# Fourth Industrial Revolution Technologies for Progress in UN SDGs

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## Abstract

COVID-19 pandemic has accelerated the development and adoption of fourth industrial revolution technologies, 4IR helps to contain the pandemic, to protect and deliver essential services to billions of people, to learn remotely, to perform work from anywhere, and to restore resilience of economies. 4IR technologies are indispensable in attaining the UN Sustainable Development Goals 2030 by countries as well as by companies. Benefits of 4IR include lower greenhouse gas emissions, reduction of solid waste going into land, incinerators, and oceans, improved healthcare, low-carbon products and services, better jobs, sustainable farming, protecting the environment and biodiversity, and mitigating extreme weathers and rising sea levels. Enthusiasts are already envisioning a fifth industrial revolution, 5IR-facilitated societies. This article presents a discussion of basics, trends, challenges, solutions, and opportunities for inclusive and equitable sustainable development.

## Introduction

COVID-19 pandemic has affected all economies and lives of around 7.9 billion people. Pandemic exposed the vulnerabilities of inadequately prepared communities and individuals. United Nations Development Program, UNDP projected that more than 200 million people fall into extreme poverty by 2030 due to COVID-19 effects. This number is in addition to 470 million or 6% of world population estimated to be living in extreme poverty by 2030. More than 1.25 billion students worldwide affected by the lockdowns, and students in the developing countries have limited or no access to online learning and thus growing up with no learning. Low-income countries are in firefighting mode with daily issues. Hence several countries gone off the track of environmental sustainability goals endorsed by 193 nations at the 2015 Paris agreement. Income and gender inequalities are rising in all countries. High-income nations and large companies are building post-pandemic economic growth and new jobs creation via carbon neutral circular economies. If proactive actions with long-term perspectives are not taken, a good proportion of developing countries as well as small and medium enterprises will be left behind in the emerging future led by green growth and sustainability. In other words, the United Nations 2030 Sustainability Development Goals, SDGs will be missed (Liu and Ramakrishna, 2020). Climate change is the impending challenge, and all nations are underprepared (Tamil Selvan and Ramakrishna, 2021).

This article examines the role of fourth Industrial Revolution, 4IR technologies in building carbon-neutral circular economy for sustainable development (Ramakrishna *et al*, 2020 and Ramakrishna, 2021A, 2021B). Sustainability underpinned by the carbon neutral circular economy is about reduction of carbon (GHG) emissions as well as circular solid waste management to reduce pollution and waste generation, to alleviate resources depletion, to regenerate biodiversity, and to overcome rising sea levels and extreme weathers for the well-being of humans and preserving Earth for the future generations. It aims to deliver quality economic growth, jobs, & living conditions. 4IR technologies are several as indicated in Robotics, automation, internet of things (IoT), artificial intelligence, machine learning, big data analytics, block chain, 5G, cloud computing, nanotechnology, and additive manufacturing often mentioned in the media and national strategies (Figure 1). Augmented reality, digital twins, sensors, wearables, intelligent materials & systems, materials informatics, brain-machine interface, and quantum computing are also 4IR technologies. Information on each of these technologies is vast and growing.

### Robotics and Automation

Robots are conceived to assist humans in repetitive and hazardous jobs. They are categorized into manipulators & industrial robots, mobile robots, and humanoid robots based operation, movement, control and sensor. Sensing elements of robots make use of the specialist behaviors of materials such as thermal-sensitive, photosensitive, force-sensitive, piezoelectric, vision, etc. Sensing element produces a useful signal. Signals processed by the controllers and facilitate robot performing certain functionalities. Nanotechnology and advanced electronic hardware chipsets capable of handling complex algorithms contributed to the evolution of controllers to be more precise added with cognitive capabilities. Robots are finding uses in diverse sectors of economy and society to aid in the productivity and sustainability of manufacturing of products as well as delivery of services. Automation of process industry, manufacturing industry, assembly industry, packaging industry, warehousing, quality control and inspection, and transportation logistics primarily enabled by the mass production of specialist robots and coordinating them via big data analytics, block chaining, machine learning, and artificial intelligence.

### Internet of Things (IoT) and Industrial Internet of Things (IIoT)

When several physical objects are connected digitally such a system is known as the Internet of Things (IoT) or Industrial Internet of Things (IIoT). More than 50 billion physical objects are digitally connected with cost-effective and energy efficient sensors. Many more billions of objects and machines will be connected in the coming decades. The ubiquitous connectivity accrues benefits such as information sharing and coordination leading to new functions and services that were previously not feasible, as well as greater device or equipment reliability since their status queried on a regular basis. Such systems are already deployed in the manufacturing industry, autonomous vehicles, traffic management, shipping, power grids, immigration and check points, security services, buildings and construction, solid waste management, precision agriculture and farming, and flood control in canals and water ways, to name a few. This 4IR technology has the ability to make the systems more agile and responsive, reduce equipment downtime and achieve greater efficiencies in operations leading to reduced costs. For example, precision farming will save water, energy, and fertilizers thus leading to lower carbon footprint and resources efficiency. Another example is the manufacturing industry equipped with 4IR technologies, which is also known as digital manufacturing or smart manufacturing or intelligent manufacturing. 4IR technologies will enable all players in the value chain of products at the supply chain, enterprise and shop floor levels to be digitally connected and data analytics-driven, thus achieving intelligent coordination for demand and supply matching, faster time to market, mass customization, and reduction of waste generation.

