Fourth Industrial Revolution for the Earth

Harnessing the 4th Industrial Revolution for Sustainable Emerging Cities

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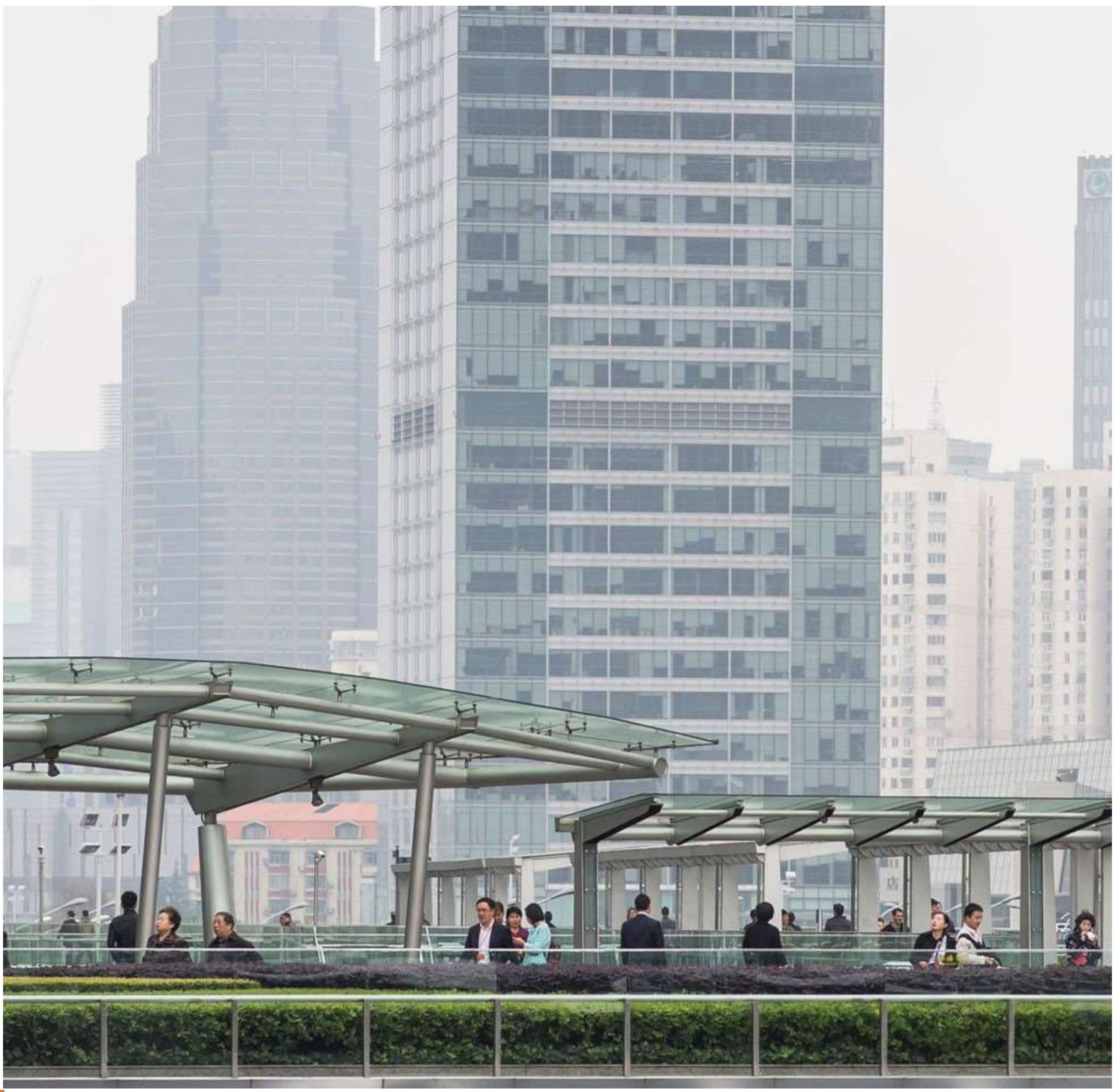

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About the Fourth Industrial Revolution for the Earth initiative

The World Economic Forum is collaborating with PwC (as official project adviser) and the Stanford Woods Institute for the Environment on a major global initiative on the Environment and the Fourth Industrial Revolution. Working closely with leading issue experts and industry innovators convened through the World Economic Forum's Global Future Council on the Environment and Natural Resource Security – and with support from the MAVA Foundation – this initiative leverages the platforms, networks, and convening power of the World Economic Forum and its new Center for the Fourth Industrial Revolution in San Francisco. It also brings Stanford University's cutting edge research departments and its deep connections with the Silicon Valley technology community together with the global insight and strategic analysis on business, technology, investment and policy issues that PwC offers. Together with other interested stakeholders, this unique partnership is exploring how 4IR innovations could help drive a systems transformation across the environment and natural resource security agenda.

About the World Economic Forum

The World Economic Forum is an independent international organization committed to improving the state of the world by engaging business, political, academic and other leaders of society to shape global, regional and industry agendas.

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Preface – The fourth industrial revolution and the earth

Industrialisation has led to many of the world's current environmental problems. For example, climate change, unsafe levels of air pollution, the depletion of fishing stocks, toxins in rivers and soils, overflowing levels of waste on land and in the ocean, loss of biodiversity, and deforestation can all be traced to industrialisation.

As the Fourth Industrial Revolution (4IR) gathers pace, innovations are becoming faster, more efficient, and more widely accessible than before. Technology is also becoming increasingly connected; in particular, we are seeing a merging of digital, physical and biological realms. New technologies are enabling societal shifts by affecting economics, values, identities and possibilities for future generations.

We have a unique opportunity to harness this Fourth Industrial Revolution – and the societal shifts it triggers – to help fix environmental issues and to redesign how we manage our shared global environment. The 4IR could, however, also exacerbate existing threats to environmental security or create entirely new risks that will need to be considered and managed.

Harnessing these opportunities and proactively managing these risks will require a transformation of the 'enabling environment' – namely the governance frameworks and policy protocols, investment and financing models, the prevailing incentives for technology development, and the nature of societal engagement. This transformation will not happen automatically. It will require proactive, collaboration between policy-makers, scientists, civil society, technology champions, and investors.

If we get it right, it could create a sustainability revolution.

The **4IR for the Earth** series is designed to illustrate the potential of Fourth Industrial Revolution innovations and their applications to the worlds' most pressing environmental challenges. It offers insights into the emerging opportunities and risks, and highlights the roles various actors could play to ensure these technologies are harnessed and scaled effectively. It is not intended to be conclusive, but rather to stimulate a conversation amongst diverse stakeholders as a foundation for further collaborative work. This paper looks at the 4IR and sustainability in emerging cities.

Foreword

The world's emerging cities, if they intelligently harness the rapid and disruptive technological change of the 4IR, have the potential to deliver a sustainable future for all.

