 4IR

4IR innovations can be grouped into three broad categories that relate to the Digital, Physical and Biological worlds (Figure 1). As cyber-physical systems emerge, however, these distinctions become increasingly blurred and innovations cross categories, for example wearable technologies and nano-devices. Many of these innovations are nascent, but some are already reaching tipping points in their development as they are increasingly combined to create fused solutions, like the IoT and autonomous vehicles connected to smart transport networks.

Figure 1 : Examples of 4IR technologies across the innovation landscape

Biological

- Optogenetics
- Next-generation genomics
- Systems metabolic engineering
- Bioinformatics

- Neurotechnologies
- Stem cells
- Synthetic biology
- Personalised medicine
- Nanoparticles

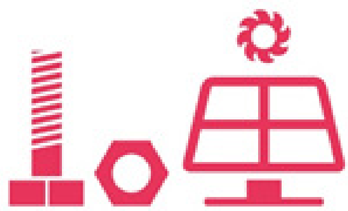
Digital

- Digital twins
- Augmented Reality
- Blockchain
- Cloud technology
- Virtual Reality
- Artificial Intelligence

- Robotics
- Internet of Things
- Big data analytics
- Industrial Internet of Things
- 3D printing
- Quantum computing

Physical

- Next-generation batteries
- Advanced materials
- Nanomaterials
- Autonomous vehicles



- Nanodevices
- Wearable technology
- Micro/nano satellites
- Organ microchips

Source: PwC analysis using WEF 4IR categories.

In our 2016 PwC Technological Breakthroughs Megatrend report[8] we screened over 150 technologies to identify the 'Essential Eight' technologies with global, cross-industry business impact in the next 5-7 years. Here we have used the same data set of 150 technologies likely to mainstream the business world within the next decade to build on the original eight to focus on those which also have the ability to address Earth challenges. Synthetic biology and advanced materials, both of which are critical to low-carbon breakthroughs, are added to the list, which we call the 'Top Ten 4IR technologies for the Earth'.

Figure 2 : Top ten 4IR technologies for the Earth

1. *Advanced materials*
   Materials with significantly improved functionality, including lighter-weight, stronger, more conductive materials, e.g. nano-materials.

2. *Cloud technology, including big data*
   Enables the delivery of computer applications and services over the internet reducing storage and computer power needs. Big data enabled by cloud allows predictive relationships to form, underpinning optimisation.

3. *Autonomous vehicles, including drones*
   Enabled by robots these are vehicles that can operate and navigate with little or no human control. Drones fly or move without a pilot and can also operate autonomously.

4. *Synthetic biology*
   Inter-disciplinary branch of biology applying engineering principles to biological systems. The market for biotechnology already exceeds $80Bn/year.

5. *Virtual and Augmented Reality*
   Computer-generated simulation of a three-dimensional image overlaid to the physical world (AR) or a complete environment (VR).

6. *Artificial Intelligence*
   Software algorithms that are capable of performing tasks that normally require human intelligence, e.g. visual perception, speech recognition and decision-making.

7. *Robots*
   Electro-mechanical machines or virtual agents that automate, augment, or assist human activities, autonomously or according to set instructions.

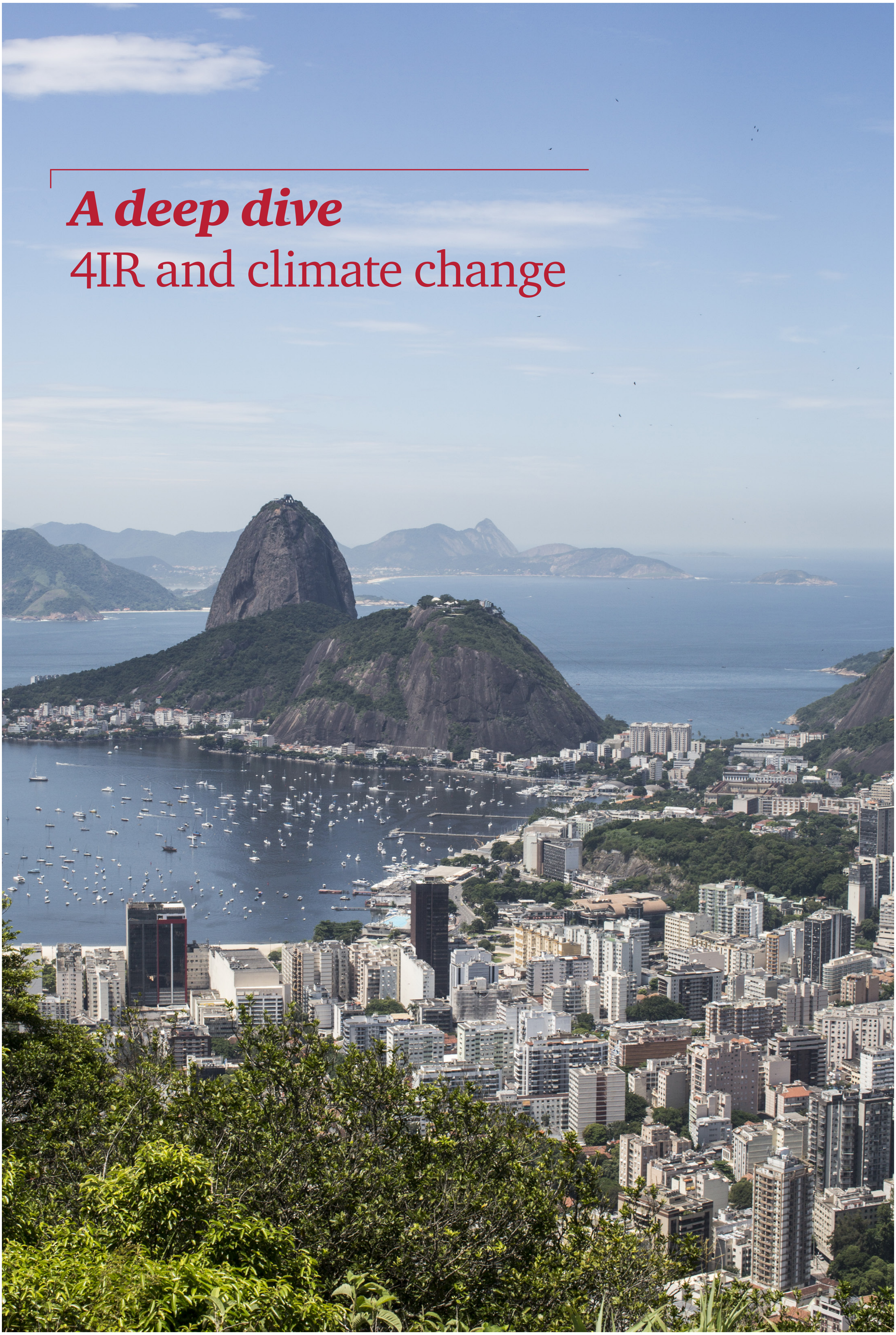
8. *Blockchain*
   Distributed electronic ledger that uses software algorithms to record and confirm transactions with reliability and anonymity.

9. *3D printing*
   Additive manufacturing techniques used to create three dimensional objects based on 'printing' successive layers of materials.

10. *Internet of Things*
    Network of objects embedded with sensors, software, network connectivity and computer capability, that can collect and exchange data over the internet and enable smart solutions.

Source: PwC analysis

[8] PwC Technology Breakthroughs Megatrend: how to prepare for its impact. 2016. http://www.pwc.com/gx/en/issues/technology/tech-breakthroughs-megatrend.pdf



A deep dive
4IR and climate change

The Intergovernmental Panel on Climate Change (IPCC)[9] has warned that our current trajectory of greenhouse gas (GHG) emissions will give rise to adverse impacts on people and ecosystems through water stress, food security threats, coastal inundation, extreme weather events, ecosystem shifts and species extinction on land and sea[10]. Scientists have set a 2°C global temperature rise as the 'safe limit' at which there is a reasonable chance of avoiding climate feedback loops and irreversible climate change. At current rates of decarbonisation, we will have used up our 2°C carbon budget by 2036 – well within most readers' lifetimes (PwC LCEI 2016[11]). The challenge of climate change is an urgent one, and will impact nearly all aspects of the Earth system and human society.