### Digital Twins

Digital twins are virtual replicas of physical devices, systems, and spaces. They leverage 4IR technologies such as IoT, IIoT, big data analytics, artificial intelligence, and computer modeling to run simulations to design and to optimize operational performance thus leading to energy efficiency, decarbonization, and optimized use of resources. They found in a number of sectors such as power plants and power grids, manufacturing plants, automotive industry, healthcare, buildings and construction industry, urban design, and urban systems.

### Artificial Intelligence

Artificial intelligence, AI, is the ability of a device or system to perceive its environment or correctly interpret external data, to learn from such data, and flexibly adapt those learnings to take actions that maximize its chance of successfully achieving its goals. AI gained strong foothold in internet search engines, home systems, social media, gaming industries, security, finance, and commerce. AI coupled with other 4IR technologies employed to increase energy efficiency, to facilitate carbon trading, and to realize the circular economy of products and services (Jose et al., 2020).

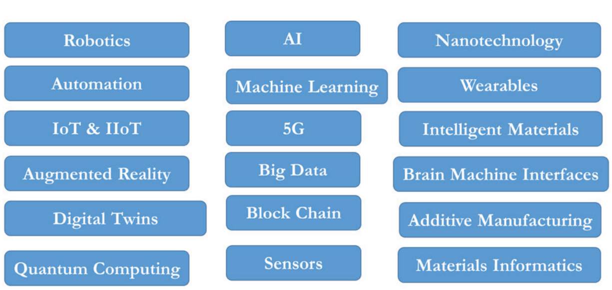


**Figure 1: A short list of fourth industrial revolution, 4IR technologies**

### Machine Learning and Deep Learning

Computer algorithms are evolving toward Artificial Intelligence instilling with the machines with the cognitive ability by the use of data known as machine learning, ML and Deep Learning, DL. ML uses sample/historical/training data to build a model so as to predict or make decisions based on the real-time data. ML is suited to model both big as well as limited data, for example in the manufacturing industry dealing with real measurements (Khayyam et al., 2020). Machine learning and AI are finding applications in agriculture, environment monitoring, health, climate change mitigation measures, smart and clean energy, smart and green cities, smart traffic management, and autonomous transportation, to name a few. DL or deep neural network learning can learn unsupervised, utilizing unstructured, unlabeled data even at higher frequencies in real time.

### Block chain Technology

Block chain technology is a decentralized, distributed ledger that records the provenance of a digital asset. By inherent design, the data on a block chain is secure and tamper proof. In other words, the digital ledger of transactions duplicated and distributed across networks of computer systems that support block chain. Hence, block chain is finding uses in certification, authentication, and records safekeeping in diverse sectors in addition to circular economy, which is an important concept of sustainability. Circular economy emphasizes three R's, i.e., reducing materials and waste, reusing products, and recycling materials. Block chain is helpful in ensuring traceability of materials and transparency of transactions. Carbon offsets and carbon credits trading, carbon tokenization would benefit from the advantages offered by block chain technology.

### Data Analytics

Quality and reliable data is necessary for making sound sustainability decisions. 4IR trend is to perform real-time data collection and analyzing dynamically for faster and effective decision-making. Software companies provide platforms for big data processing. Hyper-scale data centers support them. However, these data centers are huge energy hogs. The International Energy Agency estimates that the sector currently uses around 1% of the world's electricity. This figure could hit double-digits by 2030, making related emissions a problem. Sustainability credentials of data centers (Manganelli et al., 2021) are evaluated via indicators such as power usage effectiveness (PUE), carbon usage effectiveness (CUE), on-site energy fraction (OEF), and on-site energy matching (OEM), energy reuse factor (ERF), and water usage effectiveness (WUE). Accordingly, new data centers with improved sustainability performance will be built in countries around the world.

Data analytics coupled with other 4IR technologies such as sensors, 5G, and block chain labeling, and eco-friendly product designs facilitate transition toward zero-waste manufacturing and carbon neutral societies with low-carbon products and low-carbon services. In other words, reducing the amount of solid waste sent to the landfills or incinerators.

## Sensors, Processors, and 5G Networks

Ubiquitous digitalization is contingent on the availability of robust, power efficient and cost-effective smart sensors, faster processors, and high-speed wireless networking interfaces. For this purpose nanotechnology, quantum science, and atomic scale precision engineering of atoms enable design and fabrication of advanced sensors. Self-powered and environmentally friendly sensors, electronic skins, and molecular labeling for traceability are few such examples. More over a variety of processors from small low-end cores for sensors and actuators to more compact and power efficient for robots and intelligent devices to highest performance cores for servers. They designed to process more efficiently using algorithms and data processing arrays with low energy requirements. 5G network provides with gigabit bandwidth with low latency connectivity to enable the flow of low to high bandwidth data seamlessly in real time.

