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ANNEX A. FRONTIER TECHNOLOGY TRENDS

This annex presents the status of key frontier technologies in detail to help analyse their impact on sustainable development. Frontier technologies present economic and social opportunities as well as challenges, so their key features and status need to be well understood. This annex covers relevant technical and commercial aspects such as R&D, prices and market structure. The developments in frontier technologies have been so rapid that this attempt can only serve as a snapshot, but it can still offer a good starting point to discuss their effects on society. Among various frontier technologies, 17 are covered in this annex: AI, IoT, big data, blockchain, 5G, 3D printing, robotics, drones, gene editing, nanotechnology, solar PV, concentrated solar power, biofuels, biomass and biogas, wind energy, green hydrogen and electric vehicles.

Table 1
Frontier technologies covered in this report

Technology	Description
Artificial intelligence (AI)	AI is normally defined as the capability of a machine to engage in cognitive activities typically performed by the human brain. AI implementations that focus on narrow tasks are widely available today, used for example, in recommending what to buy next online, for virtual assistants in smartphones, and for spotting spam or detecting credit card fraud. New implementations of AI are based on machine learning and harness big data.
Internet of things (IoT)	IoT refers to myriad Internet-enabled physical devices that are collecting and sharing data. There is a vast number of potential applications. Typical fields include wearable devices, smart homes, healthcare, smart cities and industrial automation.
Big data	Big data refers to datasets whose size or type is beyond the ability of traditional database structures to capture, manage and process. Computers can thus tap into data that has traditionally been inaccessible or unusable.
Blockchain	A blockchain refers to an immutable time-stamped series of data records supervised by a cluster of computers not owned by any single entity. Blockchain serves as the base technology for cryptocurrencies, enabling peer-to-peer transactions that are open, secure and fast.
5G	5G networks are the next generation of mobile internet connectivity, offering download speeds of around 1-10 Gbps (4G is around 100 Mbps) as well as more reliable connections on smartphones and other devices.
3D printing	3D printing, also known as additive manufacturing, produces three-dimensional objects based on a digital file. 3D printing can create complex objects using less material than traditional manufacturing.
Robotics	Robots are programmable machines that can carry out actions and interact with the environment via sensors and actuators either autonomously or semi-autonomously. They can take many forms: disaster response robots, consumer robots, industrial robots, military/security robots and autonomous vehicles.
Drones	A drone, also known as an unmanned aerial vehicle (UAV) or unmanned aircraft system (UAS), is a flying robot that can be remotely controlled or fly autonomously using software with sensors and GPS. Drones have often been used for military purposes, but they also have civilian uses such as in videography, agriculture and in delivery services.

Gene editing	Gene editing, also known as genome editing, is a genetic engineering tool to insert, delete or modify genomes in organisms. Potential applications include drought-tolerant crops or new antibiotics.
Nanotechnology	Nanotechnology is a field of applied science and technology dealing with the manufacturing of objects in scales smaller than 1 micrometre. Nanotechnology is used to produce a wide range of useful products such as pharmaceuticals, commercial polymers and protective coatings. It can also be used to design computer chip layouts.
Solar photovoltaic (Solar PV)	Solar photovoltaic (solar PV) technology transforms sunlight into direct current electricity using semiconductors within PV cells. In addition to being a renewable energy technology, solar PV can be used in off-grid energy systems, potentially reducing electricity costs and increasing access.
Concentrated solar power	Concentrated solar power (CSP) plants use mirrors to concentrate the sun's rays and produce heat for electricity generation via a conventional thermodynamic cycle. Unlike solar photovoltaics (PV), CSP uses only the direct component of sunlight and can provide carbon-free heat and power only in regions with high direct normal irradiance (DNI).
Biofuels	Biofuels are liquid fuels derived from biomass, and are used as an alternative to fossil fuel-based liquid transportation fuels such as gasoline, diesel and aviation fuels. In 2020, biofuels accounted for 3 per cent of transport fuel demand.
Biogas and biomass	Biogas is a mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment. Biomass is renewable organic material that comes from trees, plants, and agricultural and urban waste. It can be used for heating, electricity generation, and transport fuels.
Wind Energy	Wind energy is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines. Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote and offshore ones.
Green Hydrogen	Green hydrogen is hydrogen generated entirely by renewable energy or from low-carbon power. The most established technology for producing green hydrogen is water electrolysis fuelled by renewable electricity. Compared to electricity, green hydrogen can be stored more easily. The idea is to use excess renewable capacity from solar and wind to power electrolysers which would utilize this energy to create hydrogen, which can be stored as fuel in tanks.
Electric Vehicles	Electric vehicles (EVs) use one or more electric motors for propulsion. They can be powered by a collector system, with electricity from extravehicular sources, or autonomously by a battery. As energy-consuming technologies, EVs create new demand for electricity that can be supplied by renewables. In addition to the benefits of this shift, such as reducing CO_2 emissions and air pollution, electric mobility also creates significant efficiency gains and could emerge as an important source of storage for variable sources of renewable electricity.

Source: UNCTAD

While discussed independently in the following sections, frontier technologies are increasingly interrelated, and they often expand each other's functionalities. For instance, AI uses big data securely stored in the blockchain to improve predictions using machine learning.[1] An increasing number of devices connected within an IoT network contribute to building up big data as data collection tools.[2] 3D printing can create more complex items that require more data by leveraging big data and items can be printed remotely through IoT[3] with AI-enabled defect detection functions.[4] Industrial robots assist 3D printing at various production stages such as replacing a printer's build plate, washing, curing and final finishing of additively manufactured parts.[5] 5G has the potential to allow near-instantaneous response for robots by dramatically shortening the response time.[6]

A. SUMMARY OF FRONTIER TECHNOLOGIES

1. ARTIFICIAL INTELLIGENCE

The United States and China have traditionally driven research on AI. During the period of 2000-2021, 438,619 AI-related publications were issued. Of these, nearly half were published in three countries: the United States (90,202), China (81,857) and the United Kingdom (29,011). The top three affiliations were the Chinese Academy of Sciences (4,831/China), the Centre National de la Recherche Scientifique (3,295/France), and Carnegie Mellon University (2,887/United States). During this same time period (2000-2021), 214,365 AI-related patents were granted, the three top assignee nationalities being China (70,847), the US (41,911), and the Republic of Korea (16,135). The top three current patent owners in 2021 were Samsung Group (3,066/Republic of Korea), Ping An Insurance Group (3,013/China), and LG Corp (3,240/Republic of Korea).

American and Chinese companies lead AI service provision. The top AI service providers commonly referred to include Alphabet, including their affiliates, Google and DeepMind, Amazon, Apple, IBM, Microsoft, Alibaba, and Tencent.[7] The top AI service users measured by spending on AI are the retail, banking, and discrete manufacturing sectors.[8] Prices of AI depend on applications and their requirements, but overall the trend is for increasing affordability.[9] Developing AI-based tools takes increasingly fewer resources: between 2018 and 2022, the cost to train systems decreased by 64 per cent, while training times improved by 94 per cent.[10] For instance, a basic video/speech analysis AI platform is estimated to cost $36,000-$56,000, an intelligent recommendation engine might cost $20,000-$35,000 and an AI-driven art generator might cost $19,000-$34,000.[11]

The market for AI ($65 billion in 2020) is growing rapidly. Private investment increased 103 per cent in 2021 compared to 2020 (from $46 billion to $96.5 billion). Supply-side market growth is driven by factors including growth in big data allowing for increased learning, improved productivity, distributed application areas, greater availability of government funding, and advances in image and voice recognition technologies.[12] However, a shortage of AI technology experts represents a significant restraint on supply.[13] Demand-side growth is primarily driven by the increasing adoption of cloud-based applications and services and solutions that use AI to increase efficiency. Commonly cited challenges that might limit the expansion of the AI market include cybersecurity, regulatory compliance, privacy concerns, and equity and fairness.[14]

The AI labour market is thriving. One study using detailed data on online job vacancies found that demand for AI skills has risen sharply in the United States across industries and occupations. The number of positions seeking AI skills increased tenfold between 2010 and 2019, and four times as a proportion of all job postings. The highest demand for AI skills was in IT occupations, followed by architecture and engineering, scientific, and management occupations.[15]

2. INTERNET OF THINGS

China and the United States also lead research on IoT. Between 2000 and 2021, 139,805 IoT-related publications were issued, led by China (28,461), India (21,188) and the United States (17,318). The three leading affiliations were the Chinese Academy of Sciences (1,420/China), Beijing University of Posts and Telecommunications (1,415/China) and the Chinese Ministry of Education (1,085/China). During the same period, 147,906 patents were assigned, with three top nationalities of recipients being China (100,958), the Republic of Korea (17,374), and the United States (13,406). The three current leading owners in 2021 were Samsung Group (9,035/Republic of Korea), Qualcomm (2,477/United States), and State Grid Corporation of China (1,552/China).

American companies are major IoT service providers. The top IoT service providers (IoT platformers) commonly referred to include Accenture, TCS, IBM, EY, Capgemini, HCL and Cognizant.[16] The top sectors deploying IoT solutions include the manufacturing, home, health, and finance sectors.[17] The price of an IoT system depends on the type of application, but costs are only decreasing: the average cost of an IoT sensor has dropped from $1.40 in 2004 to $0.38 in 2020.[18] Currently, for instance, instance, ECG monitors range between $3,000and $4,000; environmental monitoring systems are priced from $10,000, energy management systems cost $27,000 and up, and building and home automation starts from $50,000.[19]

The IoT market is already large and is expanding at a fast pace: McKinsey estimates that it will enable $5.5 trillion to $12.6 trillion in value globally by 2030, up from $1.6 trillion in 2020.[20] Supply-side growth is driven in particular by advances in semiconductor technology which enable the development of lower-cost, lightweight, and more efficient devices.[21] On the demand side, growth is mainly driven by rising demand for advanced consumer electronics in growing economies, increasing adoption of smart devices and internet-enabled devices, the rise of tele-healthcare services, and the emergence of automation technology in various sectors.[22] However, cybersecurity risks and privacy concerns could negatively affect market growth here as well.[23]

The growth of the IoT market has led to skills shortages. According to one study, the number of online job advertisements that included “IoT” increased by 32 percent between July 2021 and April 2022.[24] In 2021, LinkedIn data suggests there were over 13,000 IoT-related job openings in the United States alone.[25]

3. BIG DATA

China and the United States are the front-runners of big data R&D. During the period spanning 2000-2021, there were 119,555 publications related to big data with three top countries being China (39,484), the United States (23,821) and India (8,970). The three leading affiliations were the Chinese Academy of Sciences (2,339/China), Ministry of Education China (1,186/China) and Tsinghua University (1,149/China). Within the same period, there were 72,184 patents with top nationality of assignees being China (62,605), the Republic of Korea (5,302) and the United States (2,031). The top three current owners were State Grid Corp. of China (1,534/China), Ping An Insurance Group (1,189/China) and Baidu Inc. (468/China).