Policy progress has been made over the past twenty years, both globally and at a national level, culminating in the 2015 global Paris Agreement and the national-government-proposed emissions targets that underpin the agreement. Meanwhile, technological progress has been fast-paced in some areas. This has included renewable energy, where globally wind and solar PV are currently the fastest-growing sources of electricity, and have become technologically mature and commercially competitive, according to the IEA[12].

Notwithstanding such policy development and technological progress, however, each year the world still has a steeper mountain to climb to reach its overall carbon (and greenhouse gas) goals. The PwC Low Carbon Economy Index, for example, shows that the rate of global decarbonisation required is increasing year-by-year. In 2016 the annual rate of decarbonisation required has risen to 6.5% to remain within the agreed 2°C global carbon budget – more than double the actual 2.8% decarbonisation rate the world economy recorded last year and four times the 21st century average. To have a realistic chance of meeting a 2°C global temperature rise limit therefore – and keeping the 1.5°C objective in the Paris Agreement realistically in play – a step-change in low-carbon transformation is required, and rapidly.

An acceleration in decarbonisation of the economy will require both policy and investment support for more rapid deployment of technologies already developed, and the need for breakthrough innovations and technologies to deliver a step-change in emissions reduction.

We have divided the solutions space into five climate solution levers that are the biggest contributors to global GHGs (Figure 3). Within each of these climate levers there are known technical solution areas which require innovation to realise their potential and enable scale of deployment (Figure 4).

In the following section we showcase how our top ten 4IR technologies for the Earth help to deliver advances for each of these solution levers. In the final section we highlight how multiple 4IR technologies can come together to lead to game-changing climate solutions.

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[9] https://www.ipcc.ch/

[10] IPCC 5th Assessment Report, 2013-2014. https://www.ipcc.ch/report/ar5/

[11] PwC Low Carbon Economy Index 2016. http://www.pwc.co.uk/services/sustainability-climate-change/insights/low-carbon-economy-index.html

[12] International Energy Agency, 2016: Next Generation Wind and Solar Power – From Cost to Value

Figure 3 : Our five climate solution levers[13]

Clean power

The global power sector accounts for

25%

of global Greenhouse Gas (GHG) emissions

And is central to decarbonisation and electrification goals. Investment of around

$20 trillion

is likely to be required by 2040

Smart transport systems

The transport sector accounts for nearly

15%

of global GHG emissions

And just over

50%

of current global oil demand

Sustainable production and consumption

Industry accounts for just over

20%

of global GHG emissions

While circular economy models could add up to

$1 trillion

to the global economy by 2025

Sustainable land-use

Agriculture, deforestation and degradation accounts for

25%

of global GHG emissions

And food production could need to rise by

60%

to feed a global population of 9bn by 2050

Smart cities and homes

Cities are responsible for up to

70%

of global GHG emissions. Buildings alone account for 40% of global energy use

The proportion of the world's population in urban areas is expected to rise to

60% ***by 2030***

Source: PwC analysis, IPCC, New Climate Economy, IEA, UNEP, FAO, C40

[13] Note that if we take GHG emissions from buildings, then these five levers add up to 100% of GHG emissions. Cities and homes more broadly is cross-cutting, and therefore the emissions figure here is not additive to the others.

Figure 4 : Technical innovations to implement the five climate solution levers

Clean power

- Cheap renewables generation
- Advanced energy storage
- Clean fossil fuels
- Next-generation grid management
- Carbon capture, sequestration and use
- Energy efficiency
- Renewable heat
- Next-generation nuclear fission
- Nuclear fusion

Smart transport systems

- Clean liquid and gaseous fuels
- System efficiency solutions
- Clean long-haul transport
- High-efficiency engines
- Next generation batteries
- Energy-dense gaseous fuel storage
- Technology enabled transport systems

Sustainable production and consumption

- Circular economy recycling solutions e.g. cradle to cradle
- Sharing economy
- Reduced waste and energy production
- Clean chemicals, steel, cement, and paper production
- Extreme durability for energy-intensive products and materials
- Extreme efficiency of IT/Data centres
- Supply chain transparency
- CO_2 extraction from manufacturing

Sustainable land-use

- Land-use transparency
- Low-emissions agriculture
- New-techniques in forest management
- Reduced losses in the supply chain
- Soil sequestration
- Low-emissions sources of protein
- Reduced emissions from livestock
- Reduced deforestation

Smart cities and homes

- Connected homes
- High-efficiency heating, cooling, lighting, and appliances
- High-efficiency windows and insulation
- Building energy storage
- Technology-enabled urban planning and building design
- Next-generation commercial building management

Source: PwC, building on Breakthrough Energy Coalition 'Landscape'

Emerging applications of 4IR technologies to address climate change

To help provide answers on how 4IR innovations could be deployed towards building a low-carbon future, we have undertaken a mapping of key emerging applications across each of the Top Ten 4IR technology areas (Figure 5).

The mapping is not exhaustive but representative of the most prominent innovations at concept prototyping (e.g. Hyperloop[14]), early adoption (e.g. 3D printed buildings) and in some cases scaling rapidly (e.g. Industrial IoT and on-demand shared mobility services). We anticipate many new examples will emerge over coming months and years. The challenge for innovators, investors and governments alike is to not only identify and scale these pioneering innovations, but also to mainstream sustainability considerations into wider 4IR technological breakthroughs.

Figure 5 : Top-ten 4IR technologies for the Earth – applications for a low-carbon economy

Advanced materials 1

- **Perovskite (solar cell) coatings:** To potentially double the efficiency of solar cells.
- **Graphene applications:** Energy efficient, lightweight material usable across sectors, from solar cells to transport.
- **Efficient concrete:** To reduce materials in production and absorb carbon dioxide as it hardens.
- **Designer carbon:** Nanotechnology-inspired material to make carbon capture sequestration, energy storage devices and solar more powerful and efficient.
- **Solar sprays:** Providing solar cell capability to vehicle and building coverings, including roofs.
- **Advanced battery manufacturing:** To improve energy storage and renewables' potential.
- **Heat reducing materials:** Paint coatings that reduce heat absorption from the sun, reducing air-conditioning needs.
- **Next-generation ceramics:** Advanced ceramics for nuclear fission and fusion applications.
- **Super insulating and acoustic materials:** To improve buildings' efficiency.
- **Advanced carbon fiber composites:** To provide ultra-light and ultra-strong materials e.g. for Hyperloop applicatons.
- **Nanotechnology in fuel cells:** Using nanotechnology to provide better fuel cell performance and durability.

Cloud technology, including big data 2

- **Land-use detection and monitoring:** To track and verify deforestation.
- **Renewable energy peer-to-peer platforms:** To enable individuals to trade and optimise household renewable energy supply and demand.
- **Virtual energy storage networks:** To enable users to buy and sell excess renewable energy back to the grid.
- **Cloud computing homes heating:** Domestic heaters/servers that utilise waste heat from cloud data processing.
- **Cloud-based appliance control:** Using cloud-based platforms to manage appliance use.
- **Ecosystem genetic code bank:** To verify and protect ecosystems by recording genetic codes.
- **Vehicle-infrastructure communication:** Using the cloud to better manage traffic flows and improve efficiency.
- **Building Information Modelling:** Using a single and real-time collaborative cloud-based design mode.
- **Digital planning processes:** Using large datasets to enable participatory planning processes.
- **Weather-forecast-controlled farming:** Using the cloud and big data to manage irrigation devices.