## Nanotechnology

Nanotechnology methods enable building of materials and devices on the scale of atoms and molecules. A nanometer is one-billionth of a meter, and 100,000 nanometers is the thickness of paper. Nanotechnology harnesses enhanced materials characteristics such as color, thermal conductivity, electrical conductivity, quantum entanglement, and reactivity at such length scales. Application of Nanotechnology in decarbonization span across

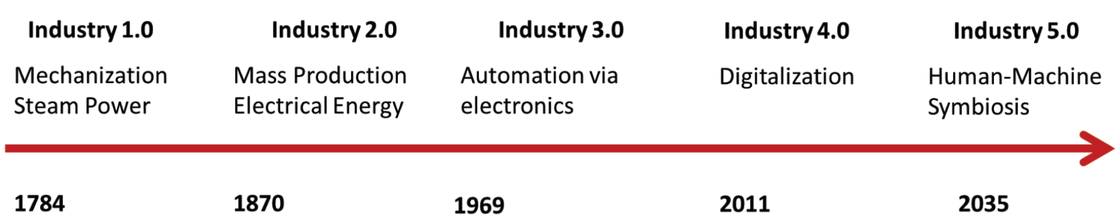


Figure 2: Industrial Revolutions

| UN SDG | Sectors | Robotics & Automation | IoT, IIoT | Digital Twins | AI, Machine Learning | Block chain | Data Analytics | Sensors & 5G | Nanotechnology | Additive Mfg, 3D Printing |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Family income | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ |
| 2 | Food | ☺☺ | ☺☺☺ | ☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺ |
| 3 | Health | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ |
| 4 | Education | ☺☺ | ☺☺☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺ | ☺☺☺☺☺ | ☺☺☺☺ | ☺☺☺ | ☺☺☺ |
| 5 | Gender equality | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ |
| 6 | Water and Sanitation | ☺☺ | ☺☺☺☺ | ☺☺ | ☺☺ | ☺ | ☺☺☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺ |
| 7 | Energy | ☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺☺ | ☺ | ☺☺☺☺☺ | ☺☺ | ☺☺☺ | ☺ |
| 8 | Economic Growth | ☺☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺☺ | ☺☺☺☺ | ☺☺ | ☺☺ | ☺ |
| 9 | Infrastructure | ☺☺☺ | ☺☺☺☺ | ☺☺☺☺☺ | ☺☺☺☺ | ☺☺ | ☺☺☺☺☺ | ☺☺☺☺ | ☺☺☺ | ☺☺ |
| 10 | Social mobility | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ |
| 11 | Urbanization | ☺ | ☺☺☺☺ | ☺☺☺☺☺ | ☺☺ | ☺☺ | ☺☺☺☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺ |
| 12 | Consumption & Production | ☺☺☺ | ☺☺☺ | ☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺ | ☺ |
| 13 | Combating Climate Impact | ☺ | ☺☺ | ☺☺ | ☺☺☺☺ | ☺☺☺☺☺☺ | ☺☺☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺ |
| 14 | Oceans & Water Resources | ☺ | ☺ | ☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺ | ☺☺☺☺ | ☺ |
| 15 | Terrestrial Ecosystems | ☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺☺☺ | ☺ | ☺ |
| 16 | Peace & Security | ☺☺ | ☺☺ | ☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺☺☺☺ | ☺☺☺ | ☺☺ | ☺ |
| 17 | Trade & Commerce | ☺☺ | ☺☺ | ☺ | ☺☺☺ | ☺☺☺☺☺ | ☺☺☺☺☺ | ☺ | ☺ | ☺ |

Figure 3: Mapping of 4IR technologies on to the UN SDGs and diverse sectors

many sectors. For example, processing and washing of textiles, protection of crops in agriculture, enhancing the yields of aquafarming, longer life packaging of food, wastewater treatment (Ang et al., 2021), solid waste management, cooling the buildings, insulation, renewable energy harvesting and storage, monitoring and sensing of environment, air & water, lighter & stronger materials for mobility, and anti-microbial and anti-viral surfaces.

### Additive Manufacturing or 3D Printing

Additive manufacturing or 3D printing involves direct making of products by layer-by-layer disposition of materials using digital data from a 3D model. Process is suited to reduce the resources consumption per product while improving the functionality, integration, and flexibility of product manufacturing. It is also suited to re-manufacture used components to recover value beyond the traditional 3Rs approach, i.e., reuse, recycle, and recover. According to the United Nations Environment Program, UNEP manufacturing is responsible for 20% of global CO2 emissions. COVID-19 highlighted the need for resilient manufacturing within the countries and communities (Teymourian et al., 2021). Additive manufacturing is one of the ways to attain resiliency and sustainability goals in products and services sectors with improved productivity, cost savings, product customization to the markets, resources efficiency, and mitigating manufacturing's negative environmental impact.