American companies lead the big data market. The leading providers of big-data-as-a-service measured in terms of revenue include Amazon, Microsoft, IBM, Google, Oracle, SAP and HP.[26] Top users of big data measured by spending on big data service are banking, discrete manufacturing, and professional services.[27] The cost of a big data system varies depending on the objective. For example, the average cost of building a data warehouse with cloud storage has been estimated at $359,951 per year, while the average cost of building one with on-premises storage is pegged at $372,279 per year.[28]

The big data market is already expanding quickly, particularly in developed economies, and will continue to add economic value as its uptake across industries drives impressive efficiency improvements.[29] Supply-side growth is driven by factors including growing Internet user coverage, increasing adoption of cloud services and solutions, and continual major growth in data production.[30] However, the lack of skilled workers represents a concurrent constraint to supply.[31] Growth in demand is driven by an increasing awareness of the efficiency-related benefits and novel solutions that big data approaches can yield, particularly in finance, but also in other industries from electricity generation to as they use them for risk management, demand modelling, customer service, and real-time analytics.[32] However, lack of awareness of the benefits of big data as well as privacy and security concerns continue to somewhat dampen market growth.

The big data industry has driven a boom in demand for data scientists. According to Glassdoor data, job openings for data scientists have increased by 480 per cent since 2016 and 650 per cent since 2012.[33] In the United States, the Bureau of Labor Statistics predicts a growth rate of 36 per cent between 2021 and 2031.[34] Globally, the job market for data scientists and analysts will number in the tens of millions.

4. BLOCKCHAIN

As with most of these technologies, China and the United States lead research efforts into blockchain technology. During the 2000-2021 period, there were 27,964 publications related to blockchain, led by China (7,014), the United States (3,906), and India (3,069). The top three affiliations were Beijing University of Posts and Telecommunications (413/China), the Chinese Academy of Sciences (402/China) and the Chinese Ministry of Education (271/China). During this same period, 63,767 patents were granted, the top three assignee nationalities being China (29,088), the United States (10,591), and the Cayman Islands (5,408). The top current owners were Advanced New Technology Co. Ltd. (3,540/Cayman Islands), Alibaba Group Holdings (3,256/Cayman Islands) and Ant Group Co. Ltd. (2209/China).

Top providers of blockchain (blockchain-as-a-service providers)[35] service include Alibaba (China), Amazon, IBM, Microsoft, Oracle (all United States) and SAP (Germany).[36] American companies are thus the leading blockchain service providers. The top users of blockchain by industry, measured by spending on blockchain service, were banking, process manufacturing, and discrete manufacturing.[37] Blockchain is a feature-dependent technology, so the final price depends on the specific project requirements. The development cost of an NFT marketplace is estimated between $50,000 to $130,000, that of a Decentralized Autonomous Organization (DAO) is between $3,500 to $20,000, while a cryptocurrency exchange app costs between $50,000 to $100,000.[38]

The blockchain market has grown particularly rapidly in the past decade and projections suggest this will only accelerate, forecasting that the business value generated by blockchain will reach $176 billion by 2025 and $3.1 trillion by 2030.[39] On the supply side, the application fields of blockchain have expanded to include various financial transactions (online payments and credit and debit card payments) as well as IoT, health and supply chain management.[40] However, challenges relating to scalability and security, regulatory uncertainty, and difficulties with integrating the technology within existing applications act as potential market constraints. Demand-side growth is primarly driven by growth in online transactions, currency digitization, secure online payment gateways, and growing interest from the banking, financial services and insurance sector alongside businesses' increasing acceptance of cryptocurrencies as a means of payment.[41]

The blockchain job market is growing rapidly. Global demand for blockchain developers is estimated to have increased by between 300 and 500 per cent in 2021, driven by hiring from the five biggest blockchain employers: Deloitte, IBM, Accenture, Cisco, and Collins Aerospace.[42] Blockchain developers continue to be well remunerated, with median annual incomes of $136,000 in the US, $87,500 in Asia, and $73,300 in Europe.

5. 5G

China and the United States also lead 5G research. During the period 2000-2021, 13,045 publications related to 5G were issued, led by China (3,236), the United States (1,446) and India (1,224). The top affiliations were Beijing University of Posts and Telecommunications (402/China), Nokia Bell Labs (225/United States) and University of Electronic Science and Technology of China (179/China). During the same period, 32,412 patents were granted, with the top assignee nationalities being China (15,869), the

Republic of Korea (12,646), and the United States (1,858). The top current owners are Samsung Group (11,920/Republic of Korea), Huawei (1000/China) and LG Corp. (744/Republic of Korea).

The leading vendors of end-to-end 5G network infrastructure include Ericsson, Huawei, Nokia, ZTE, Samsung, and NEC.[43] Certain industries are expected to be particularly heavy users and major beneficiaries of the 5G rollout. These include mobile operators and network providers, machinery and industrial automation companies, component and module vendors, and manufacturing businesses.[44] 5G mobile line prices vary depending on the carrier and features. However, costs remain high: the monthly cost of a single line of service with unlimited access to the 5G nationwide network in the US starts at $70 for Verizon, $65 for AT&T, and $60 for T-Mobile.[45] The leading early adopters of 5G technologies are China, Republic of Korea, the United Kingdom, Germany, the United States, Switzerland, and Finland.[46]

PwC estimates 5G's economic impact in 2022 to be $150bn and projects that it will reach $1.3 trillion by 2030.[47]

The rollout of 5G will take time, approximately five years to achieve broad coverage. It is already widespread though, with Ericsson predicting one billion subscriptions by the end of 2022 and 4.4 billion by 2027.[48] Projections based on current trajectories predict that it will generate $7 trillion of economic value by 2030.[49] One constraint is introduced by the necessity of upgrading 5G infrastructure, notably microcell towers and base stations as the high costs associated with upgrades impede wide diffusion.[50] In terms of demand, growth is mainly driven by rising demand for mobile broadband, the growing use of smartphones and smart wearable devices, surging demand for mobile video, rapid developments in IoT and an ever-growing number of connected devices, initiatives in multiple countries towards the development of smart cities, and the shift in consumer preference from premise-based to cloud-based solutions.[51]

5G adoption is set to create large opportunities in the job market. It is estimated that in the US alone in 2034, 4.6 million 5G-related jobs will be created, driven largely by employment in the following sectors: agriculture, construction, utilities, manufacturing, transportation and warehousing, education, healthcare, and government.[52] By 2035, the global 5G value chain is expected to support 22 million jobs globally.[53]

6. 3D PRINTING

The story with 3D printing is similar, with the United States and China driving research. During the period 2000-2021 period, 36,367 publications related to 3D printing were made available, led by the United States (8,896), China (7,515), and the United Kingdom (2,586). The top affiliations were the Chinese Ministry of Education (631/China), the Chinese Academy of Sciences (571/China), and Nanyang Technological University (491/Singapore). Within the same period, there 70,799 new patents were assigned, with assignees' nationalities dominated by China (42,691), the United States (9,069), and Germany (4,705). The top patent owners in 2022 were Hewlett-Packard (1,632/United States), Xi'an Jiaotong University (563/China) and Beijing University of Technology (559/China).

The largest 3D printing companies include Stratasys, 3D Systems, Materialise NV, EOS GmbH and General Electric.[54] Top users by sector, measured by spending on 3D printing technology, were discrete manufacturing, healthcare and education.[55] The cost of 3D printing has dropped markedly in the recent years and are expected to continue to do so.[56] Currently, an entry-level 3D printer can cost as low as $100, while an industrial 3D printer starts at $10,000.[57]

The 3D printing market has been growing at a fast pace. Globally, it was valued at $12 billion in 2020, expected to rise to $51 billion by 2030.[58] Supply-side growth is mainly driven by increasing variety in the materials that can be 3D printed (major shift from plastic to metal), increases in the production speed, increases in the size of printable objects, reduction of errors, decreases in development costs and time, the ability to build customized products, and government spending on 3D printing projects.[59] However, the still relatively high cost of 3D printing when compared to many products' traditional methods of production, combined with the scarcity of skilled labourers, may hamper the market growth. This has however not prevented demand-side growth, driven by an increase in applications in healthcare, consumer electronics, automotive, dental, food, fashion, and jewelry.[60]

The 3D printing industry's demand for labour is increasing as its rapidly growing market requires more skilled professionals. It is estimated that the industry will create 1.7-2.8 million new jobs in 3D-printing-enabled manufacturing in the United States, and between 3 and 5 million new skilled jobs in total. Auxiliary jobs are also increasingly sought after, with the industry needing engineers, software developers, material scientists, and a wide range of business support functions including sales, marketing and other specialists.[61]

7. ROBOTICS

Robotics research is led by the United States. Among the 276,027 publications related to robotics published in 2000-2021, the United States (69,909), China (38,494) and Japan (20,527) led the way. Top affiliations were the Chinese Academy of Sciences (3,676/China), Harbin Institute of Technology (2,568/China) and Carnegie Mellon University (2,484/United States). During the same period, 122,940 patents were granted, with most assignees coming from the United States (48,164), followed by China (27,502) and Germany (5,205). The top three patent owners as of 2022 are Johnson & Johnson (3,438/United States), Intuitive Surgical Inc. (3,383/United States) and Medtronic Inc. (1,834/United States).

Manufacturers from a diverse collection of countries are dominate robotics sales and production. The four largest industrial robotics manufacturers are ABB (Switzerland), Fanuc (Japan), KUKA (Germany) and Yaskawa (Japan), while the largest autonomous vehicle manufacturers include Alphabet/Waymo (United States), Aptiv (Ireland), GM (United States), and Tesla (United States).[62] The top industry spenders on robotics were discrete manufacturing, process manufacturing and resource industries.[63] There are many types of robots and price depends on the type.

As the costs of production in robotics have decreased (e.g., through increasing production in lower-cost regions, lower R&D costs, and economies of scale) prices have followed: there has been a more than 50% drop in average robotics costs since 1990.[64] This increased affordability, combined with greater volumes of production, is in turn driving a democratising increase in market size.

The current estimate of job growth in robotics is modest in comparison to some of these other technologies, in part because in many economies it is already further developed than they are. In the United States, for instance, there were 167,100 active robotics engineers in 2022 with the robotics engineer job market is expected to grow by between 1 and 5 per cent between 2020 and 2030.[65] Robotics careers include robotics engineers, software developers, technicians, sales engineers, and operators.[66]

8. DRONE TECHNOLOGY

The United States and Canada drive research into drone technology. During the period of 2000-2021, the biggest contributing countries to the 23,526 publications on drone technology were the United States (5,047), China (3,028), and the United Kingdom (1,411). The top affiliations were the Centre National de la Recherche Scientifique (CNRS) (220/France), the Chinese Academy of Sciences (220/China) and Beihang University (151/China). During the same period, there were 48,613 patents assigned worldwide, dominated by China (22,209), the United States (7,791), and the Republic of Korea (6,318). The top three current owners of patents in 2022 were SZ DJI Technology Co. Ltd. (1,705/China), Qualcomm (891/United States) and LG Corp. (704/Republic of Korea).