[14] Hyperloop is a proposed mode of super high speed land-based transportation of passengers and freight that propels a pod-like vehicle through a near-vacuum tube. See: http://www.spacex.com/hyperloopalpha.

Autonomous vehicles 3

- **Mobility-on-demand services:** To maximise efficiency and utilisation of the vehicle network, including car sharing.
- **Open-sourced driver assistance programmes:** Software to improve autonomous vehicles' functionality and energy efficiency.
- **App-based autonomous vehicle networks:** Using the cloud and apps to optimise (including in efficiency) a network of autonomous vehicles.
- **Autonomous vehicles in industry:** Self-driving industrial vehicles to streamline manufacturing and production processes.
- **Drones for renewable energy maintenance:** To ensure that renewable installations are operational more of the time.
- **Drones for high-resolution real-time aerial data solutions:** To more efficiently manage land-use, transport, pollution etc.

Synthetic biology 4

- **Bioplastics:** Plastic alternatives made of biomass which use less much energy to produce.
- **Stem cell cultivation:** Using biotechnology instead of animals to produce synthetic proteins, including meat.
- **Genome editing in plants:** To make crops more productive and resistant to climate change, including drought.
- **Synthetic biofuels from genetically modified algae:** Replacing fossil fuels with plant-based alternatives.
- **Converting agricultural waste into surfactants:** Improving efficiency and reducing raw material usage for product manufacture.
- **Carbon capture and utilisation:** Using synthetic biology to convert carbon dioxide into useful feedstocks or products.

Virtual and Augmented Reality 5

- **Virtual meetings:** Reducing the need for international business travel.
- **Supply chain monitoring:** Virtual factory visits improving efficiency and reducing international business travel.
- **Virtual learning experiences:** Immersive environmental learning experiences to alter consumer behaviour.
- **Virtual shopping:** Ability to shop virtually reducing urban traffic and congestion.

Artificial Intelligence 6

- **AI optimised energy system modeling and forecasting:** Decreases unpredictability, and increases efficiency, power balancing, use, and storage of renewable energy.
- **Neural networks for solar:** Improve frequency, reliability and affordability of photovoltaic energy.
- **Machine-automated land-use change monitoring:** To detect and monitor de/reforestation.
- **Auditory cue responsive lighting and heating:** To utilise lighting and heating only when required.
- **Sustainable building design:** To maximise energy and product efficiency in building design.

Robots 7

- **Preventing pollution and emissions:** Monitoring and preventing the release of harmful greenhouse gases.
- **Optimising the manufacturing process:** Precision manufacturing reducing energy consumption.
- **Precision strength:** Robots minimising the need for larger less-efficient machines.
- **Eliminating product waste:** More efficient use of raw materials.

Blockchain 8

- **Renewables cryptocurrency:** Global currency to trade solar power across countries.
- **Emissions trading platforms:** Zero cost real-time transactions for emerging Emissions Trading Systems (ETS) and future public and corporate schemes.
- **Micro-generated grids:** Blockchain-enabled markets to expand renewables' penetration.
- **Virtual power plants:** Connecting and optimising energy-generating resources virtually.
- **Supply chain monitoring, product tracking, origin chasing:** To verify product origins and sustainable sourcing.
- **Finance provision:** Blockchain-enabled affordable access to capital including forest bonds, and payment by performance etc.

3D printing 9

- **Solar cells:** More efficient and less costly production of solar cells, with less waste.
- **Solar spray:** Thin solar spray to expand solar usage to building and vehicle surfaces.
- **Printed cars:** Streamlined process of printing cars that are lighter and more efficient.
- **Printed buildings:** Allowing simplified building, reducing raw materials usage and waste, increasing energy efficiency.
- **Localised production reducing transport:** Local production of global designs, reducing final product transportation.
- **Optimised product design:** Additive manufacturing utilises only the raw materials needed, reducing waste.
- **Intelligent packaging:** Reducing food waste.

Internet of Things 10

- **Smart home-system heating, hot water and lighting:** Meters and sensors that more efficiently manage central heating and applicances including air conditioners, hot water systems and lighting.
- **Industrial lifecycle tracking:** Optimise maintenance, energy efficiency, recycling and remanufacturing of industrial machinery.
- **Intelligent grids:** Sensor-based grid management, which sometimes incorporates Blockchain technology.
- **Product web-identity:** Enables companies to track products' supply chains and reduce waste and energy usage.
- **Peer-to-peer energy networks:** Using sensors to facilitate local renewable energy markets via the cloud.
- **Smart urban mobility systems, including transport and parking:** Sensor-based real-time traffic-flow management.
- **Smart urban energy, water, waste systems:** Using sensors to better manage municipal resource use and waste collections.
- **PAY-G energy services for off-grid:** IoT sensors and mobile money systems combine to enable off-grid access.
- **Genetic code banks:** Using sensors and tagging technology to log genetic codes, which enable financial transactions.

Top ten 4IR technologies for the Earth mapped to climate solution levers

We also map these top ten 4IR technologies to how they are currently being applied across each of the five climate solution levers (Figure 6). By narrowing down the spectrum of 4IR technologies to a starting list of the top 10 for sustainability and industry, we provide some focus and clarity, but would expect a much wider solution set over time in reality.

Each climate solution lever stands to benefit a great deal from 4IR, as seen in the following snapshots:

Figure 6 : 4IR technology applications for a low-carbon economy – by climate solution lever

1. Clean power

Block chain
- Renewables cryptocurrency
- Emissions trading platforms
- Micro-generated grids
- Virtual power plants

3D printing
- Solar cells and sprays
- Wind turbines

Internet of Things
- Intelligent sensor-based grid management
- Peer-to-peer energy networks for distributed grid
- PAY-G energy services for off-grid

Autonomous vehicles
- Drones for renewable energy maintenance

Advanced materials
- Perovskite solar cell coatings
- Graphene applications
- Solar sprays
- Advanced battery manufacturing
- Heat reducing materials
- Next generation ceramics for nuclear
- Nanotechnology in fuel cells
- Designer carbon for CCS

Cloud and big data
- Renewable energy peer-to-peer platforms
- Virtual energy storage network

Artificial Intelligence
- Optimised energy system modeling and forecasting
- Neural networks for solar energy
- PAY-G energy services for off-grid

Synthetic biology
- Synthetic biofuels

Smart grids, connected to each other via the cloud, and utilising the IoT, big data analytics and machine learning, can significantly increase the energy efficiency of the existing grid. Enhanced predictability of demand and renewables supply, can also enhance energy storage and load management, and assist the integration and reliability of renewables.

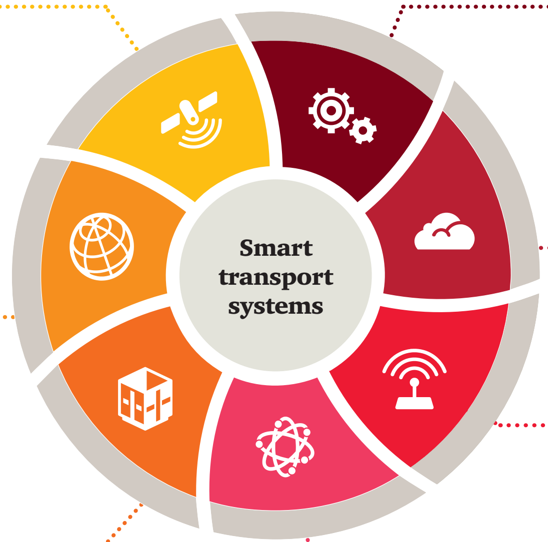
The energy performance and affordability of renewables and battery storage solutions can also be increased through innovations such as perovskite solar cell coatings, designer carbon, graphene applications and battery nano-solutions (all advanced materials), neural networks as a solar boost convertor (AI), and 3D solar panels (3D printing). A distributed peer-to-peer grid leveraging distributed renewables can be facilitated through a fusion of IoT, Blockchain, AI, cloud and big data.