To get a sense of 4IR technologies impact on economies and human development, Figure 2 compares them with earlier industrial revolutions. Steam power and mechanization drove the first industrial revolution. Electrical energy and mass production underpinned the second industrial revolution. Electronics led automation facilitated the third industrial revolution. Per capita incomes, quality of infrastructure, living standards, education attainment levels, and improved average life spans in several nations around the world underscore the importance of IR technologies. Hence, it is in the best interests of emerging countries and small and medium enterprises to embrace 4IR technologies for respective contexts and needs.

Building on the success and promise of 4IR, technologists and policy makers envision fifth industrial revolution, 5IR. 5IR will be more toward human–machine collaboration for example a seamless mix of robots and humans. 5IR involves seamless merging of physical world with digital world via advances such as cognitive computing, space computing, brain-machine interfaces, quantum computing, intelligent materials, and beyond 5G network technologies. It aims to transform the relationships between technology and living spaces and habitats of people so that the economic development is more equitable and safe environment for creative activities. Considering the integrative scope of 5IR, Japan calls it as data driven Society 5.0.

Figure 3 attempts to map 4IR technologies on to the UN SDGs and economic sectors. It is clear that diverse 4IR technologies facilitate economic growth and job creations in various sectors while progressing on seventeen UN SDGs. An exhaustive discussion is not possible here due to the space constraints of the article. However, in order to illustrate key take away pointers, a case study of Singapore is described in the following section.

## Case study on Singapore

Singapore is an island nation of 720 square kilometers land and a city-state with 5.6 million residents. Despite not endowed with natural resources, and faced with uncertain future at birth as a nation in 1965, Singapore has transformed from a low-income country to a high-income country over the past five decades. Singapore is systematically implementing seventeen UN SDGs with 169 targets and 247 indicators. Singapore made significant strides in water and sanitation (SDG6), healthcare (SDG3), education(SDG4), family income (SGD1), gender equality (SDG5), social mobility (SDG10), and sustainable urbanization (SDG11) with nearly 50% green cover.

Yet, Singapore recognizes its vulnerability to extreme weathers and rising sea levels caused by climate change. Singapore Prime Minister Lee Hsien Loong attended the Earth Day climate summit hosted by the US President Joe Biden. The summit acknowledged that no country tackle the climate change alone. He emphasized the critical role of technological innovations and public as well as private finances in realizing carbon neutral and climate-resilient economies. Singapore is turning to technology to reduce its emissions and mitigate climate change effects. Singapore emitted 53 million tons of $CO_2$ in 2019, which is around 0.1% of global emissions. Singapore ranks 27th out of 142 countries in terms of emissions per capita, and 126th of 142 countries in terms of $CO_2$ emissions per dollar GDP. As a responsible nation, Singapore making systematic efforts to control annual $CO_2$ emissions to less than 65 million tons by 2030, half it by 2050 and reduce it to zero before 2100. Singapore emissions comprise about 60% from industry, 15% from transport, and remaining from the building and household sectors. Ongoing carbon emissions reduction measures include enhancing energy efficiency, ramping up of solar energy adaption, zero-emission buildings, electrification of transport, sustainable urban farming, transition toward zero waste economy, and reforestation. Also exploring the potential of green hydrogen, importing renewable electricity via regional power grid, and carbon capture utilization and storage technologies in addition to carbon offsets and carbon trading. SG Green Plan 2030 is a whole-of-nation effort for climate action, sustainable development and decarbonization of economy (Carrière et al., 2020; Rezvani Ghomi et al., 2021). Herein, the role of 4IRs in realizing UN SDGs is elaborated. Singapore is one of the most advanced countries in adapting latest and emerging technologies. For example, Singapore in fact demonstrated to the world as a role model in using tracing app and Bluetooth tokens to manage, control and combat the community spread of COVID-19 in Singapore. Singapore made notable progress with SDG1, i.e., end poverty in all its forms, SDG5, i.e., gender equality and empower all women and girls, and SDG10, i.e., reduce inequality.

### Food (SGD2)

SDG2 is to end hunger, achieve food security and promote sustainable agriculture. Only 1% of Singapore's land used for agriculture and hence most of its food is imported. COVID-19 disruptions to supply chains underscored the food security. Singapore embarked on urban farming to meet its 30% of nutrition needs by 2030. Technological innovations are employed for sustainable urban food production. Indoor multi-tier farming automation and precision agriculture via sensors and IoT; hydraulic engineering and 24/7 monitoring for quality, preventive and on demand maintenance; drone, nanotechnology and AI enabled micronutrients delivery; energy efficiency by implementing green energy conversion and storage technology and infrastructure; water efficiency; nanotechnology advances enabled durable food packaging (Bigdeloo et al., 2021); recycling of resources; web based apps matching the demand and supply and avoid wastage are few examples. In addition, science-led feed and nutrients customization for higher yields. In aquaculture, to maximize production, 4IR technologies would be useful to find a sweet spot where fish fed optimally without causing deterioration of oxygen levels in water, and ensuring quality of water and surrounding environment in terms of harmful bacteria, viruses and pathogens. Singapore is also facilitating lab grown, plant based meat alternatives or synthetic meat industry. Such novel food production leverages 4IR in cell culturing, culture medium, and coloring, texture, structure and scaled up manufacturing, and safety evaluation. They are associated with lower greenhouse gas emissions and agriculture land needs, while improving resources efficiency, antibiotic resistance and mitigating zoonotic diseases.