American manufacturers are dominant in the military drone space while the commercial drone space is more diverse, though Chinese companies play an outsized role. Companies commonly referred to as top manufacturers of commercial drones are 3D Robotics (United States), DJI Innovations (China), Parrot (France), and Yuneec (China), while military drone makers include Boeing (United States), Lockheed

Martin (United States), and Northrop Grumman Corporation (United States).[67] Top industries measured by spending on drone technology were the utility, construction, and discrete manufacturing sectors.[68] The price of commercial (non-amateur) drones begins at $2000 per unit, while military drones range in price from $800,000 to $400 million per unit.[69]

The commercial drone market, which has already experienced significant growth, is set to continue expanding. In the US market alone, the industry grew from around $40 million in 2012 to around $1 billion in 2017 and is expected to have an annual impact of $31 to $46 billion on the country's GDP.[70] The industry with the largest potential market for commercial applications of drone technology is infrastructure, with an estimated addressable market value of $45.2 billion.[71] Digitization and technological improvement in cameras, drone specifications, mapping software, multidimensional mapping, and sensory applications are driving growth. However, health and safety, privacy and national security regulations are expected to negatively affect the market while satellite imagery, though expensive, represents a competing industry that might impede market growth, particularly as satellite services do not share the same regulatory issues. On the demand side, increasing demand for GIS, LiDAR, and mapping services from sectors including agriculture, energy, tourism, construction, mapping and surveying, and emergency services are contributing to growth.[72]

As the drone industry grows, so does its job market. In Australia, drones are expected to support 5,500 full-time job equivalents on average per annum between 2020-2040.[73] In 2020, a year marked by economic uncertainty and job losses, drone companies reversed the trend, increasing their labour force by an average of 15%.[74]

9. GENE EDITING

Gene editing research is, as is the trend, led by the United States and China. In 2000-2021, publications related to gene editing numbered 24,802, led by the United States (9,881), China (5,106), and the United Kingdom (2,099). The top affiliations were the Chinese Academy of Sciences (994/China), Harvard Medical School (696/United States), and the Chinese Ministry of Education (573/China). Within the same period, 13,970 patents were granted, with the most assignees coming from the United States (6,482), followed by China (3,834) and Switzerland (673). The three current owners were Massachusetts Institute of Technology (427/United States), the University of California (360/United States), and Harvard University (337/United States).

Companies commonly referred to as top gene editing service providers include CRISPR Therapeutics (Switzerland), Editas Medicine (United States), Horizon Discovery Group (United Kingdom), Intellia Therapeutics (United States), Precision BioSciences (United States), and Sangamo Therapeutics (United States).[75] Gene editing is used by pharma-biotech companies, academic institutes and research centres, agrigenomic companies, and contract research organizations.[76] The price of gene editing varies by technology and application. The cost of human gene therapies addressing genetic medical conditions currently ranges from $373,000 to $2.1 million but can cost as much as $5 billion to develop.[77]

The gene editing market is growing but some concerns persist. Supply remains driven by large funding for research and development and technological improvement in genetic engineering technologies.[78] On the demand side, the market is driven by increasing cases of genetic and infectious diseases, the food industry's increasing focus on genetically modified technologies, and increasing demand for synthetic genes. However, ethical issues concerning the misuse of gene editing as well as its potential effect on human health may dampen growth.[79]

Labour demand in gene editing is expected to soar with the gene editing market's expected growth from $5.20 billion in 2020 to $18.50 billion in 2028. In the United Kingdom, it has been estimated that 18,000 new jobs will be added between 2017-2035, while in the United States, 22,500 new medical scientist and biomedical engineer jobs are expected to be added between 2021 and 2031.[80]

10. NANOTECHNOLOGY

Nanotechnology research is led by the United States and China. Between 2000 and 2021, 186,827 nanotechnology-related publications were issued, led by the United States (52,135), China (31,502), and India (13,448). The top affiliations were the Chinese Academy of Sciences (5,451/China), the Chinese Ministry of Education (3,581/China) and Centre National de la Recherche Scientifique (CNRS) (2,390/France). Within the same period, 6,175 patents were assigned, with the top nationalities of beneficiaries being China (1,395), the United States (1,253), and the Russian Federation (922). The three biggest owners were Aleksandr Aleksandrovich Krolevets (224/Russian Federation/Individual), Harvard University (90/United States) and PPG Industry Inc. (76/United States).

Top nanotechnology companies include BASF (Germany), Apeel Sciences (United States), Agilent (United States), Samsung Electronics (Republic of Korea), and Intel Corporation (United States). The major users of nanotechnology include medicine, manufacturing, and energy.[81]

On the supply side, the market is driven by technological advancements, increasing government support, private sector funding for R&D, and strategic alliances between countries. In terms of demand, the market is driven by a general growing demand for device miniaturization.[82] Concerns related to environmental, health, and safety risks, as well as nanotechnology commercialization risk constraining market growth.[83]

The nanotechnology job market is expected to grow, but at a modest rate. In the United States, the nanotechnology engineer job market is set to grow by 6.4 per cent between 2016 and 2026.[84] Expected salaries in the United States range between $35,000-$50,000 for associates to $75,000-$100,000 for doctorate degrees.[85]

11. SOLAR PHOTOVOLTAIC

Solar PV research is led by India, the United States, and China. During the period 2000-2021, 19,875 publications related to solar PV were presented, led by India (6,169), the United States (2,850) and China (1,692). The top affiliations were the Indian Institute of Technology Delhi (817/India), Vellore Institute of Technology (219/India) and National Renewable Energy Laboratory (199/United States). Within the same period, 38,425 patents were granted, with the most assignees coming from China (31,361), the Republic of Korea (1,792), and the United States (1,578). The top three owners in 2022 are State Grid Corp. of China (290/China), Tianjin University (152/China), and Wuxi Tongchun New Energy Tech (139/China).

Top solar panel manufacturers include Jinko Solar (China), Canadian Solar (Canada), Trina Solar (China) First Solar (United States), SunPower (United States), and Hanwha Q CELLS (Republic of Korea).[86] The biggest users of solar PV technology include the residential, commercial and utilities sectors.[87] The prices of solar PV panels have decreased significantly, the average upfront cost for commonly used residential PV systems (6kW) dropped from $50,000 to the range of $16,200- $21,420 in ten years between 2008 and 2018, while the national average cost of a residential PV system in the United States is now estimated at $2.94 per watt.[88]

The concentrated solar power market size is set to continue expanding. The IEA recorded a negative impact of COVID-19 due to the pandemic hampering construction efforts. However, they project an overall increase in global implementation of the technology from 2023 to 2025 onwards, with a push for worldwide economic recovery encouraging increased installation of both private and commercial-purpose PV systems, with potential for an approximate 165 GW rise in per annum capacity overall.[89]

Solar is widely acknowledged as key to efforts to combat climate change. Chinese estimates have projected that if solar photovaltic energy was installed in the remaining construction area available for it in the country (estimated at approximately 6.4 billion metres squared), it would generate 1.55 times the territory's annual electricity usage per year.[90]

Solar PV is the largest employer among the different renewable energy industries, already accounting for close to 4 million jobs worldwide.[91] In the United States, the industry has experienced an average annual growth rate of 33% in the last decade alone.[92] The International Renewable Energy Agency (IRENA) estimates that around 15.4 million people will be employed in solar PV under the 1.5°C Scenario.[93]

12. CONCENTRATED SOLAR POWER

Concentrated solar power research is led by the United States. Across 2000-2021, the 3,195 publications related to concentrated solar power came out of the United States (595), Spain (484), and China (389). The top affiliations were the German Aerospace Center (131/Germany), University of Seville (72/Spain), and the Centre National de la Recherche Scientifique (CNRS) (68/France). Within the same period, 1,101 patents were assigned, the most recipients of which came from the United States (454), Belgium (79), and Germany (79). The top three current patent owners are Cockerill Maintenance & Ingenierie SA (79/Belgium), Brilliant Light Power, Inc (59/United States), and General Electric (56/United States).

Companies considered to be leaders in the concentrated solar power space include Abengoa Solar, S.A. (Spain), Ibereolica Group (Spain), ENGIE (France), NextEra Energy Resources (United States), and BrightSource Energy (United States). Concentrated solar power serves industrial, commercial and residential sectors.[94] The global weighted-average cost of electricity for concentrated solar power was estimated at $ 0.108/kWh in 2020.[95]

On the supply-side, growth in the market is driven by government support for the adoption of renewables, the integration of concentrated solar power into hybrid power plants, and advancements in heat transfer technology such as proppants, high-temperature salts, and CO_2 along with a growing ability to minimize light reflection through new coatings for receivers.[96] On the demand-side, market expansion is driven by concentrated solar power plants' ability to supply power on-demand rather than being weather dependent. However, there remain concerns in terms of high capital costs, limited supply of land mass in high solar radiation zones, limited access to water resources, and challenges with the accessibility of transmission grids.

Worldwide, the concentrated solar power industry has created an estimated 32,000 jobs to-date.[97] Jobs in the concentrated solar power space are set to grow with IRENA and the ILO predicting 1.6 million concentrated solar power jobs to have been created by 2050.[98]

13. BIOFUELS

Biofuels research is led by the United States. During the period 2000-2021, biofuels publications numbered 74,801, originating in large part from the United States (18,386), China (10,085), and India (6,896). The top affiliations were the Chinese Academy of Sciences (1,626/China), the Chinese Ministry of Education (1,225/China), and the University of São Paulo (847/Brazil). Within the same period, 22,325 patents were granted, largely to beneficiaries from the United States (6,988), China (3,798), and France (1,083). The three largest patent owners were Royal Dutch Shell (560/United Kingdom), Bayer AG (470/Germany) and BASF SE (339/Germany).

Leading biofuel production companies include Cosan (Brazil), Verbio (Germany), ALTEN Group (France), Archer Daniels Midland Co. (United States), Argent Energy UK Ltd. (United Kingdom), REG (United States), Cargill Inc. (United States), Louis Dreyfus (France), and Wilmar International Ltd (Singapore). The main users of biofuels are the transportation, heating and electricity generation sectors.[99] The cost of biofuel production depends on methods used. In 2020, the average production cost of biofuels made using cellulosic ethanol was $4 per gallon-gasoline equivalent (gge). Biofuels produced using the pyrolysis-biocrude-hydro treatment pathway had a cost estimate of $3.25/gge, biofuels produced using biomass to liquid (BTL) had an average cost of $3.80/gge, while hydrotreated esters and fatty acids (HEFA) biofuels were estimated to have an average cost of $3.70/gge.[100]

The global biofuels market is projected to expand rapidly: the IEA estimates that demand for biofuels will most likely grow by 41 billion litres, or 28 per cent, over the period 2021-2026.[101] The market is currently driven by demand-side factors as national policies such as obligatory blending take effect and national ambitions for energy security increase, the latter having been amplified by the conflict in Ukraine and the 2022 global energy crisis. Growing demand for fuel in the transportation sector and moves to transition to a low-carbon economy also contribute significantly. On the supply-side, preferential taxes, subsidies and mandates have driven biofuel prices lower and helped increase production.[102] However, the key challenge to biofuels is their continued low cost-competitiveness relative to fossil fuels. Furthermore, biofuel feedstock production may cause changes to land use patterns, place strain on water supply, generate air and water pollution, and increase food costs.[103]

Worldwide, the liquid biofuel market employs an estimated 2,411,000 people.[104] Although biofuel jobs declined between 4 and 5 per cent in the United States in 2020 due to knock-on effects from the Covid-19 pandemic, declines in biofuel employment were less severe than those in the job markets for other kinds of fuels. Biofuel employment is projected to rebound, accompanying the gradual recovery from the pandemic.[105]

14. BIOGAS AND BIOMASS

Biogas and biomass research is led by China and the United States. Between 2000 and 2021, 400,062 biofuel-related publications were put out, led by China (79,658), the United States (77,614), and India (27,183). The top affiliations were the Chinese Academy of Sciences (17,175/China), the Chinese Ministry of Education (8,554/China), and the University of the Chinese Academy of Sciences (6,245/China). Within the same period, the 251,251 registered patents were assigned primarily to residents of China (99,328), the United States (38,856), and France (13,713). The three top patent owners in 2022 were Xyleco (3,808/United States), BASF SE (2,694/Germany), and Evonik Industry AG (1,694/Germany).