Today's emerging economies attract more urban citizens than ever before. Cities in Asia and Africa are forecast to absorb 90% of the world's 2.5 billion new urbanites by 2050.[1]

Cities have always been melting pots of innovation and economic activity, attracting increasing numbers of people and providing transformational economic opportunities. We have seen how urbanisation has increased productivity, fostered innovation and raised incomes to create today's global metropolitan powerhouses of Dubai, London, New York, Seoul, Shanghai, and Singapore.

It is in emerging cities like Bogota (Columbia), Lagos (Nigeria), Mumbai (India) that the battle for a sustainable future will likely be lost or won.

Many developing countries see the challenge of sustainable urbanisation as a defining one. Rapid and poorly managed urbanisation often proceeds at the expense of both liveability and the environment. More often than not, cities have not been well planned, managed or funded and the supply of urban infrastructure and services has subsequently failed to keep up with the needs of people and the economy. The consequences have included alarming levels of poverty, disease, inequality and environmental damage. Urban dwellers in these emerging cities are hardest hit: 98% of large emerging cities do not meet the World Health Organisation (WHO)'s air quality guidelines.[2] Negative environmental impacts also hit productivity and the economy, with these constraints being acutely felt in China, India and increasingly urban Africa.

Cities need to advance from incremental to transformative action on the environment to enable society to meet the Sustainable Development Goals (SDGs).

Global efforts, including the UN's New Urban Agenda, the Paris Agreement on climate change and innovative peer-to-peer networks like C40 and the Coalition for Urban Transitions, are all helping cities to build strong policy agendas for environmental change. But while progress is being made, efforts need to accelerate sharply.

As the fastest-ever period of technological innovation, the 4IR presents great promise to leapfrog traditional development and accelerate the transition to a more sustainable urban future.

4IR technologies such as artificial intelligence (AI), autonomous vehicles and drones, the Internet of things, advanced materials, 3D printing and biotechnology are particularly relevant. Many are already showing promise at reshaping urban sectors - including transport, energy, waste, water, and buildings – and change will only accelerate. Cities can harness these pioneering technologies, combined with each other and with new business models, to not only enhance urban economic productivity but to reduce environmental impact and increase wellbeing. The 4IR, however, also presents its own set of risks. Emerging cities need to invest in the enabling technological infrastructure and skills to ensure they don't get left behind, and to minimise unintended harmful impacts of the 4IR.

This paper explores how the 4IR is changing environmental sustainability in emerging cities, shining a light on existing and future opportunities for these cities to harness innovation for sustainable outcomes.

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4IR and the agenda for change

Balancing the impact of complex interactions between cities and the natural environment (from resource use and ecosystem services to pollution) will be vital for a sustainable future. In emerging cities, action to address the following key challenges will be particularly important for delivering environmental sustainability and could be supported by 4IR innovations:

1. **Smart planning and construction** to make better use of the built environment;
2. **Sustainable transport and logistics** to increase mobility and connectivity;
3. **Clean energy and utilities** to improve efficiency of urban systems and the environment;
4. **Urban health and resources** to lower pollution and improve liveability and affordability;
5. **Resilient urban systems** to enable cities to prepare for, and withstand, environmental shocks and disasters.

Smart planning and construction

Based on a study of 50 global cities, inefficient urban sprawl is projected to directly contribute to nearly 60% of the expected rise in energy use.[3] One estimate puts the annual cost of sprawl in the USA at USD1 trillion per annum.[4] The trend of reducing densities and higher costs is spreading across emerging cities.[5]

While the co-location of people, jobs, services, entertainment and shops defines the built environment, uncoordinated development and sprawling single-use construction patterns characterise many of today's rapidly-growing cities. Low capacity and ineffective urban policy, planning, regulation and incentives mean urban space is not used as well as it could be. This is costly, but also results in higher greenhouse gas (GHG) emissions and air pollution resulting from increased private transport share, inefficient services, fewer open spaces, and extensive grey infrastructure. Socially, poorly planned cities are worse off too because people with lower incomes are typically marginalised, living in poorly constructed homes in disconnected, unserviced settlements.

Mixed use development, which is compact and well-connected, offers a better model for the economy and environment. Solutions to make more out of scarce, valuable urban space include:

- Integrated, digital urban planning, transparent land-use planning, monitoring and management, and clear property rights that allow for the development of shared spaces
- Denser, integrated and mixed use communities close to transport nodes, e.g. transit-oriented development
- Multifunctional buildings optimising floor space 24/7
- Next generation building codes using digital design and nano-materials to radically reduce embodied carbon in production
- Just-in-time offsite, pre- and modular fabrication improving construction efficiency and flexible, reusable building parts
- Smart residential and commercial building management reducing costs of inefficient energy and water use

Technologies of the 4IR can offer new tools for city authorities, private developers and residents to properly plan, visualise and manage urban development and operations. Drones, sensors and big-data-powered simulations aided by AI can simplify these processes and improve engagement with citizens leveraging new ways of generating and using data. Advanced materials, 3D printing, Blockchain and AI, can support intelligent building design and streamline construction contracting.

Sustainable transport and logistics

In Mexico City, traffic jams are estimated to cost 33 billion pesos (USD1.8 billion) per year in lost time and productivity because 85% of road space is taken up by private cars, which only account for 30% of commutes.[6]

High connectivity and the smooth movement of people and goods define a well-functioning city. Yet, many cities have struggled to meet demands for existing transport and traffic systems, let alone improve connectivity within and between places. As well as the major, well-documented, impact on air quality and public health, the result is longer and costlier commutes and firms unable to take advantage of close markets for logistical efficiency gains.

Without technological change, the traditional, car-dominated cities of the 20th century will not survive rapid urbanisation and increasingly stringent air pollution regulations. Solutions, some costlier than others to implement, include:

- Integrated intra- and inter-urban transport and logistics systems, reducing the need for private vehicles
- Real-time transport and traffic management and monitoring
- Cleaner vehicles and low-carbon mobility solutions that allow people to walk and bike more freely
- Platforms to better utilise existing and new forms of shared and ambient mobility, e.g. bikes, buses, autonomous vehicles
- Mixed-use neighbourhoods and better use of home services improving access to goods and services

Exploiting 4IR technologies could transform not only the daily commute, but also delivery logistics, inclusion and productivity. Autonomous vehicles providing on-demand mobility services are one, much-debated, option. Deploying AI and sensors also offer options. These are based on IoT, for predictive and real-time traffic flow and pollution management, advanced materials for low-carbon and clean fuel options, drones for deliveries, and virtual reality (VR) for remote meetings.