2. Smart transport systems

Autonomous vehicles
- Mobility-on-demand services
- Open-sourced driver assistance programmes
- App-based autonomous vehicle networks
- Autonomous vehicles in industry
- Drones for real-time traffic data

Virtual and Augmented Reality
- Virtual meetings
- Virtual shopping

3D printing
- Printed cars
- Localised production reducing transport



Advanced materials
- Advanced battery manufacturing
- Graphene applications
- Advanced carbon fibre composites
- Nanotechnology in fuel cells

Cloud and big data
- Vehicle-infrastructure communication

Internet of Things
- Smart urban mobility systems, including transport and parking

Synthetic biology
- Synthetic biofuels

Source: PwC research and analysis

Smart transport systems can be realised by employing a number of 4IR technologies working in conjunction. 3D printing and advanced materials enable lighter, more efficient vehicles and local production, with the potential to reduce further energy needs and emissions. 4IR solutions within advanced materials also play a key role in enabling low and zero emissions vehicles (electric vehicles (EVs), fuel cells and hydrogen) to compete with and ultimately replace the carbon-intensive internal combustion engine. Electrification of short-haul transportation enabled by advanced material breakthroughs for inexpensive energy dense batteries help to make zero-emissions EVs cost and performance competitive. Autonomous vehicles can improve the energy efficiency of road transport, in addition to rapidly progressing cost-competitive vehicle sharing services. The cloud and big data enable vehicles to communicate with transport infrastructure to manage better vehicle flows, eco-driving and network efficiency. Autonomous drones and sensors linked to IoT platforms can offer real-time traffic and logistics information for optimised routing.

Low-emissions long-haul transport solutions include the use of synthetic biology for advanced biofuels in international aviation and shipping. Elsewhere Hyperloop – a super high speed vacuum-based transportation system – is at the early stages of prototyping by a number of companies. It is projected that Hyperloop can be fully self-powered by solar panels along the tunnel surface. Advanced materials are planned for the tunnel, the vehicle, and for next-generation rechargeable battery storage devices.

3. Sustainable production and consumption

Synthetic biology
- Synthetic proteins from stem cells
- Bioplastics

Internet of Things
- Active tracking and optimisation of industrial machinery
- Product web-identity and supply chain tracking

Autonomous vehicles
- Autonomous vehicles in industry
- Drones for high-resolution real-time aerial data

Robots
- Optimised manufacturing processes
- Precision strength capabilities
- Eliminated product waste
- Preventing pollution and emissions

Advanced materials
- Efficient concrete
- Graphene applications

Blockchain
- Supply chain monitoring and origin tracing

Virtual and Augmented Reality
- Supply chain monitoring
- Virtual learning experiences
- Virtual shopping

3D printing
- Locally produced 3D printed products
- Energy efficient 3D printed buildings
- Optimised product design
- Intelligent packaging

A solution that is already being rapidly adopted is the 'Industrial IoT' (IIoT) which combines smart machines, smart materials, and smart products across an industrial value chain. The result is advanced production optimised for resource consumption and cost including energy, raw materials and water, whilst also enabling connection with customer devices to optimise lifespan performance. Wider 4IR technologies incorporated by the IIoT platform include Virtual Reality (VR) product simulators to optimise smart product design, sensor-driven computing, industrial big data analytics, energy efficient robotics, and intelligent machine applications (e.g. AI leveraging digital twins[15] that enable lifespan performance optimisation and smart meters). 4IR technologies like IoT connected sensors and Blockchain also revolutionise the ability to track and monitor products from origin through supply chains (e.g. web apparel identities), driving increased transparency accountability around sustainable manufacturing and consumption.

More broadly circular innovation looks to increase energy efficiency and reduce waste by putting re-use, remanufacturing, and recyclability at its core. It is estimated that accelerating circularity across global supply chains can yield over US$1 trillion per year by 2025 to the global economy[16]. Examples include: the IoT to identify when industrial machinery needs maintenance in order to maximise energy efficiency and increase product lifespan; 3D printing to allow for local manufacturing; advanced materials to design energy efficient or fully renewable, recyclable or biodegradable products; and cloud and IoT-supported digital sharing platforms to maximise utilisation of assets.

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[15] A digital twin is a digital copy that is created and developed simultaneously with the real machine, allowing concepts to be tested and refined before manufacture. http://gelookahead.economist.com/digital-twin/

[16] Ellen MacArthur Foundation, January 2014, 'Towards the Circular Economy Vol. 3: Accelerating the scale-up across global supply chains.'

4. Sustainable land-use

Internet of Things
- Ecosystem genetic code bank

Blockchain
- Supply chain monitoring and origin tracing
- Finance provision, including forest bonds

3D printing
- Intelligent product packaging

Autonomous vehicles
- Drones to monitor and manage land-use
- Autonomous vehicles in farming

Artificial Intelligence
- Machine-automated land-use change detection

Cloud and big data
- Land-use detection and monitoring
- Ecosystem genetic code bank
- Digital planning processes
- Weather-forecast-controlled irrigation devices

Synthetic biology
- Bioplastics
- Synthetic proteins from stem cells
- Genome editing in plants
- Biofuels from genetically-modified algae
- Converting agriculture waste into surfactants
- Carbon capture and utilisation

IoT, sensors, AI and cloud-enabled 'precision agriculture' can use on-farm sensors and connected machinery to access real-time data for farmer smart devices that can optimise how much water, energy, fertiliser and feed to use, increasing productivity whilst reducing energy use and product waste. Smart tracking and chasing systems using IoT connected sensors and tagging and GPS, supported by cloud computing can also support traceability of consumer goods and agribusiness supply chains, reducing food waste and GHG emissions. AI, Blockchain and the IoT together offer the ability to create a digital registry of biological and biomimetic knowledge assets in ecosystems like the Amazon[17] enabling natural assets to be valued, innovative biodiversity based value products and value chains to be developed, and rights and obligations protected. Via biomimicry of tagged natural forms and ecosystems, further 4IR enabled sustainability solutions can be developed, utilising nanoscience or bio-synthesis to create microbial fuel cells, and new energy generation and carbon sequestration technologies.

Low emissions protein development advances fuse together synthetic biology, AI, cloud and big data. Efforts harnessing synthetic biology are under way to develop new plant-based meat alternatives and lab grown meat, though many of these innovations remain some way from mass commercialisation, and safety must be considered hand-in-hand with sustainability benefits.

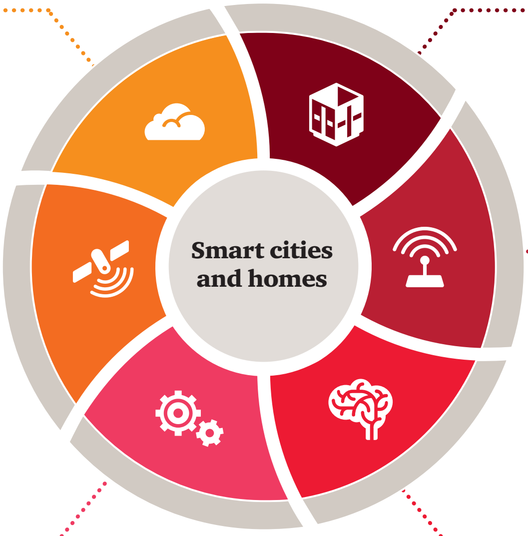
[17] Nobre et al. 2016: Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm, PNAS vol. 113 no. 39.