Major biogas and biomass producers include Future Biogas (United Kingdom), Air Liquide (France), PlanET Biogas Global (Germany), Ameresco (United States), Quantum Green (India), Envitech Biogas (Germany), and Weltec Biopower (Germany). The main users of biogas and biomass are the industrial, transportation, residential and electric power generation sectors.[106] The cost of producing biogas varies between \$2/MBtu to \$20/MBtu.[107] Biomass power plants generate electricity that generally costs around \$0.030 and \$0.140/kWh; but certain projects can cost up to \$0.250/kWh.[108]

The global biogas markets is projected to grow rapidly, while the biomass market is expected to undergo transformation as it transitions from traditional to sustainable methods. While biomass constitutes 9 per cent of the world's energy production, biogas represents only a 0.3 per cent share of total primary energy. Despite this, the IEA projects significant growth for sustainable forms of both, driven by their flexibility, simplicity, and ecological necessity. The transition towards a low-carbon economy, growing demand from power generation companies, and the adoption of biomass in fuel cell technology. On the supply-side, biomass costs are dropping due to favorable government policies including loans for the establishment of biomass power plants while the availability of sustainable feedstocks for biogas purposes is set to grow by 40 per cent over the period to 2040.[109] However, the market is limited by challenges which include scarce land areas for energy-growing crops and technical hurdles that limit the commercial feasibility of biomass as a replacement for fossil fuels at higher blending rates when compared to coal.[110]

The biomass and biogas job markets are anticipated to keep growing. Solid biomass employs an estimated 765,000 individuals worldwide, while biogas employs approximate 339,000 people.[111] It is estimated that biomass production creates 73 permanent full-time direct jobs per 100MW of installation capacity.[112]

15. WIND ENERGY

Wind energy research is again led by China and the United States. 2000-2021 saw 37,514 publications related to wind energy, led by China (5,376), the United States (5,359) and India (4,254). The top affiliations were the Technical University of Denmark (545/Denmark), North China Electric Power University (364/China), and Delft University of Technology (359/Netherlands). Within the same period, 58,134 patents were assigned, mainly to applicants from China (32,991), Germany (11,630), and the US (2927). The top three current owners are Wobben Properties GMBH (3062/Germany), Wobben Aloys (1966/Germany), and Senvion SE (1884/Germany).

The companies frequently cited as leading in the wind energy space include Vestas (Denmark), Siemens Gamesa (Spain), Goldwind (China), GE (United States), and Envision (China) (BizVibe, 2022). The major users of wind energy include the agricultural, residential, utility and industrial sectors (Hartman, 2021). The global weighted-average cost of electricity of new onshore and offshore wind farms was $ 0.053/kWh and $ 0.115/kWh respectively in 2019.[113]

The global wind energy market continues to grow as installation and maintenance costs decrease. In 2021, wind electricity generation increased by a record 273 TWh (up 17 per cent compared to 2020), making it the fastest growing of all power generation technologies.[114] Given the increasing affordability and profitability of wind and the large number of high-wind areas that have not yet been exploited for it, potential for growth is strong. Demand-side drivers of growth in the wind energy market include increasing demand for renewable energy sources and continually growing energy consumption globally. With energy prices increasing significantly, demand for increasingly cost-effective renewable energy is growing.[115] On the supply-side, offshore wind farms have circumvented challenges related to sea depth while benefitting from high wind speeds. Barriers in the wind energy sector include technological ones related to grid connection and integration and the lack of supporting infrastructure. There are also economic challenges, notably the high initial cost of capital and long payback periods, shortages in financing channels, immature offshore supply chains, and outdated regulatory frameworks.[116]

The wind energy job market, already significant, currently employing 1.25 million people worldwide, is expected to experience rapid growth.[117] 3.3 million new jobs are expected to be created as a result of the additional 470GW of wind capacity expected to be installed by 2025.[118]

16. GREEN HYDROGEN

Green hydrogen research is led by China. Across 2000-2021, 802 green hydrogen publications were issued, led by China (140), Germany (100), and the United States (74). The top affiliations were the Chinese Academy of Sciences (22/China), the University of Birmingham (13/United Kingdom), and the Chinese Ministry of Education (12/China). Within the same period, 58 patents were assigned, predominantly to applicants from China (30), the United Kingdom (5), the US (4) and Australia (4). The three top current owners are Anglo-American Corp. (4/UK), Xi'an Thermal Power Research Institute (4/China), and Johnson Matthey (3/UK).

Major green hydrogen companies include Air Liquide (France), Air Products and Chemicals, Inc (United States), Engie (France), Green Hydrogen Systems (Denmark), Siemens Energy Global GmbH (Germany), Toshiba (Japan), and Tianjin Mainland Hydrogen Equipment Co. Ltd (China).[119] The largest users of green hydrogen include heavy industry and the transportation, heating and power generation sectors.[120] Green hydrogen costs remain high, currently estimated at around 2.5-6 USD/kg H2.[121]

Demand in the global hydrogen market is growing because of the need for increased flexibility and dispatchability of renewable power systems, green hydrogen's broad potential use across the entire economy, and several countries with large renewable resources seeking to become net exporters. On the supply-side, the market is flourishing courtesy of technological improvement and market-readiness of several items in the hydrogen value chain.[122]

However, several barriers remain significant. Green hydrogen has higher production costs relative to grey hydrogen even when carbon pricing increases the costs of competing fossil fuels. Significantly, there remains a shortage of dedicated infrastructure for the transport and storage of green hydrogen, a still-small market for it, and difficulties in drawing clear distinctions between grey and green hydrogen in national energy statistics. Challenges also remain concerning the measurement of its sustainability.[123]

Green hydrogen is estimated to create as many as 2 million jobs between 2030 to 2050 as investments in electrolyzers and other green hydrogen infrastructure increase and as it becomes increasingly widely adopted as a fuel source.[124]

17. ELECTRIC VEHICLES

Electric vehicle research is led by China, the United States, Germany, and South Korea. From 2000 to 2021, of the 79,732 publications related to electric vehicles, most came from China (22,375), followed by the United States (13,108), and Germany (5,408). The top affiliations were the Beijing Institute of Technology (1,814/China), Tsinghua University (1,685), and Tongji University (900/China). Within the same period, of the 206,049 patents assigned, most went to China (94,124), the Republic of Korea (23,193), and the US (19,059). The top three current owners are LG Corp (7181/Republic of Korea), Toyota Group (6945/Japan), and Hyundai Motor Group (6817/Republic of Korea).

Leading electric vehicle manufacturers include Tesla (United States), Renault–Nissan–Mitsubishi Alliance (France/Japan), Volkswagen (Germany), BYD (China), Kia and Hyundai (Republic of Korea).[125] The major users of electric vehicles include the transportation, e-commerce and delivery industries.[126] Between 2021 and 2022, supply chain problems and component shortages have in fact raised the average cost of a new electric car in the United States by 22 per cent, to $54,000 (compared to a 14 per cent increase for internal combustion engine cars).[127]

Nearly 10 per cent of global car sales were electric in 2021, four times the market share in 2019. This rate of growth is projected to continue or accelerate. Demand is being driven by supportive government policy in the form of fuel economy and emission targets, city access restrictions, and financial incentives, along with growing corporate and consumer interest in purchasing electric vehicles to meet sustainability objectives.[128] On the supply-side, technological innovations have improved the driving range, cost competitiveness, and time required to charge for many electric vehicles. Crucially, charging infrastructure is becoming more widespread and accessible, and automotive manufacturers have made ambitious strategic commitments to promote electric vehicle production and consumption.[129] Further impetus comes from the growing success of Chinese manufacturers' focus on producing small EVs at much lower price points: in 2021, the sales-weighted median price of EVs in China was only 10% more than that of conventional offerings, compared with 45-50% on average in other major markets.[130]

However, barriers remain including concerns about electric vehicles' range, high battery prices, a shortage of charging infrastructure in certain countries, and concerns about the environmental harms of electric vehicle charging and battery production.[131]

Electrifying the transportation industry is expected to support job growth. It is estimated that nearly 200,000 additional permanent jobs will be created in Europe by 2030 as result of employment in ten sectors: battery manufacturing, charger manufacturing, wholesales, installation of the chargers, grid connection, grid reinforcement, civil and road work, charge point operation, charge point maintenance and electricity generation.[132] It is likewise expected that more than the transition to electric transport will lead to a net global net global increase of 2 million jobs despite losses the combustion engine sector. While there might be job losses in the auto repair and maintenance industries, these would be offset by gains in economy-wide induced jobs and increased power sector jobs.[133]

B. TECHNICAL NOTE

1. PUBLICATIONS

Publication data were retrieved from Elsevier's Scopus database of academic publications for the period 2000-2021. This period was chosen because, according to Elsevier, the data on papers published after 1995 are more reliable. The Scopus system is updated retroactively and, as a result, the number of publications for a given query may increase over time.[134] The publication search was conducted using keywords against the title, abstract and author keywords (title-abs-key). The search queries used for each frontier technology are listed below:

Technology	Search query
AI	TITLE-ABS-KEY (ai OR "artificial intelligence") AND PUBYEAR > 2000 AND PUBYEAR < 2021
IoT	TITLE-ABS-KEY (iot OR «internet of things») AND PUBYEAR > 2000 AND PUBYEAR < 2021
Big data	TITLE-ABS-KEY ("big data") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Blockchain	TITLE-ABS-KEY (blockchain) AND PUBYEAR > 2000 AND PUBYEAR < 2021
Robotics	TITLE-ABS-KEY (robotics) AND PUBYEAR > 2000 AND PUBYEAR < 2021
Drone	TITLE-ABS-KEY (drone) AND PUBYEAR > 2000 AND PUBYEAR < 2021
3D printing	TITLE-ABS-KEY ("3D printing") AND PUBYEAR > 2000 AND PUBYEAR < 2021
5G	TITLE-ABS-KEY ("5g communication" OR "5g system" OR "5g network") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Gene editing	TITLE-ABS-KEY (gene-editing OR genome-editing OR "gene editing" OR "genome editing") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Nanotechnology	TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2000 AND PUBYEAR < 2021
Solar PV	TITLE-ABS-KEY ("solar photovoltaic" OR "solar pv") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Concentrated solar power	TITLE-ABS-KEY ("concentrated solar power") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Biofuels	TITLE-ABS-KEY ("biofuel") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Biogas and biomass	TITLE-ABS-KEY ("biogas " OR "biomass") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Wind energy	TITLE-ABS-KEY ("wind energy") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Green hydrogen	TITLE-ABS-KEY ("green hydrogen") AND PUBYEAR > 2000 AND PUBYEAR < 2021
Electric vehicles	TITLE-ABS-KEY ("electric vehicle ") AND PUBYEAR > 2000 AND PUBYEAR < 2021

Source: UNCTAD.