### Health (SDG3)

SDG3 is about ensuring healthy lives and ensure well-being for all, at all ages. Singapore life expectancy is among the highest in the world, and the high quality healthcare is affordable to all. Due to aging demographics, going forward, Singapore needs to provide expanded eldercare services. Innovative technologies including robotics, AI, IoT, telemedicine, personalized medicine, minimally invasive surgeries, stem cells, regenerative medicine, synthetic biology, nanomedicine, neural interfaces, electroceuticals and mind-inspired technologies to be developed with Singapore population mix in mind. More science advances and bioengineering and biomedical technology innovations will prepare Singapore for future epidemics, low fertility rates, mental health issues, life style diseases and other healthcare burdens.

### Education (SDG4)

SDG4 is about ensuring inclusive and equitable quality education and promote lifelong learning opportunities for all. COVID-19 has accelerated digitalization of education at all levels. Going forward, blended learning comprising online learning as well as in-person learning will be a mainstream approach. Rapidly changing jobs market as well as lifelong learning attitudes place emphasis on reskilling and acquiring updated knowledge. 4IR innovations to be adapted to improve interactions between the lecturers and students, and among the students taking full advantage of intellectual university community experience, capstone projects involving students from different time zones and industry partners, assessment tools and methods, and conducting laboratory based subjects too. Moreover, sustainability thinking to be infused into the learning of children, adults, business leaders, and policy makers. Singapore schools, colleges and universities are proactively embracing these necessary changes.

### Water and Sanitation (SDG6)

SDG6 is ensuring availability and sustainable management of water and sanitation for all. Higher energy efficient and cost-effective innovative technologies are needed to maximize the yield on every drop of rain that falls on Singapore, desalination of seawater, and circular water or zero wastage of water. Sanitation further enhanced via deep tunnel sewerage system, DTSS to meet the future demands of wastewater collection, treatment, reclamation and disposal. A network of wireless sensors or smart water grid will function as a real-time platform to monitor water flows and minimize water leaks. Improved engineering solutions in terms of drainage systems, pumps, and barrages are necessary for managing heavy rain events, storm water floods, and rising sea levels. Singapore converts solid waste into energy. For example by mixing greasy waste with used water sludge and digesting them together produced biogas, which then converted into electricity. Such an approach makes the solid waste management process more sustainable and viable.

### Energy (SDG7)

SDG7 is about ensuring access to reliable, affordable, sustainable and modern energy for all. The World Economic Forum (WEF) ranks Singapore 21st globally in its Energy Transition Index (ETI) 2021. This reflects Singapore progress toward a more inclusive, sustainable, and affordable and secured energy system. Singapore relies heavily on pollutive natural gas to meet its electricity and energy needs. To shift toward greener sources, Singapore is ramping up solar power capacity from 260 MW to 2 GW between now and 2030, amounting to an increase from less than 1% to 4% of electricity demand. Floating solar PV farms and roof top solar farms are creative solutions but need further engineering innovations to mitigate associated heat island effects and potential leachates. 4IR technologies such as sensors, IoT, big data analytics and digital twins are necessary to remotely monitor the electricity generation and to make accurate forecasts. Robotics and automation are helpful to align the solar modules to the sun directions. AI and machine learning are useful in assess defects in the solar panels and take proactive preventive maintenance steps. Nanotechnology is helpful to keep the solar modules free from dust accumulation as well as enhance the efficiencies of solar photovoltaics. Further engineering advances needed to cut the price of solar energy in half by 2030. In parallel, Singapore may capture carbon emissions from power plants and industries and store it permanently in subterranean reservoirs such as saline aquifers, depleted oil and gas reservoirs or depleted coal seams. Carbon Capture and Storage, CCS solutions require engineering innovations in terms of cost efficient capture technologies, transportation and pumping into the reservoirs with long-term safety and environmentally robust ways.

Hydrogen is perceived to be a clean fuel and energy source of the future. 'Green hydrogen' is manufactured by using renewable electricity for the electrolysis of water. Whereas the 'blue hydrogen' or industrial hydrogen is produced from either natural gas via methane steam reforming or from coal via coal gasification. Both processes produce $CO_2$ emissions and aforementioned CCS technology used to capture emissions. The blue hydrogen is 50% cheaper than the green hydrogen. Hydrogen economy requires infrastructure and engineering solutions in terms of cost-effective production, safe storage, and fuel cells technology. Innovations are needed to lower the cost of clean hydrogen by 80% by 2030, to be competitive with natural gas.