Clean energy and utilities

India is already the world's third-largest user of energy, yet its urban population is still expected to grow by nearly half a billion people in the coming decades. As a result, it is set to record the world's fastest growth in residential energy demand, at an average annual rate of 3.2% between 2012 and 2040.[7]

Cities are our biggest opportunity to mitigate climate change. They account for more than 70% of global energy use and GHG emissions to power their buildings, industry, utilities and infrastructure.[8] India has set an ambitious electric capacity target of 57% coming from renewable sources by 2027.[9] This requires huge investment in renewable, decentralised and controllable energy solutions. South Africa has already auctioned over 5 gigawatts of renewable generating capacity to the private sector, for nearly R200 billion (USD15 billion) in just four years.[10]

Improvements to fossil-fuel generated power and heat include renewable energy generation coupled with energy efficiency measures. These key solutions include:

- Renewable, decentralised energy generation such as rooftop solar, city heat networks and peer-to-peer energy systems
- Temperature sensors, smart meters and occupant controls for efficiency and to control energy and water use
- Intelligent grid management helping utilities monitor assets, model use and ensure efficient and cost-effective operations
- Advanced batteries for energy storage and electric vehicles
- Waste-to-energy plants including associated district heat and cooling networks

The 4IR technologies can offer new efficiencies in *generation* through virtual power plants. These integrate various energy sources through IoT and cloud-based platforms for more reliable power supply, decentralised energy storage networks and quad generation. For *transmission*, sensor-based electric and water grids can be used,[11] while in *distribution* and *consumption,* the technologies include Blockchain-enabled asset and contract management, and demand forecasting and AI-powered modelling.

Urban health and resources

In China, health costs related to urban air pollution are estimated to exceed 10% of GDP.[12] In South Africa, domestic and municipal sectors could reduce water use by up to 30% just by addressing physical leaks and household water wastage.[13]

Degraded air quality, dirty water and unsustainable waste practices are contributing to deteriorating health and economic productivity in many emerging cities. In Kolkata (India), investing INR13.1 billion (USD204 million) to improve efficiency in the waste sector could reduce waste-related GHG emissions by 41% by 2025.[14] Planning new cities and retrofitting existing ones requires a paradigm shift given rapid urbanisation and growing environmental pressures.

The urban 'anatomy' of energy networks, green spaces, water and waste systems must transform from their current wasteful linear ways into resource-efficient ones. Key solutions include:

- Sharing economy principles for developing smart solutions and efficient supply chains, which can help meet human needs within minimal footprints, improve the quality of life and reduce economic losses from waste
- Circular economy design for remanufacturing, refurbishing, and recycling to keep components and materials circulating, reduce damage and manage negative environmental effects
- Integrated municipal and industrial waste management
- Life-cycle assessments of water quality, management and re-use
- Air pollution sequestration and purifiers, including biofilters
- 'Living' building façades, green spaces and urban agriculture

Municipalities also have the difficult balancing task of ensuring more stringent environmental quality controls and rules do not leave poorer members further marginalised. 4IR innovations will be integral to delivering a better environmental quality of life in cities. Opportunities include developing urban farms on rooftops and on building walls, making underutilised spaces greener and less polluting through bioengineering, tracking water quality and waste types for recycling, creatively re-using waste, and educating people in the correct practices to minimise water use and waste with the help of IoT, Blockchain and VR.

Resilient urban systems

More than 95% of registered deaths from storms and floods between 2000 and 2013 were recorded in low- and middle-income countries.[15] If action isn't taken, sea level rises and flooding could cost coastal cities USD1 trillion by 2050.[16] Cyber-attacks on urban infrastructure could cost insurers billions of US dollars.[17]

Emerging cities have to continually manage change, and often respond to natural hazards and human catastrophes, like conflict and mass migration. Demographic, economic, political, and cyber shocks can also have an impact on the city environment because reduced financing abilities, different priorities and compromised systems can divert scarce funds and focus from key sustainable infrastructure and low-carbon investments.

Climate change is increasing the frequency of extreme weather events, with underlying geopolitical unrest and social inequality exacerbating vulnerability to these shocks. Cities will need to be at the forefront of averting and tackling negative impacts, from damaged infrastructure to related infectious disease outbreaks. Solutions include:

- Real-time, integrated and adaptive urban management systems and change management to better adapt to, learn from and respond to shocks
- Integrated financial, procurement and governance systems
- Enhanced risk monitoring and prediction, combined with up-to-date cyber security measures, for flexible, reliable city and utility functions as well as insurance management
- Disaster-ready urban infrastructure and buildings, and smart emergency response systems for natural and man-made disaster prevention, mitigation and recovery

The 4IR technologies have immense potential to promote predictability and transparency in risk preparedness and responses: IoT and AI can predict and communicate potential shocks and disasters in real-time, while Blockchain can enhance cybersecurity, drones can deliver urgent supplies to hard-to-reach areas, and 3D printing and advanced materials can better rebuild infrastructure making it more resilient and with a lower ecological footprint.

Figure 1: Technical innovations for sustainable emerging cities

Smart planning and construction

- Multifunctional buildings
- Optimised, high-quality building design, codes and standards
- Mixed-use communities, flexible and shared spaces
- Efficient residential and commercial building management
- Transparent land use planning, monitoring and management
- Integrated, digital planning processes

Sustainable transport and logistics

- Integrated, cost-efficient transport systems
- Shared, ambient and on-demand mobility services
- Low-carbon transport systems, including clean fuels and alternative materials
- Regional mobility and logistics
- Real-time traffic flow management
- Efficient logistics and supply chain monitoring

Clean energy and utilities

- Decentralised and peer-to-peer renewable energy systems
- Advanced energy storage networks
- Operations optimisation, asset monitoring and management
- Intelligent, sensor-based grid management
- Clean energy distribution and accessibility
- Pattern recognition, use modelling and forecasting

Urban health and resources

- Circular economy, resource and supply chain efficiency
- Integrated municipal and industrial waste management
- Waste reduction through sharing economy principles and intelligent packaging
- 'Living' buildings, green spaces and urban food production
- Water quality, management and re-use
- Air pollution sequestration and purifiers

Resilient urban systems

- Smart emergency response systems
- Vendor due diligence and enhanced risk management, monitoring and prediction
- Disaster-ready infrastructure and buildings
- Natural and man-made disaster mitigation, prevention and recovery
- Integrated financial, governance and procurement systems
- Real-time, integrated, adaptive urban management

Transforming business as usual in emerging cities

To accelerate sustainable urban development patterns in emerging economies, the following five key 4IR innovations are 'game-changers' that fuse a range of technologies and provide opportunities for emerging cities to tackle current and future environmental challenges.