2. PATENTS

Patent publication data were retrieved from PatSeer database. To align with the publication data, the search period was set as 2000-2021. The patent publication search was conducted using keywords against the title, abstract and claims (TAC). The search queries used for each frontier technology are listed below:

Technology	Search query
AI	TAC:(ai OR “artificial intelligence”) AND PBY:[2000 TO 2021]
IoT	TAC:(iot OR “internet of things”) AND PBY:[2000 TO 2021]
Big data	TAC:(“big data”) AND PBY:[2000 TO 2021]
Blockchain	TAC:(blockchain) AND PBY:[2000 TO 2021]
Robotics	TAC:(robotics) AND PBY:[2000 TO 2021]
Drone	TAC:(drone) AND PBY:[2000 TO 2021]
3D printing	TAC:(“3D printing”) AND PBY:[2000 TO 2021]
5G	TAC:(“5g communication” OR “5g system” OR “5g network”) AND PBY:[2000 TO 2021]
Gene editing	TAC:(gene-editing OR genome-editing OR “gene editing” OR “genome editing”) AND PBY:[2000 TO 2021]
Nanotechnology	TAC:(nanotechnology) AND PBY:[2000 TO 2021]
Solar PV	TAC:(“solar photovoltaic” OR “solar pv”) AND PBY:[2000 TO 2021]
Concentrated solar power	TAC:(“concentrated solar power”) AND PBY:[2000 TO 2021]
Biofuels	TAC:(“biofuel”) AND PBY:[2000 TO 2021]
Biogas and biomass	TAC:(“biogas” OR “biomass”) AND PBY:[2000 TO 2021]
Wind energy	TAC:(“wind energy”) AND PBY:[2000 TO 2021]
Green hydrogen	TAC:(“green hydrogen”) AND PBY:[2000 TO 2021]
Electric vehicles	TAC:(“electric vehicle”) AND PBY:[2000 TO 2021]

Source: UNCTAD.

3. MARKET SIZE

Market size data, as measured by the revenue generated in the market, is based on various market research reports available online. Since each market research report yields somewhat different numbers, the market size data was collected so that the compound annual growth rate (CAGR) was the largest. Also, the number of years between the base year and the prediction year used to calculate the CAGR varies by technology, ranging from six to nine years.

4. FRONTIER TECHNOLOGY PROVIDERS

Since there was no structured, reliable information about market share or company profit readily available for frontier technologies, the top frontier technology providers were identified through an online search, listing companies most commonly referred to as top providers. The number of companies listed is not the same across the 11 frontier technologies because there is no effective way to narrow down the list to the same number for each technology. Moreover, the online search was conducted in English, potentially leading to more favourable results for companies from English-speaking countries. Therefore, the technology providers information is indicative only and needs to be interpreted cautiously.

5. FRONTIER TECHNOLOGY USERS

Frontier technology users (sectors) are ranked according to the scale of spending by the user sectors of each technology. The exceptions were 5G, gene editing, nanotechnology and solar PV for which spending data was not available and hence estimates available online were used instead.

[1] Maryville Online, 2017; Skalex, 2018

[2] Yost, 2019

[3] Digital Magazine, 2016

[4] Gaget, 2018

[5] AMFG, 2018

[6] Ramos, 2017

[7] Ball, 2017; Patil, 2018; Botha, 2019; Bain and Company, 2021

[8] IDC, 2019b)

[9] Azati, 2019

[10] Stanford Institute for Human-Centered Artificial Intelligence, 2022

[11] Klubnikin, 2022

[12] Stanford Institute for Human-Centered Artificial Intelligence, 2022

[13] Tencent Research Institute, 2017

[14] McKinsey & Company, 2021

[15] Alekseeva et al., 2021

[16] Mondal et al., 2021

[17] CBI, 2022

[18] Stevens, 2021

[19] Singh, 2018

[20] Chui et al., 2021

[21] KPMG and GSA, 2022

[22] Dahlqvist et al., 2019

[23] Insider Intelligence, 2022

[24] Hasan, 2022

[25] Hiter, 2021

[26] Emergen Research, 2022

[27] IDC, 2021b

[28] Ahmed, 2021

[29] OECD, 2019; Byers, 2015; Claros and Davies, 2016

[30] Roser et al., 2015

[31] Markow et al., 2017

[32] McKinsey Global Institute, 2013

[33] Malas, 2022

[34] Bureau of Labor Statistics, U.S. Department of Labor, 2022

[35] Blockchain-as-a-Service (BaaS) describes the practice whereby external service providers set up the necessary blockchain technology and infrastructure for a customer for a fee. A client pays the BaaS provider to set up and maintain blockchain connected nodes on their behalf. The BaaS provider handles the complex back-end aspects for the client and their business.

[36] Akilo, 2018; Patrizio, 2018; Anwar, 2019

[37] IDC, 2021a

[38] Hardy, 2022

[39] Kandaswamy et al., 2018

[40] MarketWatch, 2019

[41] Deloitte, 2017

[42] The Blockchain Academy, 2021

[43] Gartner, 2022

[44] McKinsey and Company, 2020

[45] Cipriani, 2020

[46] Campbell et al., 2019

[47] PwC, 2021

[48] Ericsson, 2022

[49] Gergs et al., 2022

[50] Maddox, 2018

[51] Nokia, 2020; *Forbes*, 2021c

[52] Mandel and Long, 2020

[53] Campbell et al., 2017

[54] Imarc Group, 2022

[55] IDC, 2019a

[56] PwC, 2020

[57] Durbin, 2022

[58] Lux Research, 2021

[59] WEF, 2020; *Horizon: The EU Research & Innovation Magazine*, 2014; *Forbes*, 2022b

[60] WEF, 2020

[61] Bunger, 2018

[62] Automate, 2020; Technavio, 2018b; Yuan, 2018; Mitrev, 2019

[63] McKinsey & Company, 2019; Chakravorty, 2019

[64] McKinsey & Company, 2019

[65] Occupational Information Network, 2022

[66] Grad School Hub, 2020

[67] Technavio, 2018a; FPV Drone Reviews, 2019; Joshi, 2019

[68] IDC, 2018

[69] Feist, 2021; Ritsick, 2020

[70] Cohn et al., 2017

[71] PwC, 2017b

[72] Mazur and Wiśniewski, 2016

[73] Australian Government, Department of Infrastructure, Transport, Regional Development and Communications, 2020

[74] Schroth, 2021

[75] Schmidt, 2017; Philippidis, 2018; Acharya, 2019

[76] UNCTAD, 2017; World Health Organization, 2021; Fajardo-Ortiz et al., 2022

[77] Muigai, 2022; Loo, 2014

[78] *Forbes*, 2021a; Zhang et al., 2020

[79] Plumer et al., 2018; World Health Organization, 2021

[80] Bureau of Labor Statistics, U.S. Department of Labor, 2019a, 2019b; Thompson, 2017b

[81] Cox, 2019; Nano.gov, 2020

[82] Brooks, 2022

[83] Aithal and Aithal, 2016; Osman, 2019

[84] CareerExplorer, 2020b

[85] Peterson's, 2017

[86] Reiff, 2020

[87] Doshi, 2017

[88] Sendy, 2022; Solar Industry Research Data, 2022

[89] International Energy Agency, 2022a

[90] Zhang et al., 2021

[91] IRENA, 2021a

[92] Solar Industry Research Data, 2022

[93] IRENA, 2021a

[94] International Energy Agency, 2020a

[95] IRENA, 2021c

[96] IEA, 2021; Bravo and Friedrich, 2018; Alnaimat and Rashid, 2019; International Energy Agency, 2022a

[97] IRENA, 2021a

[98] IRENA, 2021a

[99] United States Energy Information Administration, 2022

[100] Witcover and Williams, 2020

[101] International Energy Agency, 2021

[102] OECD-FAO, 2020

[103] United States Environmental Protection Agency, 2022

[104] IRENA, 2021a

[105] United States Department of Energy, 2021

[106] United States Energy Information Administration, 2022b

[107] IEA, 2020

[108] IRENA, 2022b

[109] International Energy Agency, 2020c

[110] Luo et al., 2018; IRENA, 2022c

[111] IRENA, 2021a

[112] Ravillard et al., 2021

[113] IRENA, 2021b

[114] International Energy Agency, 2022b

[115] International Energy Agency, 2020b

[116] IRENA, 2019b

[117] IRENA, 2021a

[118] Global Wind Energy Council, 2021

[119] The Business Research Company, 2021

[120] IRENA, 2020

[121] KPMG, 2020

[122] IRENA, 2020

[123] Global Programme on Green Hydrogen in Industry, 2022

[124] IRENA, 2021a

[125] Business Upturn, 2021

[126] Nixon, 2022

[127] *Wall Street Journal*, 2022

[128] IEA, 2022b

[129] Hamilton et al., 2020

[130] IEA, 2022b

[131] *Business Today*, 2022

[132] Pek et al., 2018

[133] UC Berkeley and GridLab, 2021

[134] Shoham et al., 2018

ANNEX B. FRONTIER TECHNOLOGIES READINESS INDEX

A. RESULTS OF THE READINESS FOR FRONTIER TECHNOLOGIES INDEX

The Frontier Technology Index is calculated following the methodology presented in the Technology and Innovation Report 2021 (see C. Technical note).[1] The index yielded results for 166 economies with the United States, Sweden and the Singapore receiving the highest scores in 2022 on a scale of 0 to 1 (Table 2). Based on their rankings, countries are placed within one of four 25-percentile score groups: low, lower-middle, upper-middle, and high.

Table 2
Index score ranking

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
United States of America	1.00	1	1	–	High	11	18	2	16	2
Sweden	0.99	2	4	▲	High	6	2	16	11	18
Singapore	0.96	3	5	▲	High	7	8	17	4	17
Switzerland, Liechtenstein	0.94	4	2	▼	High	21	13	12	5	5
Netherlands	0.94	5	6	▲	High	4	9	15	10	31
Republic of Korea	0.94	6	7	▲	High	15	26	3	9	7
Germany	0.92	7	9	▲	High	24	17	5	12	40
Finland	0.92	8	17	▲	High	22	5	21	20	30
China, Hong Kong SAR	0.91	9	15	▲	High	9	23	29	2	1
Belgium	0.91	10	11	▲	High	13	4	23	19	48
Canada	0.90	11	14	▲	High	5	21	9	29	20
Australia	0.90	12	12	–	High	33	1	11	57	13
Norway	0.90	13	19	▲	High	3	6	27	50	6
Ireland	0.90	14	8	▼	High	26	11	22	1	105
France	0.89	15	13	▼	High	18	24	8	17	21
Denmark	0.89	16	10	▼	High	19	7	24	24	8
United Kingdom	0.89	17	3	▼	High	20	12	6	44	12

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Luxembourg	0.88	18	16	▼	High	2	16	38	37	28
Japan	0.88	19	18	▼	High	10	51	7	13	3
Israel	0.88	20	20	–	High	37	14	19	6	60
Spain	0.86	21	21	–	High	8	28	14	34	24
Iceland	0.84	22	30	▲	High	1	3	74	80	32
New Zealand	0.83	23	23	–	High	12	10	42	58	9
Austria	0.80	24	22	▼	High	39	29	25	28	36
Italy	0.79	25	24	▼	High	58	34	10	25	42
Malta	0.78	26	35	▲	High	17	25	64	18	41
Poland	0.77	27	28	▲	High	28	30	30	33	84
Slovenia	0.77	28	33	▲	High	25	15	57	21	92
Estonia	0.77	29	29	–	High	16	19	63	26	64
Czechia	0.77	30	26	▼	High	47	27	32	15	78
Russian Federation	0.76	31	27	▼	High	43	32	13	54	69
Malaysia	0.76	32	31	▼	High	30	64	28	7	16
Portugal	0.75	33	32	▼	High	35	33	31	49	29
Cyprus	0.75	34	34	–	High	42	40	39	35	23
China	0.74	35	25	▼	High	117	92	1	8	4
Hungary	0.74	36	37	▲	High	14	43	48	14	99
United Arab Emirates	0.74	37	42	▲	High	29	50	34	32	38
Latvia	0.72	38	40	▲	High	23	22	73	30	102
Slovakia	0.72	39	36	▼	High	27	49	37	27	61
Brazil	0.71	40	41	▲	High	50	55	18	51	57