5. Smart cities and homes

Cloud and big data
- Cloud-computing homes heating
- Cloud-based appliance control
- Building Information Modelling
- Digital planning processes

Autonomous vehicles
- Mobility-on-demand services
- Open-sourced driver assistance programmes
- App-based autonomous vehicle networks
- Drones for real-time traffic data

Advanced materials
- Efficient concrete
- Solar sprays
- Heat reducing materials
- Super insulating and acoustic materials



3D printing
- Solar sprays for vehicles and buildings
- Printed buildings

Internet of Things
- Smart building systems to include heating, lighting, and hot water
- Smart urban mobility, energy, water, waste systems

Artificial Intelligence
- Auditory-cue responsive lighting and heating
- Optimised sustainable building design

Buildings and cities can utilise an array of 4IR technologies to improve efficiency and reduce emissions. Central to the concept of smart cities and buildings is the cloud and big data coupled with the IoT and AI. Smart building systems operate with a range of sensor-and cloud-based AI automated diagnosis and control systems, enabling remote management of water use, heating, lighting and appliances to improve building-use efficiency. Buildings can further improve efficiency by being linked to one another via the cloud and utilising the IoT, which together enable households and businesses to buy and sell renewable energy in peer-to-peer models. At a city level, urban planners and municipalities can use similar cloud and IoT technologies to optimise performance of urban systems – transport, electricity, waste collection etc. – further reducing energy use and improving energy efficiency.

Advanced materials offer the potential to improve the efficiency of the building itself, with efficient concrete, super insulating, and heat reducing, materials all playing a role. 3D printing can enable energy efficient and local building construction, and also offers the potential for building surfaces to generate their own energy with 3D printed 'solar sprays' creating photovoltaic capability for glass and other material surfaces. Finally, many of the advances in smart transport systems come to the fore in densely-populated urban areas with the potential to further progress urban low-carbon transformation.

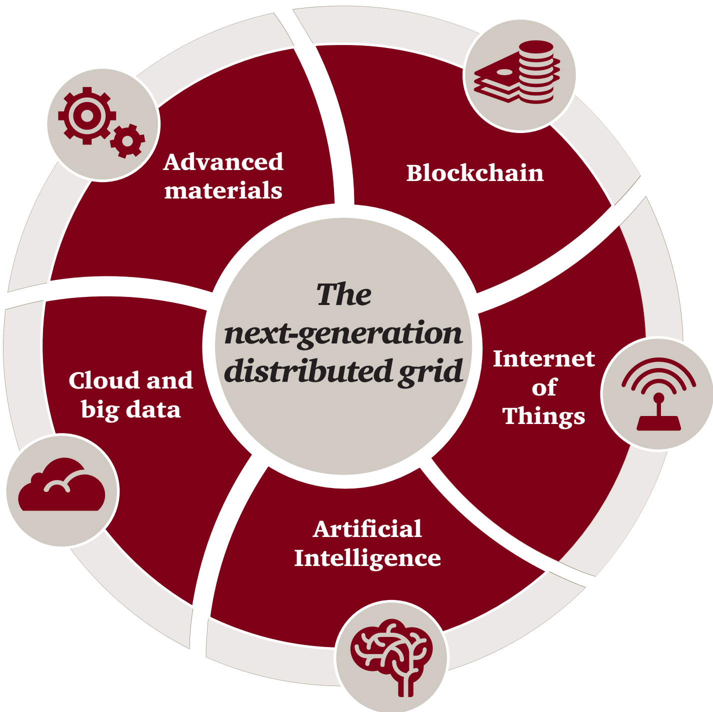
Five key emerging 4IR innovation game-changers for climate change

We have identified five key 4IR innovation game-changers, *which fuse together a number of our top ten 4IR technologies for the Earth,* and build on the technical areas within our climate solution levers. These five, when taken together, present substantial potential to move towards a zero-net-emissions economy (Figure 7).

Figure 7 : Emerging game-changing climate solutions building on multiple 4IR technologies

1) The next generation distributed grid: fusing Blockchain, IoT, AI, cloud and big data, and advanced materials

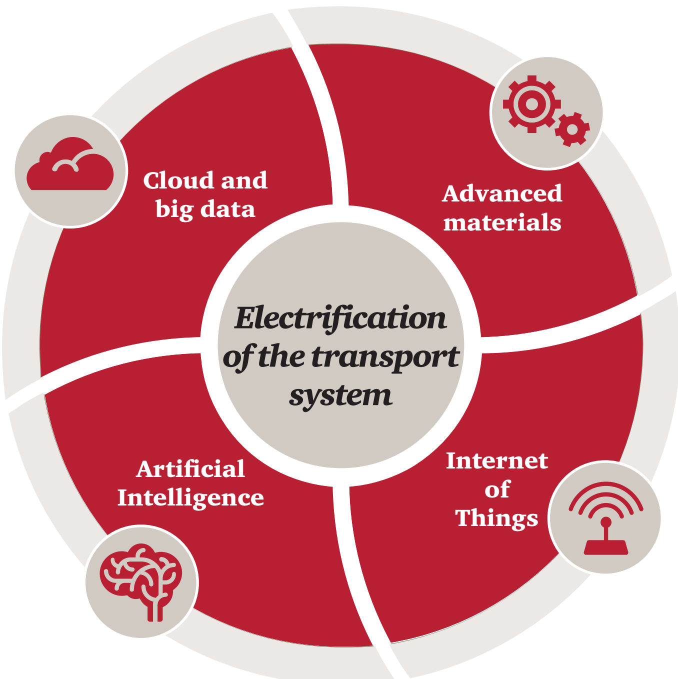
Making distributed energy possible at scale will revolutionise the useability of (and market for) renewables, increase energy efficiency, and disrupt traditional carbon intensive power grids. So-called 'virtual power plants' (VPPs) can aggregate emerging energy sources including solar panels, microgrids and energy storage installations, and optimise these resources using AI across the evolving electric grid. Blockchain can enable the scaling of micro-grids through organising, coordinating and securing transactions with smart contracts on a peer-to-peer power grid, allowing homes themselves to become anonymous agents in this grid. The IoT is a critical component of the system as it will enable billions of distributed smart devices to sense, respond and communicate data, and to buy and sell power. The cloud and its ability to harness big data is critical to data storage and optimisation of this network, as millions and ultimately billions of devices communicate and trade. Advanced materials play a key role, as new innovations like solar coatings and sprays, and advanced battery storage increase the distributed network of energy sources.



2) Electrification of the transport system: fusing advanced materials, IoT, AI, and cloud and big data

Electrification of short-haul transportation enabled by advanced battery breakthroughs for inexpensive, quick charging energy dense batteries could disrupt the market for carbon intensive internal combustion engines and make zero-emissions EVs cost and performance competitive. Advanced materials technologies will be critical, for example nano-tube lithium-ion battery technology which uses nano-materials combined with lightweight graphene to make a storage system. Other examples include solid state batteries as currently pioneered by Tesla and Dyson, or Lithium air as being developed by IBM. Digital twin technology can be used to optimise the performance of these emerging EV batteries. In addition, EVs with IoT sensors can deliver affordable smart vehicles that not only identify nearby charging stations, but improve energy efficiency through optimal navigation systems, automated driving capability, enabled ride-share services, and make EV charging more affordable via IoT and cloud-based demand-response software programs enabled by big data (e.g. Auto Grid).