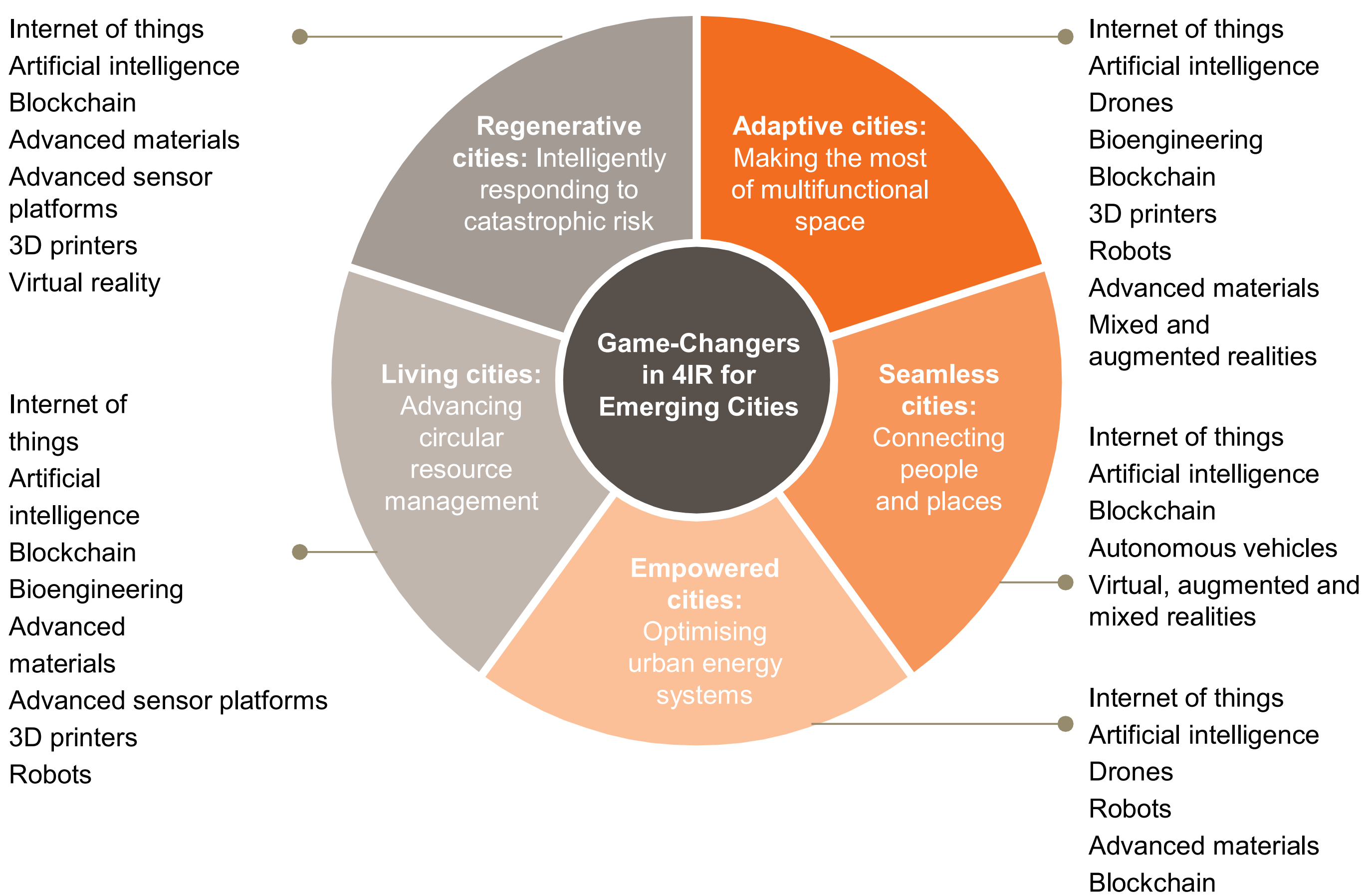
Adaptive cities: Making the most of multifunctional space

Flexing and optimising urban land, space and buildings to maximise their potential can be a game-changer for rapidly-growing cities that want to foster better density and reduce costly, inefficient sprawl.

Using 4IR technologies, existing buildings and spaces can be upgraded to become multi-use.

- **IoT** and **bioengineering** can be utilised to alter space and integrate operational systems to make lighting, heating, deliveries and waste collection more efficient based on real-time demand. For example, the Wooden Tower building re-design in Lagos represents smart, sustainable principles.[18]
- **AI** and **data analytics** alongside online and SMS engagement platforms can help cities and building managers monitor and adapt spaces based on local citizen and consumer demands at low cost. An example would be Google's Sidewalk Labs plans in Toronto (Canada) to pilot the Loft concept (a mixed-use building with a strong skeleton structure and adaptable interior for changing residential, commercial and other uses).[19] The environmental gains of adaptable space can be large through land conversion, less construction, and better utilised assets. New buildings and spaces can be designed and built on the same mixed use principles with the help of 4IR technologies.

Figure 2: 4IR innovation game-changers for emerging cities



- **Mixed and augmented realities** can be used to simulate and plan mixed use, inclusive developments, where people can satisfy their everyday needs without the need to travel.
- **Blockchain** and **AI** technologies can help automate planning processes and property developments. Brazil's Real Estate Registry Office is piloting Blockchain to improve accuracy of property ownership data with US start-up Ubitquity.[20] Use of Blockchain for land ownership is also being trialled in Costa Rica.[21]
- **Drones, 3D-printing** and **robots** can be used to construct new multifunctional buildings in a more timely and resource-efficient manner, and to deliver pop-up development that can generate economic activity on unutilised land.
- **Advanced materials** such as graphene can be very light and 200 times stronger than steel, ensuring that new building shapes and public spaces could be constructed with a far lower environmental footprint.

Seamless cities: Connecting people and places

Integrated public transport systems, on-demand mobility and intelligent traffic management will be crucial for improving air quality and connectivity in gridlocked emerging cities.

4IR innovations can improve current traffic flow and management.

- **IoT** and **AI**, coupled with big data and low-tech solutions including mobile phones and GPS navigation systems, can automate traffic monitoring and communicate congestion to vehicles on the road. This can help to optimise route planning, cut travel time and reduce GHG emissions. WhereIsMyTransport, a start-up in Cape Town (South Africa), has already started aggregating formal and informal public transport data into an open platform,[22] while Ninja Van uses algorithms and real-time tracking to enhance last-mile logistics across South East Asia.[23]
- **Blockchain** technology, combined with real-time pattern recognition data, can help cities price and trigger incentives for transport network companies to provide services during off-peak times and to complement public transport.

Technological advances can also help reduce traffic volumes.

- **Autonomous vehicles** (cars, buses and trucks), especially when low or zero-emission and deployed for shared transport and logistics services, can reduce energy use, emissions and vehicles on the road.
- **Virtual, augmented** and **mixed reality** meeting services in shared spaces could also reduce the need to travel for meetings, boosting broader connectivity and the competitiveness of smaller companies in emerging cities.

Empowered cities: Optimising urban energy systems

Smart grid management combined with decentralised, renewable energy distribution systems will empower cities and urbanites with more frugal and flexible clean energy systems.

4IR innovations can help improve efficiency and reliability of existing grid-based power distribution.

- **IoT**, **drones** and **robots**, harnessed for sensor-based grid and network management, can help utilities (and cities) monitor and inspect the health of the power system in real-time to reduce losses and improve reliability.
- **AI** and smart meters, combined with the above, can also help forecast and optimise energy generation and demand. Smart grids are being piloted from cities in Brazil to the Philippines.
- **Advanced materials, emerging battery** and **biotechnologies** offer new ways to generate, store and consume renewable energy in cities by raising capacity, (e.g. by harnessing photosynthesis in plants) and by managing peak demand (especially for solar energy on cloudy days).
- **Quad generation** technologies can optimise the heat - or in particularly hot climates the 'coolth' - provided to industry and homes through central provision and district energy centres, which measure and manage demand by cooperating with heat generation, distribution, use and reuse.

4IR innovations can also help raise access to clean energy.