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Lithuania	0.70	41	39	▼	Upper middle	31	20	59	46	100
Croatia	0.68	42	52	▲	Upper middle	41	37	60	45	70
Bulgaria	0.67	43	51	▲	Upper middle	45	52	54	36	81
Greece	0.66	44	38	▼	Upper middle	56	31	71	48	44
Romania	0.66	45	45	–	Upper middle	32	69	33	38	122
India	0.66	46	43	▼	Upper middle	95	109	4	22	75
Saudi Arabia	0.65	47	50	▲	Upper middle	46	44	20	119	77
Chile	0.65	48	49	▲	Upper middle	62	46	40	103	19
Thailand	0.64	49	46	▼	Upper middle	40	90	46	41	10
Serbia	0.64	50	47	▼	Upper middle	51	54	58	43	89
Kuwait	0.64	51	58	▲	Upper middle	44	75	70	52	37
Barbados	0.62	52	48	▼	Upper middle	34	45	86	73	47
Türkiye	0.62	53	55	▲	Upper middle	75	48	26	77	49
Philippines	0.62	54	44	▼	Upper middle	94	79	52	3	80
Belarus	0.61	55	59	▲	Upper middle	57	35	78	53	103
South Africa	0.61	56	54	▼	Upper middle	71	77	36	67	25
Costa Rica	0.61	57	61	▲	Upper middle	63	53	88	39	67
Ukraine	0.59	58	53	▼	Upper middle	61	42	49	85	114
Montenegro	0.58	59	70	▲	Upper middle	49	39	113	81	68
Bahrain	0.58	60	56	▼	Upper middle	48	58	87	94	50

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Mexico	0.58	61	57	▼	Upper middle	70	73	45	31	96
Viet Nam	0.58	62	66	▲	Upper middle	69	117	41	23	11
Uruguay	0.57	63	68	▲	Upper middle	55	47	84	63	116
Oman	0.57	64	74	▲	Upper middle	52	86	51	91	63
Argentina	0.57	65	65	–	Upper middle	74	41	62	75	141
Tunisia	0.56	66	60	▼	Upper middle	88	61	66	42	45
Qatar	0.55	67	72	▲	Upper middle	36	115	56	115	15
Kazakhstan	0.55	68	62	▼	Upper middle	82	36	69	69	124
Brunei Darussalam	0.55	69	69	–	Upper middle	54	38	95	97	93
Morocco	0.55	70	76	▲	Upper middle	73	113	53	55	33
Panama	0.54	71	67	▼	Upper middle	66	89	102	40	27
Colombia	0.54	72	78	▲	Upper middle	79	85	55	79	76
Mauritius	0.54	73	77	▲	Upper middle	96	57	82	74	34
North Macedonia	0.53	74	73	▼	Upper middle	64	67	94	61	73
Iran (Islamic Republic of)	0.53	75	71	▼	Upper middle	78	74	35	118	62
Bosnia and Herzegovina	0.51	76	80	▲	Upper middle	60	84	89	78	71
Lebanon	0.51	77	63	▼	Upper middle	84	76	77	86	26
Armenia	0.51	78	83	▲	Upper middle	65	63	105	98	54
Georgia	0.51	79	79	–	Upper middle	77	56	96	88	46

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Jordan	0.51	80	64	▼	Lower middle	80	101	61	64	43
Bahamas	0.50	81	84	▲	Lower middle	38	72	116	114	82
Republic of Moldova	0.50	82	81	▼	Lower middle	53	97	93	70	117
Egypt	0.49	83	87	▲	Lower middle	91	66	47	90	119
Peru	0.49	84	89	▲	Lower middle	86	59	72	136	74
Indonesia	0.49	85	82	▼	Lower middle	102	107	50	47	97
Fiji	0.47	86	88	▲	Lower middle	87	78	106	89	22
Trinidad and Tobago	0.47	87	75	▼	Lower middle	59	70	131	108	91
Albania	0.46	88	85	▼	Lower middle	68	81	109	99	98
Sri Lanka	0.45	89	86	▼	Lower middle	115	82	75	83	85
Ecuador	0.43	90	90	–	Lower middle	89	96	76	113	87
Belize	0.43	91	97	▲	Lower middle	85	80	127	132	59
Dominican Republic	0.43	92	95	▲	Lower middle	76	93	145	62	108
Mongolia	0.42	93	110	▲	Lower middle	83	68	120	149	88
Jamaica	0.42	94	96	▲	Lower middle	72	95	143	126	72
Saint Lucia	0.41	95	93	▼	Lower middle	93	65	160	104	52
Azerbaijan	0.40	96	100	▲	Lower middle	81	94	85	141	121
Algeria	0.40	97	98	▲	Lower middle	112	83	65	162	111
Paraguay	0.40	98	102	▲	Lower middle	67	105	131	133	86

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Suriname	0.40	99	92	▼	Lower middle	92	62	160	110	127
Saint Vincent and the Grenadines	0.39	100	120	▲	Lower middle	90	71	160	131	83
Bolivia (Plurinational State of)	0.38	101	116	▲	Lower middle	101	88	134	144	56
El Salvador	0.37	102	106	▲	Lower middle	100	125	131	59	66
Maldives	0.37	103	114	▲	Lower middle	98	60	149	158	79
Namibia	0.36	104	91	▼	Lower middle	129	111	104	66	53
Samoa	0.36	105	NA	NA	Lower middle	125	91	135	127	35
Nepal	0.35	106	109	▲	Lower middle	123	126	100	112	39
Iraq	0.35	107	126	▲	Lower middle	104	100	44	164	158
Botswana	0.35	108	111	▲	Lower middle	109	102	103	128	94
Ghana	0.35	109	103	▼	Lower middle	99	122	81	107	154
Guyana	0.35	110	108	▼	Lower middle	113	119	160	87	95
Gabon	0.35	111	94	▼	Lower middle	105	98	149	76	148
Cambodia	0.34	112	113	▲	Lower middle	122	123	121	95	14
Kyrgyzstan	0.34	113	115	▲	Lower middle	107	103	119	111	113
Guatemala	0.34	114	104	▼	Lower middle	103	136	143	71	101
Cabo Verde	0.33	115	101	▼	Lower middle	97	110	160	153	51
Bhutan	0.32	116	NA	NA	Lower middle	108	106	137	160	55
Kenya	0.32	117	105	▼	Lower middle	120	135	83	93	107

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Eswatini	0.32	118	107	▼	Lower middle	141	114	124	72	131
Nigeria	0.32	119	124	▲	Low	119	108	68	157	153
Venezuela (Bolivarian Rep. of)	0.31	120	99	▼	Low	121	87	111	159	110
Lesotho	0.31	121	NA	NA	Low	110	129	123	92	130
Libya	0.31	122	117	▼	Low	151	99	97	145	104
Honduras	0.30	123	122	▼	Low	118	139	109	123	58
Nicaragua	0.29	124	125	▲	Low	106	116	160	122	109
Pakistan	0.28	125	123	▼	Low	149	159	43	82	138
Bangladesh	0.28	126	112	▼	Low	148	131	67	135	90
United Republic of Tanzania	0.27	127	138	▲	Low	131	164	79	65	150
Senegal	0.27	128	118	▼	Low	116	155	92	116	112
Timor-Leste	0.27	129	144	▲	Low	159	104	140	60	143
Angola	0.26	130	NA	NA	Low	127	121	145	109	152
Papua New Guinea	0.26	131	119	▼	Low	150	138	111	84	136
Congo	0.26	132	135	▲	Low	136	127	137	105	149
Myanmar	0.26	133	121	▼	Low	132	143	107	101	118
Lao People's Dem. Rep.	0.25	134	127	▼	Low	130	134	152	56	133
Cameroon	0.25	135	132	▼	Low	137	120	101	117	146
Cote d'Ivoire	0.23	136	131	▼	Low	114	146	128	125	132
Sao Tome and Principe	0.23	137	140	▲	Low	143	112	160	96	134
Uganda	0.22	138	128	▼	Low	133	137	91	120	147

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Rwanda	0.22	139	133	▼	Low	134	142	99	137	126
Burkina Faso	0.21	140	148	▲	Low	128	162	126	129	115
Malawi	0.20	141	137	▼	Low	153	141	117	102	155
Togo	0.19	142	129	▼	Low	144	130	146	134	120
Benin	0.19	143	139	▼	Low	152	128	126	124	142
Vanuatu	0.19	144	NA	NA	Low	146	124	160	156	65
Mali	0.19	145	141	▼	Low	138	165	118	100	123
Madagascar	0.18	146	130	▼	Low	124	152	140	142	139
Zambia	0.18	147	134	▼	Low	142	133	115	155	144
Zimbabwe	0.17	148	136	▼	Low	126	140	111	148	162
Tajikistan	0.17	149	143	▼	Low	160	118	140	138	151
Djibouti	0.17	150	146	▼	Low	135	163	160	68	135
Solomon Islands	0.16	151	NA	NA	Low	147	144	160	147	106
Mozambique	0.16	152	149	▼	Low	140	156	123	154	125
Mauritania	0.16	153	147	▼	Low	139	160	137	150	128
Haiti	0.15	154	154	–	Low	111	153	160	146	157
Ethiopia	0.15	155	150	▼	Low	162	161	80	106	137
Comoros	0.14	156	142	▼	Low	157	132	160	140	145
Guinea	0.14	157	153	▼	Low	154	158	149	130	156
Burundi	0.12	158	145	▼	Low	161	148	149	152	129
Yemen	0.10	159	156	▼	Low	165	154	90	121	164
Gambia	0.09	160	157	▼	Low	145	151	149	161	159
Sierra Leone	0.09	161	151	▼	Low	158	149	131	143	163

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Dem. Rep. of the Congo	0.09	162	158	▼	Low	155	145	131	163	161
Sudan	0.08	163	155	▼	Low	156	157	99	165	160
Afghanistan	0.08	164	152	▼	Low	164	150	114	151	165
Guinea-Bissau	0.04	165	NA	NA	Low	163	147	160	166	140
South Sudan	0.00	166	NA	NA	Low	166	166	160	139	166
Average score	0.50									

Source: UNCTAD.

B. READINESS FOR FRONTIER TECHNOLOGIES INDEX RESULTS BY SELECTED GROUPS

Table 3
Index results - Small Island Developing States (SIDS)

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Barbados	0.62	52	48	▼	Upper middle	34	45	86	73	47
Mauritius	0.54	73	77	▲	Upper middle	96	57	82	74	34
Bahamas	0.50	81	84	▲	Lower middle	38	72	116	114	82
Fiji	0.47	86	88	▲	Lower middle	87	78	106	89	22
Trinidad and Tobago	0.47	87	75	▼	Lower middle	59	70	131	108	91
Jamaica	0.42	94	96	▲	Lower middle	72	95	143	126	72
Saint Lucia	0.41	95	93	▼	Lower middle	93	65	160	104	52
Saint Vincent and the Grenadines	0.39	100	120	▲	Lower middle	90	71	160	131	83
Maldives	0.37	103	114	▲	Lower middle	98	60	149	158	79
Samoa	0.36	105	NA	NA	Lower middle	125	91	135	127	35
Cabo Verde	0.33	115	101	▼	Lower middle	97	110	160	153	51
Timor-Leste	0.27	129	144	▲	Low	159	104	140	60	143
Sao Tome and Principe	0.23	137	140	▲	Low	143	112	160	96	134
Vanuatu	0.19	144	NA	NA	Low	146	124	160	156	65
Solomon Islands	0.16	151	NA	NA	Low	147	144	160	147	106
Comoros	0.14	156	142	▼	Low	157	132	160	140	145
Average score	0.37									

Source: UNCTAD.