### Economic Growth (SDG8)

SDG8 is about sustained and inclusive economic growth, full and productive employment and decent work for all. Sustainable tourism is beneficial to economic growth as well as earth friendly progress of Singapore. Recreation and leisure activities reimagined with the aid of 4IR technologies. Interactive three-dimensional models of Singapore landscapes created using augmented reality, mixed reality, image processing, GPS, digital twins and virtual reality supported by the Smart Nation program of Singapore. A sustainable tourism industry involves integration of sustainable hotels with green transportation and waste management in local circular economy. Integrated waste management by Alba Company involves smart waste bins, RFID tagging, mobile phone apps for uploading of photos of waste deposited by the residents, big data analytics, and web enabled platforms for earing carbon credits and trade them for incentives. Monitory Authority of Singapore has set up a two billion US dollar green fund to promote environmentally sustainable projects in Singapore and overseas. It will support the development of carbon trading and services, sustainability consultancies and environmental risk management. Self-reporting on Environmental, Social and Governance, ESG is encouraged by the investors. This means, Environmental - effects of company's operations on environment such as greenhouse gas emissions, waste and pollution and resource depletion; Social- company's ability to deal with workforce and society such as working conditions, employee relations and diversity, and ties with local communities; and Governance- corporate governance of a company which includes considerations such as broad diversity and transparency. ESG skeptics point out issues such as a) lack of common methodology, b) varying metrics, c) data gaps, and d) reliability and transparency of information and processes. There is an opportunity to increase investors as well as public confidence in ESG declarations by the companies and green-themed funds. 4IR technologies will make the ESG ratings processes more robust, dynamic and precise. Block chain, machine learning, AI and big data will enable accurate and third-party verifiable tracking of information, facts and assets. Singapore Stock Exchange backed Climate Impact Exchange, CIX aims to offer platforms and products for global trading of carbon credits. CIX is a joint venture funded by DBS bank, Temasek Holdings, Standard Chartered bank, and the Singapore Exchange. Carbon abatement or carbon-offset projects include renewable energy enterprises, projects to save rainforests and mangroves. 4IR technologies enable the verifiability of carbon offsets.

### Infrastructure (SDG9)

SDG9 is about building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. Singapore has built excellent airport, marine shipping port, and land transportation systems. Airline industry is poised to transform with 4IR technologies, alternative fuels, lightweight materials, electrical power, and fuel cell technologies. Digitalization of trade and block chaining of documentation aimed at speeding up the marine commerce. COVID-19 pandemic adaptation accelerated digital transformation facilitated by big data, AI and 5G, and created a strong demand for hyperscale data centers. Green data centers are being envisioned with higher energy efficiency or lower power usage effectiveness (PUE) by leveraging engineering innovations in cooling systems, configurations, and materials substitution suitable for tropics.

### Urbanization (SDG11)

SDG11 is to make cities and human settlements inclusive, safe, resilient and sustainable. Land Transport Authority, LTA is considering integrated infrastructure to allow people to commute across Singapore without the need to use roads. This includes a mix of 1,300 km paths conducive for cycling and walking, 500 km park connectors, and elevated skyparks for pedestrians by 2030. Further promoting and incentivizing greener modes of transportation.

Built environment sector has been leveraging 4IR to build residential homes and commercial buildings, and deep tunnel sewerage systems and transport infrastructure. Companies such as City Developments Limited, Capital Land and Lendlease employ sensors and big data analytics to enhance the green mark rating of the buildings as well as transition toward to zero energy buildings. Drones are used for checking for defects in the facades of tall buildings and skyscrapers. Automated Robots are employed to check for leakages in the deep tunnel sewerage systems, which are several meters below the ground and run for hundreds of kilometers. Singapore acknowledged for pre-fabrication of building components off-site in a factory environment with best industry standards and transport them to site for final assembly. Concrete and glass are commonly used building materials. Recently, timber considered in the construction of buildings. Mass-engineered timber is a sustainable material or low-carbon material and provides a sense of well-being and warm comfort to the inhabitants. Moving forward, sustainability thinking and solutions incorporated from the project conceptualization and design, through construction, operational maintenance and end-of-life management. Materials selection based on low-carbon materials and longer life with durability. Upcycling of post incineration waste, conversion of captured carbon emissions into concrete, additive manufacturing of building components, and 4IR technologies for tracking, tracing and monitoring to ensure higher circularity of building materials. Building information modeling and digital twins enable data-led engineering and sustainability optimized buildings and infrastructure. Enhanced design and technologies will enable buildings to have net positive impact by operating efficiently, cleanly and friendly to the environment. Interior designers are using mainly recycled and recyclable materials to lower the embedded carbon footprint of buildings and living spaces. These are in addition to water conservation and energy efficient appliances for lighting, air-conditioning and refrigeration supported by IoT sensors and data analytics. Further, Singapore aims to moderate its rising urban temperature via potential solutions such as planting million more trees and cool painting on buildings.