- **Blockchain** offers some of the most promising opportunities for expanding power access. Such technologies are showing decentralised, renewable power systems are possible with micro- and smart grids and peer-to-peer systems, as developed by Wattcoin in Ghana for example.[24]
- **IoT, Blockchain** and pay-as-you-go systems also combine to increase accessibility to power in underserved markets. The Sun Exchange leases solar cells to firms and communities in Southern Africa enabled by quick, secure and low cost payments to global investors using Bitcoin.[25]

Living cities: Advancing circular resource management

Intelligent reduction and optimised reuse of waste and materials over their life-cycle will be crucial to preserve natural resources, avoid disease outbreaks, contaminated soils and waters, and local environmental degradation in emerging cities.

By harnessing 4IR technologies, waste reduction and disposal could be done cost-effectively and quickly, particularly where political will, city-industry-citizen cooperation and budgets align. Reducing the waste burden should be a primary goal.

- **IoT, AI** and **Blockchain** can help companies and industries monitor, analyse and automate their purchasing patterns. This will help them become smarter in their inventory and supply chain management, in turn minimising deliveries of wasted products.
- **Advanced materials** used for intelligent packaging can limit waste creation. Concrete that contains graphene could clean itself and the air around it, creating a catalytic environment that breaks down larger harmful molecules into harmless compounds to lower pollution.[26] Cities can behave more like nature, mimicking the anatomy and metabolism of living structures that reuse, repurpose, regenerate and reprocess resources producing very little actual waste.
- **Bioengineering** can be used to create living building façades and urban and vertical farms that can reduce the need to transport food great distances. It can also help to clean the air and create more green space in cities. One form of urban agriculture promising great environmental benefits is aquaponics, an efficient closed loop system combining plant growing with fish farming, which has already been trialled in Brazil.

4IR innovations also offer better ways to handle waste once created.

- **IoT, advanced sensor platforms, AI** and shared data can help cities predict and track municipal and industrial waste generation and collection, analyse types of waste and optimise disposal and recycling. India's I Got Garbage cloud-based platform has helped recycle more than 5,000 tonnes of waste and supported more than 8,000 informal waste pickers since 2013 through predictive, structured solid waste management.[27]
- **Automated 3D-printing robots** can process different forms of waste into building materials; primary structures and temporary scaffolds made out of organic compounds and metal scrap are already being trialled by the likes of Terreform ONE.[28]

Regenerative cities: Intelligently responding to catastrophic risk

Smarter risk forecasting, response simulations and regenerative materials will be game-changers for protecting lives and the urban environment in emerging cities at risk of, or prone to, climate shocks and natural disasters.

Helping cities and communities plan, prepare and collaborate with each other, with business and government is critical.

- **IoT, Blockchain** and **advanced sensor platforms** together with predictive **AI** analytics, can help cities monitor tremors, sea level changes and other possible natural hazards in real-time, with thresholds for automated triggers enabling early evacuation when needed. PetaBencana.id in Indonesia combines multiple open-source sensors, AI and people's social media reports for real-time flood mapping in the capital Jakarta.[29]

Mitigating the impacts of natural disasters is another area of 4IR innovation.

- **Advanced materials** such as self-healing concrete and biomimicry can help buildings withstand earthquakes and restore after such shocks. Companies such as Flextegrity have developed building materials that could reduce earthquake-related damage through ductility, energy absorption and bio-sensitive pipe support.[30]
- **VR** offers opportunities for cities to simulate disasters and prepare response strategies, as trialled by the Singapore Defence Force,[31] while game-based platforms could also be used to train citizens in how to act in an emergency.

4IR innovations are also transforming approaches for responding to natural disasters, which often hit poorer communities the hardest.

- **Drones** have been deployed to deliver emergency supplies and assess damage after disasters. Following the devastating Hurricanes Harvey and Irma in 2017, utilities and insurance companies contracted drone firms to inspect and estimate pay-outs in southeast USA and the Caribbean.[32]
- **Portable 3D printers**, powered by renewable energy to reduce reliance on possibly destroyed electricity lines, have the potential to save lives in the aftermath of disasters, both with printing urgently needed medical supplies and through the construction of temporary shelters.

Longer horizon game changers: hyper-connected clean cities

Many of the 4IR innovations identified in this paper relate to their application within the city boundary. Cities do not exist in isolation, however, and their future prosperity and sustainability will depend on mutually beneficial relationships with other cities. Currently, there are several 4IR-related innovations in the connectivity space at concept, demonstration or early stage which could prompt the next big shift of humanity's settlement patterns. Described below are future 4IR innovations, which will help cities to connect.

While transformational innovations in this space are often early stage, emerging cities with large infrastructure deficits can seize opportunities to leapfrog and test nascent technologies that unlock new possibilities for inter-city connectivity. Emerging cities (with strong leadership and more flexible regulatory frameworks) could be prime partners for global companies and investors looking to demonstrate more pioneering connectivity solutions. Designers and planners will, however, need to ensure that any solutions are inclusive, and benefit, rather than further isolate, the poorest communities.

Innovations that are likely to evolve in the coming decades and that could fundamentally transform city-to-city public and private transport solutions, helping our future cities become clean and hyper-connected, include:

- **Ultra-high speed surface solutions:** A number of companies are in the early stages of prototyping a super high speed vacuum-based transportation system called Hyperloop. It is projected to 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. The vehicle itself will be highly automated using AI. Potential travel speeds above 500 miles per hour (805 kilometres per hour) between cities means that Hyperloop could provide a cheaper and cleaner alternative to air travel and long-haul road transport, particularly for those cities within one to two hour flight times. Feasibility studies under way in China, India, Netherlands, Scandinavia, the UAE, and the USA represent collaborative and healthily competitive development efforts. Companies that are in the early test phases for such technology include Space X, and two specialised start-ups - Hyperloop One and Hyperloop Transportation Technologies. China Aerospace Science and Industrial Corporation (CASIC) is a recent newcomer, announcing plans for an intercontinental supersonic T Flight 'flying train' based on Hyperloop technologies.[33]
- **Underground transport solutions**: Although traditionally challenged both by physics and financial feasibility, further potential could be drawn from underground space. For example, The Boring Company, led by Tesla entrepreneur Elon Musk, is in the early stages of designing high-speed transport tunnels for short- and long-distance travel[34]. The tunnels would be equipped with high-speed automated electric "skates" for short haul vehicle transport, or used as a long-haul Hyperloop vacuum-tube supersonic transport system. If this could be done efficiently, and enhanced by 4IR technology, these enterprises could play a role in tackling congestion, reducing air and noise pollution, lowering GHG emissions, and cutting travel time for passenger transport and logistics across and between cities. Many significant engineering and regulatory hurdles must, however, be overcome for this concept to become commercially viable, and serious questions exist about upfront capital and maintenance costs, seismic risk, lifecycle energy needs and the quality, safety and affordability of the passenger experience.
- **Mid- and long-distance drones**: Mega drones could provide public transport solutions that avoid the traffic jams and air pollution that accompany many surface transport solutions today. The drones would combine composite advanced materials vehicles and next-generation batteries with AI-powered autonomous driving and drone technology. Multi-passenger unmanned aerial vehicles are yet to be developed, but similar innovations are already happening on a smaller scale. Current specialised start-ups include German company Lilium[35], and China's EHang, which is developing a one-person Autonomous Aerial Vehicle prototype for Dubai.[36] Airbus also has a two-person autonomous aerial taxi, which it hopes to have ready by 2020[37]. Google, Tesla and Uber are also exploring "flying car" technologies[38].