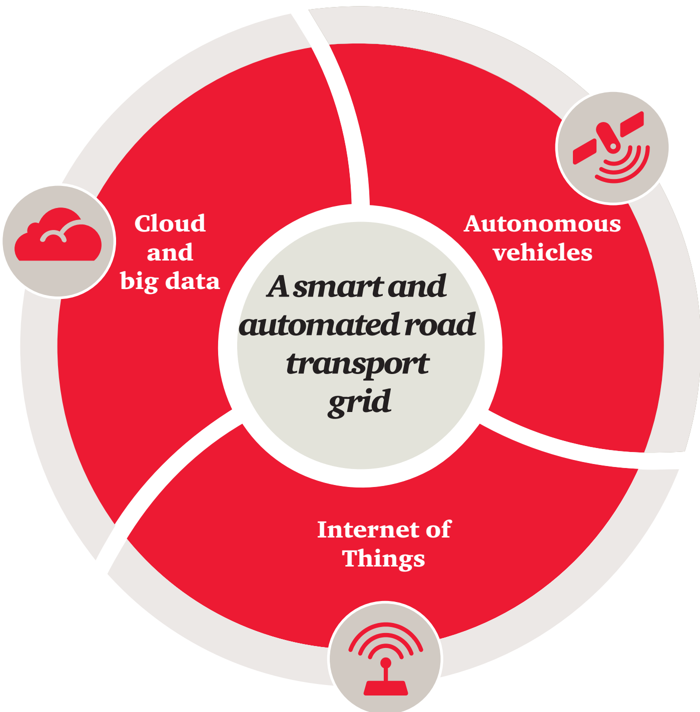
Electrification of long-haul mass transport is still in its infancy, with Hyperloop, a concept unveiled by Elon Musk's SpaceX, with the potential to be a future zero-emissions solution that will harness advanced materials for tunnel and vehicle construction, and rechargeable battery storage, in addition to Augmented Reality (AR) and VR as part of the design process to demonstrate experiences and build comfort levels of potential passengers for this new ultra-high-speed land transport solution.



3) *A smart and automated road transport grid: fusing autonomous vehicles, IoT, cloud and big data*

Widespread adoption of connected and smart autonomous vehicles deliver substantial energy use savings, but is only a transformational sustainable transport solution if the autonomous cars are themselves low, or even better, zero-emissions vehicles. Utilising sensors, navigation systems combined with GPS, cameras, and communication devices, all linked together harnessing the IoT, cloud and big data technologies, there are multiple ways in which driverless car technologies can lower energy use and GHG emissions. Examples include route optimisation reducing travel times and congestion, eco-driving practices programmed with algorithms that prioritise energy efficiency, programmed 'platooning' of cars to optimise traffic flow, and more efficient acceleration and breaking which could potentially lead to a 5-20% fuel consumption saving.

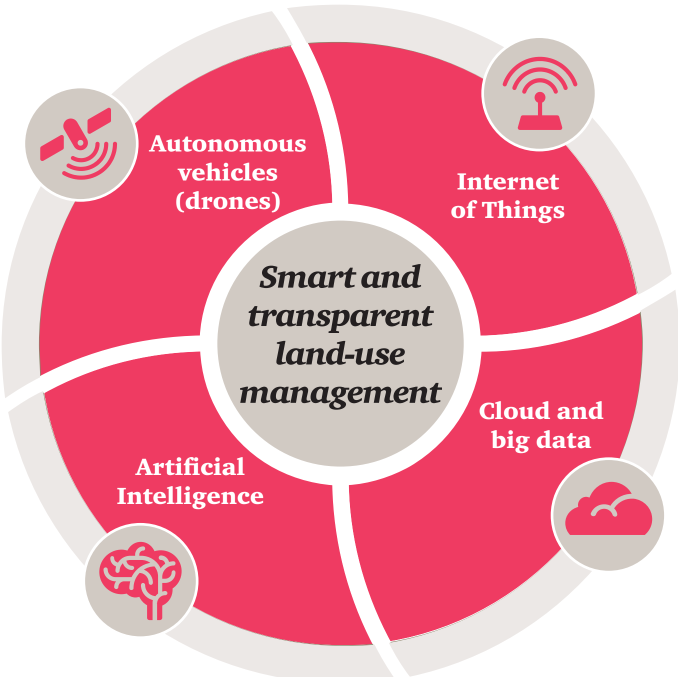
In addition autonomous cars and buses could increasingly be deployed by car-sharing or ride-sharing services. Shared vehicle services allow 'right-sizing' depending on specific user needs by journey and can lead to reduced car ownership. Likewise the availability of lower cost autonomous vehicle ride-sharing services could not only reduce vehicle ownership by 80% (MIT research) but also reduce vehicle miles travelled. A shared autonomous model using a zero-emissions fleet is likely the most transformational future scenario to reduce emissions.



4) *Smart and transparent land use management: fusing IoT, cloud and big data, AI, and autonomous vehicles (drones)*

Transparency of real-time land use practices enabled by 4IR technologies including IoT sensors, cloud and big data, drones and advanced satellites, will be a game changer for implementing climate smart land use practices, and driving accountability in agriculture and forestry value chains. Businesses, investors, and governments[18] are increasingly committing to sustainable land use. Making real commitments like those made by the 400 consumer goods and agribusiness companies that pledged to substantially reduce or eliminate deforestation from the production of agricultural commodities by 2020[19] – will require rapid and widespread adoption of new transparency and management technologies and techniques across global supply chains.

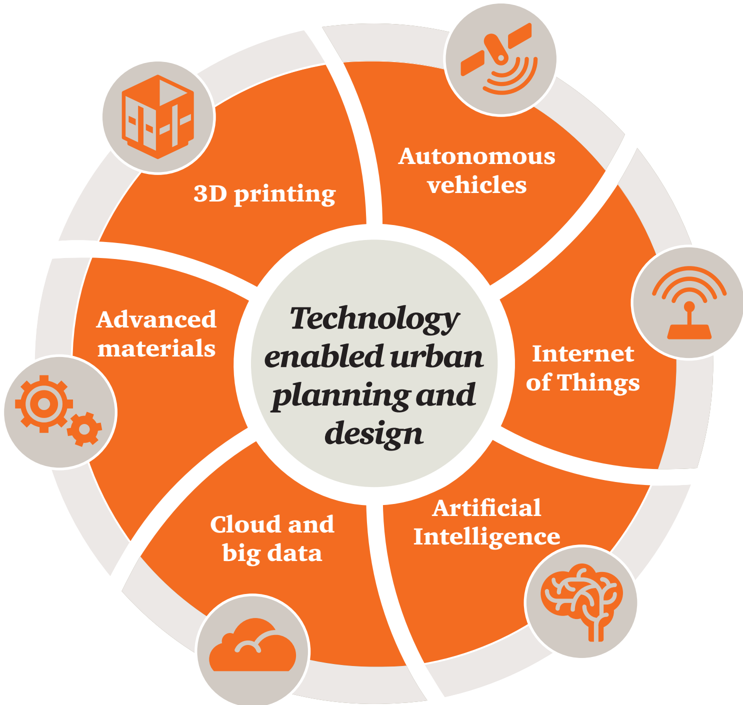
Combining satellites, cloud technology and big data, with AI machine learning, new digital public goods (e.g. Global Forest Watch[20], and ALERTS[21]) are being created to enable near-real time monitoring and tracking of land use. This will allow businesses to verify whether their commodity suppliers are in compliance with deforestation-free sourcing policies, while also allowing the public, NGOs and governments to drive accountability on instances of deforestation. Cloud technologies, big data and AI also offer the opportunity for farmers to utilise smart agriculture techniques e.g. irrigation devices that act on weather forecasts to determine their watering pattern. Autonomous vehicles, often in the form of drones, assist land-use monitoring and management of farms and plantations improving efficiency. Real-time aerial data from drones can allow more accurate agricultural management during periods of extreme or unforeseen weather events. Furthermore, cloud and big data, and AI technologies can also be used to track agricultural goods and reduce losses in the supply chain further improving land-use efficiency.