### Consumption and Production (SDG12)

Singapore's approach to SDG12 sustainable consumption and production is to become a Zero Waste Nation. 3Rs: Reducing, Reusing and Recycling thinking and cultural change is promoted via policy measures such as extended producer responsibility and state of the art end-of-life management of major waste streams namely e-waste, plastic and packaging waste, and food waste (Patil and Ramakrishna, 2020; Tan et al., 2021). Engineering innovations are needed in several areas for example, low carbon processes and materials, automatic labeling, identification using block chain and AI technology, sorting, processing and upcycling of wastes; and increasing product life and repairability via better designs.

### Combating Climate Change and its Impacts (SDG13)

SDG13 is about taking urgent action to combat climate change and its impacts. Singapore committed one hundred billion dollars by 2100 to mitigate rising sea levels and rainstorm floods. Singapore is the first country in Southeast Asia to introduce carbon tax. It is also test bedding electric cars, green buildings, sea barrages and decks, carbon tax, carbon credits, carbon offsets, and carbon trading. They supported by 4IR innovations. Singapore is sensorising water drains and canals, and dams to monitor water levels to dynamically adjust the mitigation measures and to provide early warning signals. To facilitate carbon trading, web-based platforms are created for quality carbon offset projects monitored by 4IR technologies such as AI, IoT and Big Data Analytics.

### Conserve and Sustainably Use the Oceans, Seas and Marine Resources (SDG14)

Singapore is cooperating with the International Maritime Organization, IMO which is actively pushing for decarbonization, and thus signaling transition from the conventional marine fuels to zero-carbon types such as hydrogen, ammonia and methanol so as to cut the marine transportation industry's greenhouse gas emissions by half by 2050 and net-zero emissions by 2100. Moreover, digitalization of shipping is taking place with the adoption of 4IR technologies such as block chain, machine learning, and AI. For example, the Maritime and Port Authority of Singapore (MPA) launched digitalPORT@SG™ in 2019. It facilitates a one-stop clearance platform for all vessel-related transactions via streamlining 16 different vessel, immigration and port health clearance forms into a single submission. This saves the maritime industry an estimated 100,000 person-hours each year. In the future, it will be further developed as a Just-In-Time (JIT) Planning and Coordination Platform for diverse port users such as ship owners and agents, terminal operators and marine service providers. 4IR technologies will help to shorten the turnaround time of ships calling at the Ports thus enhancing port's efficiency and reduce business costs.

### Terrestrial Ecosystems (SDG15)

SDG15 is to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and biodiversity loss. Singapore aims to have 400 kilometers of park connectors, 180 kilometers of Nature Ways and 200 hectares of skyrise greenery by 2030. Reforestation and conservation of natural carbon sinks such as rain forests are popular among the business leaders and public. About 9,165ha of land or 12.6% of Singapore's total land area may be suitable for urban reforestation, which can capture about 0.31% of Singapore's total emissions. Singapore aims to be a City in a Garden. As of 2017, there were 100 hectares of skyrise greenery in Singapore, and plans are underway to double it by 2030. Singapore is employing 4IR technologies to monitor its seven millions trees. Singapore aims to add another million trees by 2030. For example, Light Detection and Ranging (Lidar) technology to scan and inspect trees via Remote Tree Measurement System (RTMS) software to interpret the data. Global navigation satellite system for determining exact location of trees as far as one hundred meters away. Such information is automatically uploaded into a central database. 3D models of trees are built for assessment. All these technologies allow arborists to inspect the health of trees remotely, and determine whether they withstand the forces of nature. Thus allowing city living in nature and protecting humans from the damages caused by falling trees under tropical weather conditions.

### Peace and Security (SDG16)

Singapore's law enforcement agencies have been adopting 4IR technologies to further integrate operations and strengthen community partnerships. One example is the use of Unmanned Aerial Vehicles (UAVs) and image processing to provide a bird's-eye view of the ground situation and allow officers to make better-informed decisions. Another example is the introduction of automated self-clearance lanes for motorbikes at land borders. Further infusion of 4IR innovations will enable better management of crisis events and unforeseen incidents.

### Partnerships (SDG17)

SDG17 is to strengthen the means of implementation and revitalize the global partnership for sustainable development. Singapore is championing ASEAN Smart Cities Network (ASCN). It is a collaborative platform to facilitate cooperation on smart cities development, catalyze bankable projects within the private sector, and secure funding and support from external partners. Singapore government embarked on Smart Nation program to harness 4IR technologies which includes big data and faster networks to create technology based solutions. Some areas of focus include open data systems and public transport networks. For example, it encompasses hard ware like lampposts with wireless sensors and AI enabled software to process sensor data and video analytics. They are helpful to urban and operational planning, maintenance, and incident response. 4IR technologies track and analyze data related to housing, amenities and public infrastructure. Singapore collaborated UN-Habitat on a capacity-building program in support of the UN's New Urban Agenda. The emphasis of this program is to demonstrate how local challenges overcome by applying sustainable urban system principles, long-term integrated master planning, and public-private partnerships based development.