- **Advanced aircraft solutions**: Since Solar Impulse 2 circumnavigated the world, the broader potential and application of electric aircraft is starting to be realised. Airbus' E-Fan X is another early two-seat example; while Zunum Aero and DARPA are also developing airplanes for short-haul travel. For dense, highly-populated urban centres noise and air quality are growing problems. 4IR-enabled aircraft using advanced materials and next-generation batteries could enable electric aircraft for narrow-body short-haul flights. Were these to become feasible over coming decades, they could dramatically improve the urban environment and engender better connectivity between cities at a time when airport capacity and flight paths become less controversial because of fewer noise and pollution concerns in, and around, airports.
- **Harnessing space connectivity:** Advanced and nano satellites, among other technologies, are a growing frontier for city development and connectivity. Enabled by the 4IR, satellite functionality could be transformed with advanced materials, AI and Blockchain. In China, researchers are trialling quantum cryptography technologies, which use space to send information and communicate securely between cities. A USD100 million satellite, called Quantum Experiments at Space Scale, was launched from the Gobi Desert in 2016,[39] with plans to create a network of satellites and ground stations in cities to transmit quantum particles of data. Currently in its infancy, such technologies could revolutionise how cities avoid, mitigate and respond to environmental risks and catastrophes by improving detection mechanisms and reducing response times. Surrey Satellite Technologies Ltd is also creating a range of small, yet increasingly high-tech, satellite products and services, which could be better harnessed by cities. According to Nanosats.eu, there were 535 nanosatellites in orbit, as of July 2017[40].

Taken together, a range of 4IR-related innovations and breakthroughs that are anticipated in coming decades will change how cities are connected and communicate with one another. These developments are expected to change city-to-city transport fundamentally while delivering sustainable outcomes through new connectivity solutions underground, on the surface, and in the air.

Risks and challenges of the 4IR transition

The way cities look, feel and work will inevitably change with the advent of 4IR technologies. The speed of innovation is unparalleled, but the scale and effectiveness of harnessing 4IR innovations in rapidly growing cities will depend on factors such as the city's cultural or economic context, the quality of enabling infrastructure, skills development or urban ambitions. All cities, however, will need to resolve and mitigate the broader risks and challenges associated with adopting new technologies generally, and some technologies specifically, to ensure the 4IR is a sustainable revolution.

Climate and environment

Energy intensity of 4IR technologies: 4IR technologies can help to increase energy efficiency, but their underlying use of energy is a cause for concern (e.g. the power required for Blockchain and autonomous vehicles (AV) if they run on fossil-fuel-based energy). Government-led standards and incentives are needed to limit and, over time, reduce energy consumption from devices, sensors and appliances and promote renewable energy sources.

The butterfly effect: Individual cities face particular climate threats and experience differing urban heat island effects, but addressing these with 4IR innovations (including geoengineering), can have wide-ranging unintended consequences in other parts of the world. Early research suggests that bringing up deep cold waters or managing solar radiation may have damaging side effects.[41] A proliferation of AV could inadvertently increase urban sprawl because commuting time becomes converted into productive time. Technological advances can be encouraging, but further testing and development are necessary to ensuring safe and sustainable applications.

Increased rural-urban migration: Efficiency and competitiveness gains from 4IR deployment may attract more people to cities for economic opportunities, placing the urban environment under greater pressure, and posing a risk to rural areas that are behind in development. Measures to mitigate negative effects involve ensuring adequate urban and infrastructure plans. For example, central government support for smarter villages helps to ensure openings for business, and provides those living in villages and rural areas with fast digital access, in turn, lessening the need to travel or move to urban areas.

People and society

Jobs and inequality: The search for better livelihoods remains a driver of rapid urbanisation, but the world of work is changing and increased automation is inevitable as technology use rises. Governments need to ensure that the opportunities and benefits of the 4IR are widely shared within, and between cities, and that the vulnerable and marginalised are not left further behind. This is particularly true in low- and middle-income countries where unemployment is high, especially for youth. Reforms should focus on restructuring economies for a new, sustainable 4IR age, retraining those whose jobs become automated and re-evaluating the tax system and social protection schemes if there are fewer jobs available. Not doing so could exacerbate the negative environmental effects of inefficient resource and land use brought on by economic inequality.

Skills to implement and use new technologies: 4IR technologies and their applications often require specialist skills, beyond basic digital literacy. In an index of ten global cities' readiness to implement new technologies and current initiatives, Singapore came first, but according to research by PwC Russia, only 42% of its residents surveyed felt ready to use them.[42] To harness 4IR technologies for environmental sustainability in emerging cities, digital and 4IR awareness and skills need to be taught from an early age, and tailored higher education curriculums are required to equip school leavers and graduates with practical tools for work. Alongside this, older generations should not be left behind.

Human-centred design: The opportunities for operational and environmental improvements through 4IR technologies are often clearly laid out, but end-users can be forgotten. Ensuring that innovations are human-centred through user testing and that their deployment is well-communicated can ensure that 4IR technologies are adopted more quickly and can achieve their desired environmental effects.

Economy and governance

Terms of public-private partnerships: Greater data-sharing and collaborative solutions will be required between private-sector and governments to ensure new technologies in the likes of waste, water and transport, are piloted and adopted. The terms of public-private partnership engagements need to be aligned with the new wave of technologies, ensuring that there are incentives related to transparency and revenue. Efforts are required to ensure that locations that are behind the digital curve and require upfront investment in infrastructure and skills, are not forgotten.

Shape of urban governance: As 4IR technologies enable more decentralised and automatically allocated and distributed services, the way urban governments govern and manage city systems will change. Are they ready?

Having a coherent and coordinated urban 4IR strategy is necessary to manage this change and ensure its sustainability. Also required is collaboration on, and the co-creation of, new service delivery solutions with the private-sector to secure support from local government officials.

Cyber security and privacy: As more data on city operations, service providers, businesses and citizens are generated and shared digitally, balancing security and privacy concerns is already a key risk. Shared economy models function only if there is trust and transparency among and between parties. Assessing vulnerabilities and rapidly countering threats is crucial. Ensuring continuity and response planning is important to avoid funds and focus being diverted from environmental objectives.

Ensuring the 4IR is a sustainable revolution

Partnerships and a spirit of collaboration across many stakeholders will define new governance models for the 4IR and will be necessary to ensure it is a sustainable revolution.

Technological advances of the 4IR have huge potential, but can be hard to grasp fully. The applications are vast – and some may arrive faster than expected – but it can be hard to know where to start. Early successes and pilot testing of technologies in global cities can tell powerful stories of the opportunities, which will resonate more broadly across the global economy and society.