[18] The Bonn Challenge – see: http://www.bonnchallenge.org/
[19] New York Declaration on Forests – see: http://forestdeclaration.org/
[20] http://commodities.globalforestwatch.org
[21] http://planetaryskin.org/rd-programs/resource-nexus/global-land-change-detection

5) Technology enabled urban planning and design: fusing autonomous vehicles, IoT, AI, cloud and big data, advanced materials, and 3D printing

Designing IoT enabled cities with intelligent infrastructure and grids, and shared operations, can increase energy efficiency, and reduce GHG emissions and waste at the building, transport system, and municipal level. City planners can optimise urban development plans to maximise system-wide energy efficiency through using big data, open-source mapping platforms, AR and VR data visualisations, and urban design software. 5G networks with cloud-based storage can expand the cellular IoT to more devices and services. This will increase speed and capacity, infuse intelligence in the mobile network, enable sharing of resources, and strengthen the ability to share and coordinate. Cloud-based software platforms coupled with machine learning and next-generation sensors, smart meters, and energy management systems can enable optimal building energy management of appliances including hot water systems, heaters, air conditioners, ventilators and LED lighting. For example lights in buildings as well as along streets can be dimmed when no one is around. Through smart design, experts have "seen up to 70 percent reductions in energy consumption" in modern buildings[22]. Next-generation building construction can further improve building efficiency: 3D printed buildings produce less waste and often utilise recycled printed materials in their construction. Moreover, advanced materials, including efficient concrete and 'solar sprays', can improve both energy-use in construction and offer energy-generation capability once structures are built.



[22] Brookings. Achieving Sustainability in a 5G World, December 2016.

Avoiding unintended consequences

Innovating to unlock new 4IR solutions for sustainability is only one part of the challenge. A number of mainstream 4IR advances could themselves have unintended negative consequences on the planet, if not designed and scaled in a smart and sustainable way.

Unintended environmental consequences – some examples

- **Autonomous vehicles and new vehicle-sharing economy service models** could give rise to an unknown rebound effect that could potentially lead to an increase in car use, rented or owned, at the expense of public transport. As autonomous cars enable riders to use journey times productively and as autonomous taxis become more affordable with reduced labour costs, mass transit options could become less appealing. Autonomous vehicles and shared-service solutions, by default, do not currently need to be low or zero-emissions vehicles. The only way to ensure autonomous vehicles and sharing economy services are a truly sustainable solution is to put in place government policies to ensure they both go hand-in-hand with the roll-out of low-and zero-emissions vehicles and investment in sustainable mass transit.
- **Blockchain** has received negative publicity on its energy intensity; or more specifically the energy use of the mining process behind its most popular cryptocurrency – Bitcoin. The Bitcoin mining process requires 'proof of work' (POW) protocols that by design necessitate increasingly powerful computers and dedicated data centres as more miners join, which in turn increases energy consumption. The Ethereum[23] community is developing a 'proof of stake' (POS) protocol which requires far less computing power and could provide a more scalable and energy efficient digital currency alternative to Bitcoin's mining process. This is not only a sustainability opportunity, but a commercial one as currently Bitcoin's industry growth is muted by its excessive energy costs.
- **The IoT** energy consumption must be addressed upfront as it expands from a network of 23 billion connected energy-consuming devices today to 50 billion by 2020[24]. Energy efficiency must be a critical common feature of this vast network of devices, sensors and appliances. Given the distributed nature and ownership of the 'things', the challenge here in particular will be to mainstream energy efficiency principles and use of clean energy sources, across the devices and data storage solutions, particularly for the most energy hungry devices. It will require government-led public policy intervention – standards and incentives, alongside industry and ICT sector leadership, e.g. GeSI[25].
- **Cloud services** are key to data centres growing in a sustainable way, if energy efficiency and renewable sources can be prioritised, which is increasingly the case. Data storage has become much more energy efficient over recent years as it has progressively moved from backroom data centres to the cloud. Advances in leading edge data centre designs including cooling strategies, AI driven power management, sharing of resources and a transition from micro to hyperscale data centres have driven energy efficiency. University of Berkeley analysis suggests that moving from on-premise business applications to the cloud and hyper-scale data centres optimised to run efficiently could reduce energy consumption by 40% relative to current trends in the US. Furthermore as companies that run hyper-scale data centres and cloud services increasingly commit to clean energy sources (e.g. the 100% renewables commitment made by Google, Microsoft, Apple, Facebook, Salesforce, BT Group and others) the role that cloud computing can have in reducing GHG emissions will continue to improve.

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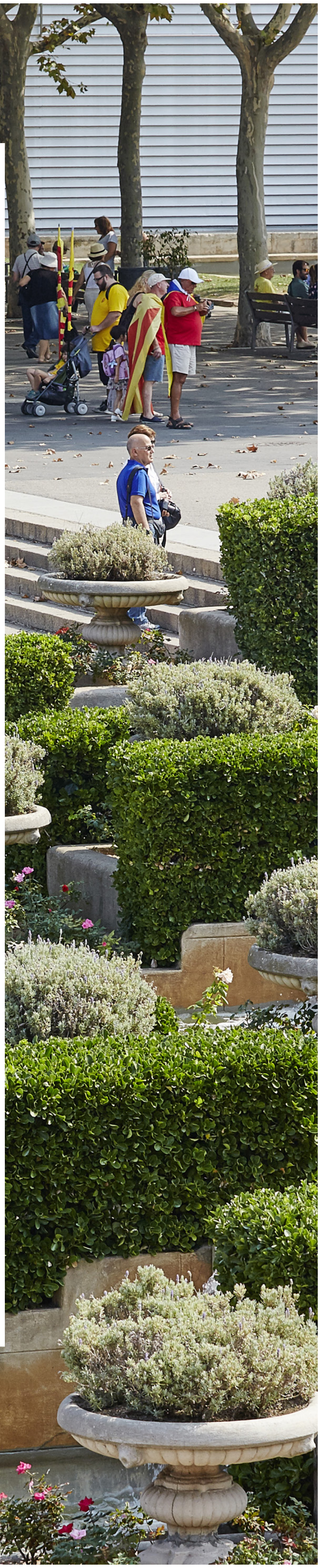
[23] https://www.ethereum.org/
[24] Statista 2016; Internet of Things: https://www.statista.com/topics/2637/internet-of-things/
[25] Global e-Sustainability Initiative. www.gesi.org



- The expanding digital economy that underpins the 4IR – with its huge (and often exponentially rising) need for data transmission, data storage and computing power – could well give rise to additional GHGs and digital waste, at the same time as offering energy and emissions savings from applying 4IR technologies for sustainability solutions. Decoupling the growth of 4IR technology markets from the direct energy use and emissions of the underlying 4IR technologies themselves will be key. Resource efficiency is not a given for each 4IR innovation but becomes a possibility if incorporated at the design stage. Such potential trade-offs make smart and sustainable 4IR technology design and performance standards (or targets) a business and government imperative.

Unintended societal consequences – some examples:

This report focuses on potential sustainable applications of 4IR technologies, with a particular focus on climate change. Nonetheless, it is hard to ignore the broader societal consequences that the development and utilisation of 4IR technologies could create. From the impacts of automation on jobs (e.g. one study contended that up to 47% of US total employment could be at risk[26]), to data privacy, cyber security, and bio-technology 'bio-errors'[27], governments and businesses have important roles to play in ensuring technology supports the broad range of societal wants and needs.