Table 4
Index results - Least Developed Countries (LDCs)

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Nepal	0.35	106	109	▲	Lower middle	123	126	100	112	39
Cambodia	0.34	112	113	▲	Lower middle	122	123	121	95	14
Bhutan	0.32	116	NA	NA	Lower middle	108	106	137	160	55
Lesotho	0.31	121	NA	NA	Low	110	129	123	92	130
Bangladesh	0.28	126	112	▼	Low	148	131	67	135	90
United Republic of Tanzania	0.27	127	138	▲	Low	131	164	79	65	150
Senegal	0.27	128	118	▼	Low	116	155	92	116	112
Timor-Leste	0.27	129	144	▲	Low	159	104	140	60	143
Angola	0.26	130	NA	NA	Low	127	121	145	109	152
Myanmar	0.26	133	121	▼	Low	132	143	107	101	118
Lao People's Dem. Rep.	0.25	134	127	▼	Low	130	134	152	56	133
Sao Tome and Principe	0.23	137	140	▲	Low	143	112	160	96	134
Uganda	0.22	138	128	▼	Low	133	137	91	120	147
Rwanda	0.22	139	133	▼	Low	134	142	99	137	126
Burkina Faso	0.21	140	148	▲	Low	128	162	126	129	115
Malawi	0.20	141	137	▼	Low	153	141	117	102	155
Togo	0.19	142	129	▼	Low	144	130	146	134	120
Benin	0.19	143	139	▼	Low	152	128	126	124	142
Vanuatu	0.19	144	NA	NA	Low	146	124	160	156	65
Mali	0.19	145	141	▼	Low	138	165	118	100	123
Madagascar	0.18	146	130	▼	Low	124	152	140	142	139
Zambia	0.18	147	134	▼	Low	142	133	115	155	144
Djibouti	0.17	150	146	▼	Low	135	163	160	68	135
Solomon Islands	0.16	151	NA	NA	Low	147	144	160	147	106
Mozambique	0.16	152	149	▼	Low	140	156	123	154	125
Mauritania	0.16	153	147	▼	Low	139	160	137	150	128
Haiti	0.15	154	154	–	Low	111	153	160	146	157
Ethiopia	0.15	155	150	▼	Low	162	161	80	106	137
Comoros	0.14	156	142	▼	Low	157	132	160	140	145
Guinea	0.14	157	153	▼	Low	154	158	149	130	156
Burundi	0.12	158	145	▼	Low	161	148	149	152	129
Yemen	0.10	159	156	▼	Low	165	154	90	121	164

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Gambia	0.09	160	157	▼	Low	145	151	149	161	159
Sierra Leone	0.09	161	151	▼	Low	158	149	131	143	163
Dem. Rep. of the Congo	0.09	162	158	▼	Low	155	145	131	163	161
Sudan	0.08	163	155	▼	Low	156	157	99	165	160
Afghanistan	0.08	164	152	▼	Low	164	150	114	151	165
Guinea-Bissau	0.04	165	NA	NA	Low	163	147	160	166	140
South Sudan	0.00	166	NA	NA	Low	166	166	160	139	166
Average score	0.19									

Source: UNCTAD.

Table 5
Index results - Landlocked Developing Countries (LLDCs)

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Kazakhstan	0.55	68	62	▼	Upper middle	82	36	69	69	124
North Macedonia	0.53	74	73	▼	Upper middle	64	67	94	61	73
Armenia	0.51	78	83	▲	Upper middle	65	63	105	98	54
Republic of Moldova	0.50	82	81	▼	Lower middle	53	97	93	70	117
Mongolia	0.42	93	110	▲	Lower middle	83	68	120	149	88
Azerbaijan	0.40	96	100	▲	Lower middle	81	94	85	141	121
Paraguay	0.40	98	102	▲	Lower middle	67	105	131	133	86
Bolivia (Plurinational State of)	0.38	101	116	▲	Lower middle	101	88	134	144	56
Nepal	0.35	106	109	▲	Lower middle	123	126	100	112	39
Botswana	0.35	108	111	▲	Lower middle	109	102	103	128	94
Kyrgyzstan	0.34	113	115	▲	Lower middle	107	103	119	111	113
Bhutan	0.32	116	NA	NA	Lower middle	108	106	137	160	55
Eswatini	0.32	118	107	▼	Lower middle	141	114	124	72	131
Lesotho	0.31	121	NA	NA	Low	110	129	123	92	130

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
Lao People's Dem. Rep.	0.25	134	127	▼	Low	130	134	152	56	133
Uganda	0.22	138	128	▼	Low	133	137	91	120	147
Rwanda	0.22	139	133	▼	Low	134	142	99	137	126
Burkina Faso	0.21	140	148	▲	Low	128	162	126	129	115
Malawi	0.20	141	137	▼	Low	153	141	117	102	155
Mali	0.19	145	141	▼	Low	138	165	118	100	123
Zambia	0.18	147	134	▼	Low	142	133	115	155	144
Zimbabwe	0.17	148	136	▼	Low	126	140	111	148	162
Tajikistan	0.17	149	143	▼	Low	160	118	140	138	151
Ethiopia	0.15	155	150	▼	Low	162	161	80	106	137
Burundi	0.12	158	145	▼	Low	161	148	149	152	129
Afghanistan	0.08	164	152	▼	Low	164	150	114	151	165
South Sudan	0.00	166	NA	NA	Low	166	166	160	139	166
Average score	0.29									

Source: UNCTAD.

Table 6
Index results - Sub-Saharan Africa

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
South Africa	0.61	56	54	▼	Upper middle	71	77	36	67	25
Mauritius	0.54	73	77	▲	Upper middle	96	57	82	74	34
Namibia	0.36	104	91	▼	Lower middle	129	111	104	66	53
Botswana	0.35	108	111	▲	Lower middle	109	102	103	128	94
Ghana	0.35	109	103	▼	Lower middle	99	122	81	107	154
Gabon	0.35	111	94	▼	Lower middle	105	98	149	76	148
Cabo Verde	0.33	115	101	▼	Lower middle	97	110	160	153	51
Kenya	0.32	117	105	▼	Lower middle	120	135	83	93	107
Eswatini	0.32	118	107	▼	Lower middle	141	114	124	72	131
Nigeria	0.32	119	124	▲	Low	119	108	68	157	153
Lesotho	0.31	121	NA	NA	Low	110	129	123	92	130

Country name	Total score	2022 rank	2021 rank	Change in rank	Score group	ICT rank	Skills rank	R&D rank	Industry rank	Finance rank
United Republic of Tanzania	0.27	127	138	▲	Low	131	164	79	65	150
Senegal	0.27	128	118	▼	Low	116	155	92	116	112
Angola	0.26	130	NA	NA	Low	127	121	145	109	152
Congo	0.26	132	135	▲	Low	136	127	137	105	149
Cameroon	0.25	135	132	▼	Low	137	120	101	117	146
Cote d’Ivoire	0.23	136	131	▼	Low	114	146	128	125	132
Sao Tome and Principe	0.23	137	140	▲	Low	143	112	160	96	134
Uganda	0.22	138	128	▼	Low	133	137	91	120	147
Rwanda	0.22	139	133	▼	Low	134	142	99	137	126
Burkina Faso	0.21	140	148	▲	Low	128	162	126	129	115
Malawi	0.20	141	137	▼	Low	153	141	117	102	155
Togo	0.19	142	129	▼	Low	144	130	146	134	120
Benin	0.19	143	139	▼	Low	152	128	126	124	142
Mali	0.19	145	141	▼	Low	138	165	118	100	123
Madagascar	0.18	146	130	▼	Low	124	152	140	142	139
Zambia	0.18	147	134	▼	Low	142	133	115	155	144
Zimbabwe	0.17	148	136	▼	Low	126	140	111	148	162
Djibouti	0.17	150	146	▼	Low	135	163	160	68	135
Mozambique	0.16	152	149	▼	Low	140	156	123	154	125
Mauritania	0.16	153	147	▼	Low	139	160	137	150	128
Ethiopia	0.15	155	150	▼	Low	162	161	80	106	137
Comoros	0.14	156	142	▼	Low	157	132	160	140	145
Guinea	0.14	157	153	▼	Low	154	158	149	130	156
Burundi	0.12	158	145	▼	Low	161	148	149	152	129
Gambia	0.09	160	157	▼	Low	145	151	149	161	159
Sierra Leone	0.09	161	151	▼	Low	158	149	131	143	163
Dem. Rep. of the Congo	0.09	162	158	▼	Low	155	145	131	163	161
Guinea-Bissau	0.04	165	NA	NA	Low	163	147	160	166	140
South Sudan	0.00	166	NA	NA	Low	166	166	160	139	166
Average score	0.23									

Source: UNCTAD.

C. TECHNICAL NOTE – READINESS FOR FRONTIER TECHNOLOGIES INDEX

The Frontier Technology Index is calculated following the methodology presented in the Technology and Innovation Report 2021. The indicators that compose the index are listed in Table VIII-6.

Table 7
Indicators included in the index

Category	Indicator name	Source	No. of countries
ICT deployment	Internet users (per cent of population)	ITU	210
ICT deployment	Mean download speed (Mbps)	M-Lab	194
Skills	Expected years of schooling	UNDP	191
Skills	High-skill employment (% of working population)	ILO	185
R&D activity	Number of scientific publications on frontier technologies	SCOPUS	234
R&D activity	Number of patents filed on frontier technologies	PatSeer	234
Industry activity	High-technology manufactures exports (% of total merchandise trade)	UNCTAD	216
Industry activity	Digitally deliverable services exports (% of total service trade)	UNCTAD	186
Access to finance	Domestic credit to private sector (% of GDP)	WB/IMF/OECD	213

Source: UNCTAD.

The underlying indicator data were then statistically manipulated to form the index. Firstly, the data were imputed using the cold deck imputation method, retroactively filling the missing values with the latest values available from the same country. After that, the Z-score standardization was conducted using the following formula:

$$X_{standardized} = \frac{x - \mu}{\sigma}$$

Where: x is a value to be standardized; μ is the mean of the population; and is the standard deviation of the population.

The standardized value of each indicator was then normalized to fall between the range of 0 to 1 using the formula below:

$$X_{normalized} = \frac{x - Min}{Max - Min}$$

Where: x is a Z-score standardized score to be normalized; is the largest score in the population; and is the smallest score in the population.