## Way forward and policy recommendations

In order to realize UN SDGs, it is necessary for the economies and societies to rapidly transition toward circular economy led carbon neutral world. Humans should emulate nature.

Earth systems are circular in nature. Whereas the human engineered systems since the first industrial revolution are in essence linear to achieve mass production. Linear systems produce waste and cause pollution (Jose and Ramakrishna, 2021). Hence, the impetus for circular economy led sustainability in recent times. Yet, sustainability gap is evident with every enabler of sustainability. Fast moving consumer goods (FMCG) companies are lagging behind respective recycling targets. Similarly, companies, businesses and service providers are yet to transition from their linear economy approaches to circular economy approaches deeply. It is true with the commerce and trade among communities, regions and countries. Financial institutions as well as investors have only committed a fraction of their resources to the sustainability projects and programs. In other words, the green financing is in the nascent stage. Nations have fallen behind the announced carbon emissions reduction targets. International standards and treaties, and regulators are in the catching up mode. Consumers are in the wait and see mode rather than influencing the businesses via their purchasing decisions. For example, according to the United Nation's environment program, fashion industry is responsible for up to 10% of global carbon emissions. Consumer choices and behaviors will have a major impact on the fashion industry's supply chains, value chains, and end of life management practices, and thus providing necessary impetus to eliminate or substantially reduce the sustainability gap in the textiles and apparel industry sector (Shirvanimoghaddam et al., 2020; Sadeghi et al., 2021).

### 4IR readiness

High-technology manufacturing found to be associated with lower emissions than medium-technology manufacturing and low-technology manufacturing (Avenyo and Tregenna, 2021). Such findings suggest that a shift toward more technology-intensive manufacturing may be a more environmentally sustainable industrialization path. Nations and companies to self-assess 4IR readiness and emulate the best practices elsewhere. This will allow them not to miss the green growth opportunities in the coming years and decades. Moreover, this enables them to safe guard against the potential climate change effects, and to perform their respective responsibilities to mitigate extreme weathers, pollution, and biodiversity loss. Knowledge of 4IR technologies in realizing UN SDGs is necessary for nurturing future ready graduates (Ramakrishna, 2021). According to the International Labour Organization, about half of 1.6 billion total workforce are in the informal sector and badly affected by the pandemic. According to the World Bank estimates, transition to low-carbon and circular economies will create trillions of dollars of economic growth and tens of millions of new jobs. In order to seize the opportunities, SMEs and MMEs to quickly absorb the importance of sustainability and embrace sustainability growth opportunities and leverage schemes and incentives provided by the governments, financial institutions and investors. They also should leverage scalable opportunities beyond the home country.

### Sustainability Governance Structures

In order to progress on sustainability vision, companies need to align their environmental, social and governance (ESG) aspects and take stock of them regularly. To signal strong alignment, companies to consider appointing Chief Sustainability Officer, CSO. For example, in Singapore the listed companies such as City Developments Limited, CapitaLand, Wilmar International, and United Overseas Bank started appointing CSOs since 2011. Certain other companies are setting up dedicated sustainability committee in respective corporate boards to assess ESG performance and produce annual reports for tracking. For example, Singapore exchange listed companies ComfortDelGro Corporation, SBS Transit Ltd and VICOM Ltd have instituted respective governing board sustainability committees. Independent studies suggest that companies with good ESG performance also performed well in terms of value creation and financial growth. This has been the experience also in USA and European countries. Realizing the importance, Singapore Stock Exchange started encouraging companies to make annual ESG sustainability reporting since 2016. It is in the interest of all stakeholders, companies to consider ESG in all the strategic decisions ranging from daily operations to long-term investments.

## Conclusions

The United Nations adopted 17 UN SDGs in 2015 to end poverty and to protect planet Earth for the well-being of current as well as future generations. UN SGDs are interrelated, and hence an action in one SDG will affect the outcomes in other SDGs. Technological advancements, financial resources, creativity, and commitment from all of society are necessary to achieve social, economic and environmental sustainability. The tasks of decarbonization of economies and mitigating climate change are essential in achieving UN SDGs. Earlier technologies fall short in enabling necessary transition to carbon neutrality or decarbonization of economy. 4IR innovations enable the desired shift toward circular economy, which is more environmentally sustainable industrialization and development path. Nations and companies to self-assess 4IR readiness and emulate the best practices elsewhere. This will allow them not miss the green growth opportunities in the coming years and decades. Moreover, this enables them to safe guard against the potential climate change effects, and to perform their responsibilities to mitigate extreme weather, pollution, and biodiversity loss for the well-being and progress of humans.

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