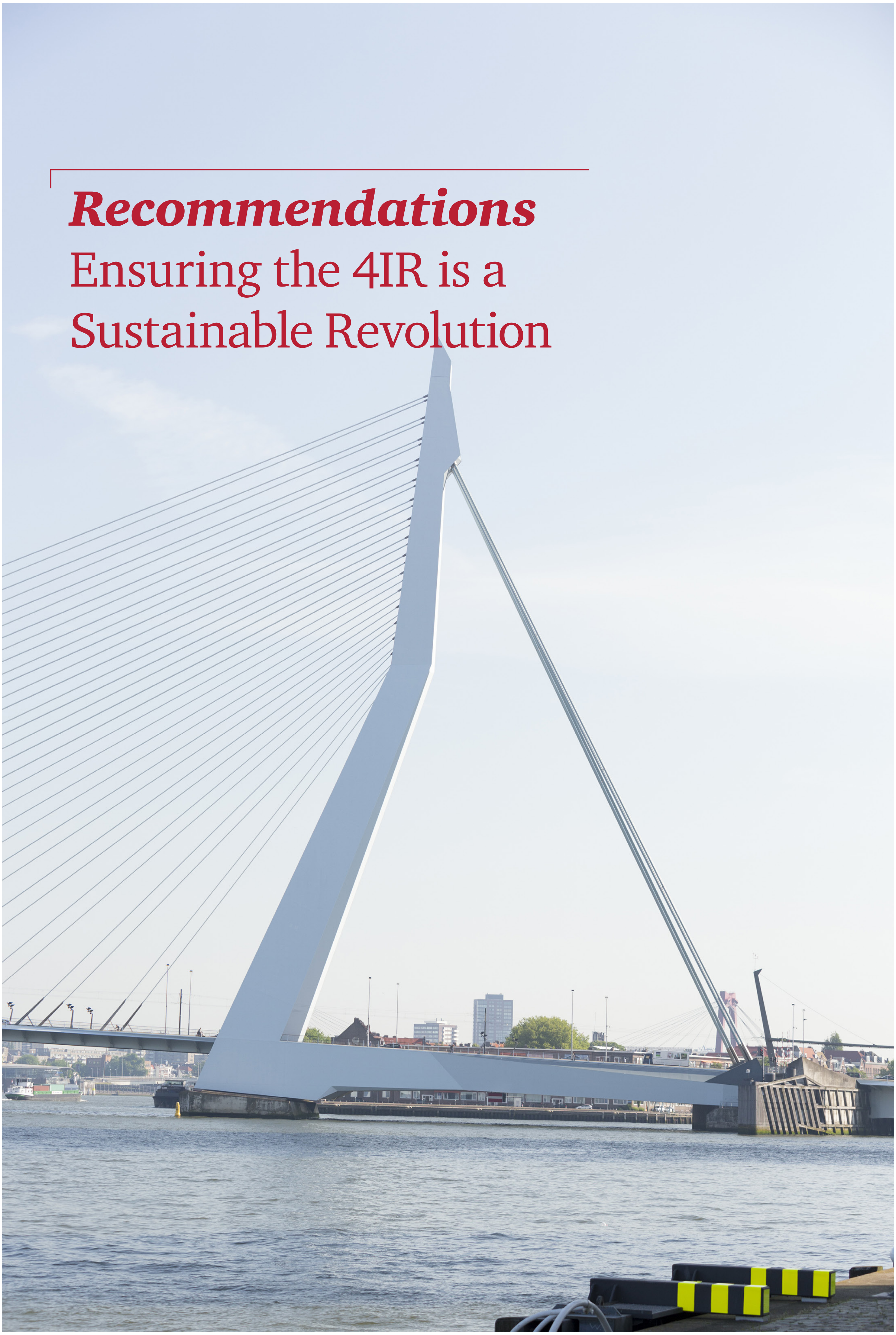
Questions relevant to this study include, how will the potential job displacement be addressed that will arise from shifting to a smart and automated road transport grid or to machine-led Industrial IoT in manufacturing? How do we avoid further rural to urban migration and pressure on developing country cities, as smart agriculture practices displaces rural jobs? The 4IR is rapidly changing the workforce of tomorrow, and the role of business and government leaders will be to ensure the by-product of rising productivity benefits is not to decimate overall job numbers. This means acting with foresight now to build in adaptability of skills, to identify where tomorrow's jobs and industries are, and to enable more flexible and sharing-based talent models.

We have not carried out a comprehensive analysis of such unintended consequences in this report, but future PwC publications will go into further detail of economic, social and environmental impacts of 4IR technologies. For now these illustrative examples show the need for governments and businesses to, as carefully as possible, develop responsible technological governance structures which are fit for purpose and meet societal wants and needs. Structural change habitually creates winners and losers, but the 4IR could be the largest structural transformation of the global economy the world has seen, and in the space of only a few decades. To really succeed for the planet and for society, innovators, industry and governments need to come together to shape flexible and robust, national and international technology governance structures that enable a 'responsible' 4IR.

[26] Frey, C. B. and Osborne, M.A., (2013). The future of employment: how susceptible are jobs to computerisation?

[27] 'Bio-errors' include the accidental release of synthetic organisms not intended to come into contact with the open environment, the mutation of synthetic organisms, or the effects of alien 'invasive' synthetic organisms.

Recommendations
Ensuring the 4IR is a Sustainable Revolution



Leveraging 4IR technologies not only for business and for short-term growth prospects, but for smart growth reasons – where 'smart' ensures long-term economic resilience and, de facto, Earth resilience – requires decisive action. To both avoid any harmful unintended consequences from new technologies, and to realise their full potential, a range of stakeholder groups will be required to play critical roles.

Priority actions for each group include the following:

Companies

- **Companies from all sectors:** Within their technology strategies and roadmaps build-in and optimise the impact of technologies on sustainability.
- **Technology pioneer companies:** Both start-ups and Big Tech firms developing 4IR innovations, to embed sustainability into design principles so that mainstream 4IR technologies are really 'smart'.
- **Taking on the challenge:** To invest in sustained innovation efforts that also take on Earth challenges and deliver the Sustainable Development Goals (SDGs).
- **Industry collaboration:** To develop industry-wide and industry-regulator collaboration to aid standard setting e.g. consensus protocols and smart contracts that include energy consumption and efficiency principles, which require common agreement and governance.

Governments

- **Technological governance:** Given the potential for disruptive social and environmental consequences, it will be essential to develop national and international technological governance structures for the new 4IR-enabled digital economy. These governance mechanisms – collaborating with industry and civil society – can help to ensure technological advances that support growth which is inclusive and sustainable, aligned to the framework laid out in the SDGs.
- **Regulatory environment:** To provide the policy and regulatory environment to enable scaling of 4IR technologies that address Earth challenges and minimise unintended consequences (e.g. autonomous vehicles emissions standards, interconnection standards and net metering policies for a distributed grid, efficiency standards for IoT devices and Blockchain systems, payment for performance mechanisms).
- **R&D investment:** To commit large scale basic and applied R&D investments into 4IR for Earth innovations and ventures, building on the efforts of Mission Innovation[28].
- **Innovative finance:** To provide innovative PPP finance solutions to support early stage commercialisation of 4IR for sustainability solutions, including risk finance (grant, concessional debt and equity), and innovation challenge funds and innovation incubators for pioneering initiatives.

Investors

- **Sustainable portfolios:** For angel, VC investors, accelerators, impact investors, to build and support a portfolio of specialised 4IR technology companies that address sustainability challenges (e.g. clean energy and resource scarcity), and support sustainability-driven value creation across broader portfolio companies in the 4IR space (e.g. AI and data, robots, 3D printing, biotech).
- **Earth-shot focus:** For 'Moon-shot' investors to prioritise the allocation of patient capital to most pressing 'Earth-shots' as per the example set by the Breakthrough Energy Coalition[29].
- **Investment criteria:** For institutional investors and asset managers to embed sustainability considerations into 4IR technology-related investment portfolios.

Research institutions

- **Academic collaboration:** For 4IR technologies for the Earth to be adopted as a priority focus, and accelerated through partnerships with industry and government. MIT, for example, has taken on climate change as a 'priority,' involving thousands of students, a third of the faculty, and more than 40 start-ups.
- **Curriculum:** To integrate sustainability into the curriculum of Digital/Technological/STEM related undergraduate and graduate courses. As an example Stanford University have developed a suite of 1-credit 'Big Earth' courses that use big data analytics to examine or solve questions about the planet.

In conclusion, the 4IR is already unlocking game-changing solutions for industry, markets and consumers. The defining characteristics of the digital age that underpin it are the rapid pace and scale of change.

This time of unparalleled human-led innovation also presents a window of opportunity to turn around the human-led pressures on our planet that scientists report are close to a dangerous tipping point.

What is needed is a 4IR that harnesses technological breakthroughs for people and the planet.

[28] http://mission-innovation.net/
[29] http://www.b-t.energy/

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