Many emerging cities already have foundations for greater technology adoption, including ICT infrastructure and skilled workers. Still, cities facing rapid urban change will need different steps, new ways of working and tailored solutions if they are to leapfrog 20th century patterns of urban development, make changes stick and meet overarching Sustainable Development Goals.

Outlined below are non-exhaustive and broad recommendations to speed up innovation, minimise environmental risks and increase the positive environmental impact of 4IR technologies for different but intertwined urban stakeholders.

***Public sector** (national and local governments, supported by international organisations)*

- **City development strategies for the 4IR**: build on 3IR-based strategies, identify quick-wins that demonstrate environmental value and applicability, and also enable planning delivery of further 4IR projects. Strategies need to be clear, tailored to cities' contexts, and integrated with a city-region strategy, which engages with, and enjoys the support of, the private-sector and citizens.
- **Create urban and national government innovation units**: to nurture and pursue innovation and context-specific 4IR applications. Cities need to show leadership and a willingness to act on the agenda of change, balancing visionary ambitions with pragmatism on risks and costs.[43]
- **Policy and regulatory environment**: to enable scaling of 4IR technologies and ensure these are developed and applied in a way that takes into account climate and the environment, business incentives and citizen needs. Governments need to set transparent, adaptable and enforceable policies, regulations and standards.
- **Innovative finance mechanisms:** to align the incentives as well as the risks of private sector delivery of city-level 4IR projects and support early-stage commercialisation. Urban and national governments need to provide innovative PPP solutions, blended and risk finance, e.g. challenge funds and viability gap funding, to enable financing for the public good and technology development.
- **Information and engagement platforms:** to ensure collection, sharing and public availability of data, cities need to lead in setting up platforms for collaboration. Exemplified by subnational Open Government Partnership[44] members or the Smart Hong Kong plan.[45]
- **Skills and retraining:** to build digital awareness (and use) among citizens, as well as to counter the negative effects from automation on jobs. Urban and national governments must promote new 4IR skills and retraining with a sustainability lens.

***Private sector** (businesses, entrepreneurs, investors, funders)*

- **Leadership on responsible business:** to ensure the 4IR is a sustainable revolution, the private sector, in alliance with governments, needs to take the lead on improving its own operations by embedding sustainability principles into 4IR technology design and investment decisions. Firms are key parts of the city economy and affect the environment locally and internationally via supply chains, often in emerging markets.
- **Urban innovation pilots:** to solve the problems that matter for emerging cities, start-ups and big tech firms ought to invest in continued innovation, as well as devising pilots for specific cities to develop truly 'smart' sustainable solutions.

- **Co-creation and collaboration:** to reach agreement and formulate the necessary governance for setting standards, sharing data and other areas of 4IR engagement. Locally, the private-sector needs to collaborate broadly with local government entities, utilities and citizens.
- **Innovation ecosystems:** to capitalise on the creative energy already found in many cities and develop local solutions. Businesses and investors can play a big role in the creation of city-based innovation hubs, incubators and accelerators supporting them to foster technology in the public interest, including those with environmental applications.
- **City investment portfolios:** to build the momentum and funding available for promising, sustainable city-focused innovations. Accelerators, angel, venture capital and impact investors can build and support portfolios of 4IR technology companies for urban environmental solutions.

Civil society *(civil society and non-governmental organisations, academia, research organisations and citizens)*

- **Educational partnerships:** to ensure vocational and university graduates are ready to enter the job market with practical tools integrating digital and sustainability. Academia, governments and the private sector could partner in education for the 4IR.
- **Community participation:** to ensure urbanites benefit from the 4IR and that smart city designs are human-centred. Civil society groups and citizens should actively take part in local and national discussions on the form and direction of urban development in the 4IR.
- **Community finance:** to speed up innovation and investment in local communities. Civil society organisations and savings groups can develop business plans, carry out pre-feasibility studies and blend private sector finance for local 4IR pilots.

Annexes

Annex 1: 4IR and emerging cities landscape overview

	Smart planning and construction	Sustainable transport and logistics	Clean energy and utilities	Urban health and resources	Resilient urban systems
3D Printing	• 3D printed buildings and rapid assembly components	• 3D printed cars • On-site and local 3D printing facilities	• 3D printed solar roof tiles • Small-scale wind turbines assembled from printed components	• Intelligent packaging for food and products • Printable sensors to monitor pollution	• Flood, heat, quake and storm-resistant 3D printed structures for shelters and homes
Advanced Materials (including nanomaterials)	• Smart, low carbon and no or low-cement concrete • Heat reducing, super insulating materials	• Advanced battery capability • Advanced carbon fibre composites for light-weight vehicles • Nanotech in fuel cells for cleaner urban air	• Graphene applications for energy generation and distribution • Solar sprays for PV building coatings • Next generation battery technologies	• Pollution absorbing or reducing films, coverings and construction materials	• Smart concrete to reinforce structures and vulnerable assets • Memory metals
Artificial Intelligence	• Machine-automated land-use change detection • Auditory-cue lighting / heating • Optimised sustainable building design	• Optimised transit routes based on traffic flow • Intelligent demand forecasting	• Intelligent energy demand forecasting • Energy usage optimisation	• Reduction in product waste by reviewing meta data on product use • Forecasting of resource intensive and polluting behaviours, patterns of consumption	• Machine-automated disaster risk prediction, monitoring and assessment • Proactive and reactive security intelligence • Traffic rerouting in emergencies
Robots	• Robots for efficient construction • Assisted assembly of pre-fabricated buildings	• Robots for repair of faulty parts and maintenance for optimal efficiency	• Assess health and explore or fix faults in pipes and on grids	• Waste collection and sorting	• Unmanned disaster response support into 'danger zones'
Drones & Autonomous Vehicles	• Drone imagery for land-use planning • Monitoring of human behaviour in the urban environment	• Autonomous vehicles for efficient networks • Drone deliveries	• Drones to monitor and maintain grids and infrastructure assets	• Drones to monitor the urban environment including air quality	• Drone deliveries for disaster response
Biotechnologies	• Living building facades and films • Biomimicry in urban design • Construction bio-materials and -processes	• Synthetic biofuels to ease land constraints • Carbon capture & use • Synthetic trees that clean the air	• Synthetic-based cleaner energy sources	• Bioplastics • Improved microbial waste management	• Biomimicry for flexible structures

Annex 1: 4IR and emerging cities landscape overview (continued)

	Smart planning and construction	Sustainable transport and logistics	Clean energy and utilities	Urban health and resources	Resilient urban systems
Energy Capture, Storage & Transmission	• Decentralised energy storage for building efficiency	• Advanced energy sources for urban electric vehicles • Next generation battery technologies	• Next generation energy storage • Decentralised grids	• Next generation energy storage for resource efficiency	• Adaptive energy distribution solutions • Mobile emergency power
Blockchain (and distributed ledger)	• Smart construction contracts • Automated planning assessments and approvals • Land registry	• Supply chain tracking and transparency • Automated payment of transport fees to reduce congestion	• Peer-to-peer and decentralised energy systems • Pay-as-you-go, smart meter payments • Net-metering through distributed generation	• Peer-to-peer sharing economy, material reuse and upcycling	• Relief payments
GeoEngineering		• Reducing air pollution		• Mitigating effects of climate change	• Changing weather patterns for disaster avoidance
Internet of Things	• Sensors in and on buildings to optimise construction pollution and operating performance for energy, water, waste and air quality	• Sensor-based traffic flow management • Smart fleet management	• Sensor-based grids and urban networks	• Sensors for pollution monitoring • Sensor-based waste monitoring and transparency	• Sensors to monitor natural hazards
New Computing Technologies	• Super high fidelity building information modelling (BIM)	• Quantum computing for optimal, ultra-efficient logistics and supply chains	• Quantum computing for efficient energy systems and utilities	• High-fidelity pollution tracking and monitoring	
Advanced Sensor Platforms	• Chemical sensors for building materials	• Real time optimisation of freight flow and rail system management	• Advanced sensors for grid management and monitoring	• Advanced nanosatellites to assess and monitor water resources • Biosensors for city-health monitoring and to sort waste for recycling	• Proactive and reactive security
Virtual, Augmented & Mixed Realities	• VR and AR for urban planning and citizen engagement • BIM user experiences	• AR journey experiences • VR meetings	• Virtual power plants • Virtual training for utilities and grid management	• VR/AR/MR experiences for behavioural change in resource use	• VR for disaster simulation • VR-based games for citizen emergency preparedness

This matrix is illustrative and non-exhaustive. The colour-coding is based on our interpretation of secondary research: dark orange indicates 4IR applications that are in use or close to deployment; light orange indicates applications that are in the development or testing phase, and; white indicates applications that are at an ideas stage with further development needed. Ongoing exploration will be required to better understand and improve the 'readiness' (technical, commercial, governance, and social) of these innovative environmental applications and to explore how the most impactful ones can be scaled.

Annex 2: List and description of 4IR technology clusters most relevant for environmental applications

4IR technology clusters	Descriptions
1. 3D Printing 2. Advanced Materials (including nanomaterials) 3. Artificial Intelligence 4. Robots 5. Drones & Autonomous Vehicles 6. Biotechnologies 7. Energy Capture, Storage, and Transmission 8. Blockchain (and distributed ledger) 9. GeoEngineering 10. Internet of Things 11. Neurotechnologies 12. New Computing Technologies 13. Advanced Sensor Platforms 14. Virtual, Augmented and Mixed realities	The following high-level descriptions are provided as background – they are not intended to be exhaustive. **3D Printing** – Additive manufacturing techniques used to manufacture three dimensional objects based on 'printing' successive layers of materials. **Advanced Materials (including nanomaterials)** – Set of nanotechnologies and other material science technologies that can produce materials with significantly improved or completely new functionality, including lighter weight, stronger, more conductive materials, higher electrical storage e.g. nano-materials, biological materials or hybrids. **Artificial Intelligence** – Computer science learning algorithms that are capable of performing tasks that normally require human intelligence and beyond, e.g. visual perception, speech recognition and decision-making. **Robotics** – Electro-mechanical, biological, and hybrid machines enabled by artificial intelligence that automate, augment, or assist human activities, autonomously or according to set instructions. **Drones & Autonomous Vehicles** – Enabled by robots autonomous vehicles can operate and navigate with no, little or no human control. Drones fly or move in water without a pilot and can operate autonomously or be controlled remotely. **Biotechnologies** – Encompassing bioengineering; biomedical engineering; genomics, gene editing, and proteonomics; biomimicry; and synthetic biology; this technology set has applications in energy, material, chemical, pharmaceutical, agricultural, and medical industries to mention but some. **Energy Capture, Storage, and Transmission** – New energy technologies range from advanced battery technologies through to intelligent virtual grids, organic solar cells, spray-on solar, liquid biofuels for electricity generation and transport, and nuclear fusion. **Blockchain (and Distributed ledger)** – Distributed electronic ledger that uses cryptographic software algorithms to record and confirm immutable transactions and/or assets with reliability and anonymity without a central authority and that allows to automate contracts that relate to those assets and transactions (smart contracts). **GeoEngineering** – Large-scale, deliberate interventions in the earth's natural systems in order to, for example, shift rainfall patterns, create artificial sunshine, or alter biospheres. **Internet of Things** – Network of advanced sensors and actuators in land, in air, in oceans and in space embedded with software, network connectivity and computer capability, that can collect and exchange data over the internet and enable automated solutions to multiple problem sets. **Neurotechnologies** – Enable humans to influence consciousness and thought through decoding what we are thinking in fine levels of detail through new chemicals that influence our brains for enhanced functionality and help us interact with the world in new ways. **New Computing Technologies** – Includes technologies such as quantum computing, DNA-based solid state hard drives, and the combining of 3IR tech (big data, cloud) with the other technologies (e.g. internet of things; advanced sensor platforms). Quantum computers make direct use of quantum-mechanical phenomena such as entanglement to perform large scale computation of a particular class of currently impossible tasks by traditional computing approaches.

Annex 3: List and description of 4IR technology clusters most relevant for environmental applications

4IR technology clusters	Descriptions
	• **Advanced Sensor Platforms (including satellites)** – Advanced fixed and mobile physical, chemical and biological sensors for direct and indirect (remote sensing) of a myriad of environmental, natural resource and biological asset variables from fixed locations or in autonomous or semi-autonomous vehicles in land, in machines, in air, in oceans and in space • **Virtual, Augmented and Mixed realities –** Computer-generated simulation of a three-dimensional space overlaid to the physical world (AR) or a complete environment (VR)

Annex 4: The fourth industrial revolution for the earth initiative

The World Economic Forum Environment and 4IR initiative is designed to raise awareness and accelerate progress across this agenda for the benefit of society. Specific environmental focus areas will be looked at in depth in the first phase of the project, so as to explore in detail how to harness 4IR innovations to better manage some key environmental challenges. The first wave of focus areas will include:

- Air Pollution
- Biodiversity
- Cities
- Climate change and GHG monitoring
- Food Systems
- Oceans
- Water Resources and Sanitation

Working from these thematic areas the World Economic Forum – supported by Stanford University and PwC (as project adviser), and advised by the members of the Global Future Councils on the Future of Environment and Natural Resource Security and specific 4IR technology clusters – will seek to leverage their various networks and platforms to:

- **Develop a set of insight papers,** taking a deep dive into the possibilities of 4IR and each of these issues
- **Build new networks of practitioners** and support them to co-design and innovate for action on the environment in each of these issue areas, leveraging the latest the 4IR has to offer.
- Design a **public-private accelerator for action**, enabling both government, foundational, research organization and commercial funds to be pooled and deployed into scaling innovative 4IR solutions for the environment
- Help government stakeholders to **develop and trial the requisite policy protocols** that will help such 4IR solutions for the environment to take root and get to scale.

The Environment and 4IR project will be driven jointly out of the World Economic Forum Center for the Fourth Industrial Revolution in San Francisco and other Forum offices in New York, Geneva and Beijing.

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