After these procedures, a principal component analysis (PCA) was conducted, mainly because of its advantage to remove correlated features among indicators and reduce overfitting. Based on the variance explained criteria method, PCA found that three principal components could retain more than 80 per cent of the variation. Thus, the final index was derived by assigning the weights generated by PCA with rotation to the three principal components, and then standardized and normalized to fall within the range of 0 to 1 (Table 8).

$$\text{Readiness Index} = ((0.4685/0.8290) * (\text{PC1}) + (0.2421/0.8290) * (\text{PC2}) + (0.1189/0.8290) * (\text{PC3}))_{\text{standarized \& normalized}}$$

Table 8
Breakdown of principal components

Variable	PC1	PC2	PC3	Unexplained
ICT (access)	0.4520	0.0037	-0.0760	.1588
ICT (speed) (log)	0.4588	-0.0586	0.0786	.1807
Skills (education)	0.4543	-0.0352	0.0120	.1896
Skills (labour)	0.4753	-0.1126	0.1673	.1602
R&D (publication) (log)	-0.0786	0.7197	-0.0065	.1117
R&D (patent) (log)	0.0428	0.5432	0.1539	.1248
Industry (high-tech) (log)	0.1824	0.3692	-0.0686	.2965
Industry (digital)	0.0187	0.0260	0.9189	.04899
Access to finance (log)	0.3336	0.1804	-0.2952	.2602

Source: UNCTAD.

Separately, PCA was also performed on each building block of the index to derive the score and country ranking within each building block. Here again, PCA used the minimum number of principal components that could retain more than 80 per cent of the variation. PCA was not conducted for the access to finance building block as it contained only one indicator.

$$ICT\ deployment = (\text{PC1})_{standarized\ \&\ normalized}$$

$$Skills = (\text{PC1})_{standarized\ \&\ normalized}$$

$$R\&D\ activity = (\text{PC1})_{standarized\ \&\ normalized}$$

$$\text{Industry activity} = ((0.6426) * (\text{PC1}) + (0.3574) * (\text{PC2}))_{\text{standarized \& normalized}}$$

[1] For more details, please refer to Annex of Technology and Innovation Report 2021 (UNCTAD, 2021a).

ANNEX C. EXAMPLES OF CATCH-UP TRAJECTORIES IN SELECTED GREEN INDUSTRIES

This section of the Annex presents insights from empirical evidence regarding green windows of opportunities in additional sectors, beyond those already presented in the chapter. Namely: Biogas and biomass, concentrated solar power (CSP), wind power, and electric vehicles (EVs).

1. BIOGAS AND BIOMASS

China

In 2020 China was the leading country in bioenergy production after a very rapid catch-up of the Chinese biomass industry, with an increase of the total installed capacity from almost zero in 2005 to around 5,300 MW in 2015, compared with, for instance, a capacity of 7,600 MW in Germany.[1] The take-off of the biomass industry is explained by the introduction in 2006 of the first renewable energy law in China, which included a favourable feed-in tariff for biomass power which was approximately double the coal tariff and therefore provided strong incentives for investments in biomass power plants. These institutional changes in the energy sector clearly define an endogenous window of opportunity. Representatives of the leading pioneer company in the industry influenced and directly contributed to drafting the initial policies and regulations instrumental to the sector's further development.

In the Chinese biomass industry, the build-up of production, and later of innovative capabilities, was started by one leading private company established in Beijing in 2004 by a Chinese-Swedish entrepreneur with experience as a senior adviser for Volvo. The company has managed to catch up with industry incumbents, initially through licensing foreign technologies and strategic acquisitions of foreign companies, enabling access to skilled labour. More recently, the company followed a strategy of rapid international expansion and diversification into new technologies such as waste-to-energy plants[2] and bioethanol production.[3] Moreover, thanks to knowledge spillover, which consisted of labour mobility towards local competitors and interactions with local suppliers, many domestic firms could take advantage of the window of opportunity, creating a dynamic sectoral system. Due to the dominance of the DUI (doing-using-interacting) mode of learning in this industry, labour turnover with high employee mobility from the leading company to the competitors played a role as a key channel for knowledge transfer. Moreover, the design institutes, which are State-Owned Enterprises (SOEs) responsible for the design of plants, also benefitted from on-site training, careful quality supervision, and continuous interaction with the leading pioneer company, contributing to diffusion of knowledge in the domestic sectoral system. Finally, demonstration effects are also important because local firms have been able to copy and imitate, thanks to the weak protection enforced on the patenting activity of the leading firm. Domestic competitors could copy components officially protected by patents due to weak enforcement of intellectual property laws.

Following a trajectory from domestic imitation to global leadership, the Chinese biomass industry has been able to progress from new-to-the-country technology to world-class technology and technological upgrading was achieved faster than global market success. Chinese firms also operate globally and have acquired global market leadership at the expense of western producers.

Thailand

In biogas, Thailand is one of the largest producers in the world, with the largest domestic market in the Global South after China and Türkiye.[4] Thailand offers another interesting example of a policy-led window of opportunity. Since the 1980s, anaerobic wastewater treatment has been developed to produce biogas in cassava starch factories. Still, in the beginning, most factories were not interested in investing in biogas production due to high investment costs. However, in the early-2000s, this changed radically when the Thai Government introduced a proactive strategy to attract private investors to the industry. In the following years, it introduced several measures, including financial subsidies for the construction and design of biogas production plants, tax incentives for firms involved in waste transformation, the Small Power Purchase Tariff program for increasing the proportion of electricity generation from biogas and the enforcement of an environmental law taxing companies producing pollution.[5]

The development of a strong sectoral system is also one of the key factors in the success of the biogas industry in Thailand. The existence of a network of private and public actors has helped to disseminate biogas technology. The domestic research sector has developed various more efficient and less expensive technologies than imported ones. Some technological solutions designed in Thailand have also been adopted abroad, as in the case of the UN project Cows to Kilowatts in Nigeria.[6] Thanks to extensive training programmes, mainly conducted through public institutions such as research centres and universities,[7] domestic capability has been built in the setup and maintenance of the production systems. This has created in the private sector the confidence that, in case of problems, a network of public and private consultants could provide adequate technical support.[8]

Thai biogas companies started from relatively low levels of capabilities, and from 1991 to 2017, they have all transitioned to higher levels.[9] At the same time, the Thai biogas industry has built up an innovative domestic capacity able to satisfy a relatively large domestic market. Moreover, they confirm that experience-based (DUI) learning in this industry is important because of the nature of biogas systems that require adaptation to the local contexts. The relevance of external knowledge is also stressed because firms relying only on firm-internal learning mechanisms exhibit low capability levels. In contrast, firms involved in external domestic and external foreign sources of knowledge have reached a higher level of innovative capacities. A further interesting finding is that for building capabilities, firms need to engage in different learning mechanisms – firm-internal, external-domestic, and external-foreign – involving various types of activities – productivity-driven, innovation-driven and human-resource-related.

Pakistan

Differently from the Chinese and Thai cases, in Pakistan, the existence since 2009 of a Biogas Program to promote an efficient replacement of traditional wood fuel and animal manure for domestic use of cooking and heating in rural areas has not generated an extensive adoption of biogas technology. Lack of coordinated government initiatives, regulations and construction standards for biogas plants, and inconsistent policies have hindered the programme's effectiveness.[10] Biogas technology has vast potential in the country to create jobs and generate income. However, there is still a lack of technical competencies. Very little has been done to persuade farmers, sugar mill owners, and private investors to adopt and invest in biogas technology in the country.

Mexico

Similarly, challenges are seen in the case of the palm oil industry in the Mexican state of Tabasco.[11] Weak regulations and public policies, lack of competent providers and absence of capability-building efforts to adapt imported technologies have not allowed the state to take advantage of the market opportunity deriving from the valorization of the variety of biomass resources from harvest and agro-industrial residues available in the country. Moreover, the increasing production and the lack of proper management of solid by-products generate a growing impact on the environment with residues left on the ground or openly burned. In contrast, they could be transformed into energy within a proper management system, establishing a sustainable palm oil industry.

Viet Nam

Similar to China and Thailand, Viet Nam has started to exploit its great potential to generate biomass energy from rice husks – a by-product of rice processing that is otherwise often wasted. One example of public-private collaboration is with Decathlon, whose many suppliers operate in Viet Nam, which has set an ambitious target to use 100 per cent biomass for industrial heat and power by 2030. In collaboration with GIZ, Viet Nam has started a project to support the development of a sustainable market in the biomass industry and build capability among consultants, project developers, and investors on how to draw up feasibility studies. The project also promotes technology partnerships between national and international companies and research and development institutions to develop locally adapted solutions.[12]

Bangladesh

The case of biogas production in Bangladesh is also interesting because it shows that despite the existence of favourable preconditions for the development of the industry, the lack of policies and their weak implementation, as well as the lack of infrastructure hinder large-scale production and have diminished the capacity of the country to exploit the potential windows opportunity.[13] In this country, several NGOs have invested in biogas projects decades ago. The country has also established an articulated system of government and non-government organizations involved in R&D projects related to biomass energy. Nevertheless, a proper subsidy policy to encourage biogas plant installation has not been implemented, and little has been done in terms of training programs among farmers to increase awareness and diffuse a correct waste management policy. Besides, public investments in research with the involvement of national universities have been minimal.

African countries

Several national programs have been introduced in African countries, also thanks to international initiatives such as the “Biogas Partnership Programme” and “Biogas for a Better Life,”[14] which contribute to the transfer of some basic knowledge, creating an initial base of specialized competences in the countries involved. However, national programmes have not been followed by coherent measures to build an effective sectoral system, developing domestic production and technological capacity, and overall biogas production is still limited.[15]

2. CONCENTRATED SOLAR POWER

In CSP, in 2020, the two leading countries in terms of installed capacity were Spain and the United States, followed by Morocco, China, and South Africa, which have been responsible for the bulk of capacity additions in the past five years.[16]

Morocco

Morocco’s decision to invest in CSP was driven by the need to satisfy a demand for electricity picking in the early evening. While solar PV has lower costs, it can only generate electricity when the sun is shining. CSP, on the other hand, allows thermal storage. The investment was made possible by accessing concessional financing from the World Bank, the African Development Bank and other European financing institutions. The involvement of international financial institutions was driven by the opportunity to support the development of a new technology that could play a critical role in the global shifting away from fossil fuels. The Clean Technology[17] has also invested in the Moroccan CSP project, contributing to building some initial domestic capacity. After successive projects and a dropping in the CSP price, the industry has also started attracting private investors. Moreover, CSP plants are often developed in remote areas, bringing development and jobs to poorer communities.[18]

The sectoral system is still very immature in the country. However, some incentives have been provided for higher value-added domestic manufacturing of parts and components, increasing the sourcing of local components.[19] In general, notwithstanding the political commitment toward renewable energies is quite strong in Morocco, it has been observed a lack of a coordinated approach between the multitudes of potential donors and a limited capacity in promoting technology and knowledge transfer to build up a solid domestic capability in the industry.[20]

China

The development of the Chinese CSP industry is still a recent and ongoing phenomenon, but it has followed a rather different path compared to other renewable industries in the country, which initially have been largely dependent on foreign imported technologies and, as in the case of solar PV, also driven by foreign demand. In the case of CSP, however, China has exploited a technological window deriving from decreasing investments in demonstration projects in incumbent countries, creating a space in the global industry. In the late 2000s and early 2010s, the CSP global market was almost entirely dominated by Spain thanks to generous support policies, which were abandoned in 2012. In the United States, the support measures were largely stop-and-go which caused some bankruptcies in the industry. In both countries, the interest and investments in the CSP industry were largely resized. In 2015, in China, the National Energy Administration asked for bids to develop CSP demonstration programmes, and in 2016, 20 projects were selected and funded by the government, domestic utilities and project developers and domestic banks. At the same time, there was a substantial investment in R&D activity in Chinese universities in collaboration with domestic firms, with the only limited acquisition of foreign technology licenses.[21]

The knowledge is mainly domestic in the Chinese CSP industry, rooted in domestic research institutes and corporate R&D. The whole industry innovation system is largely dominated by domestic actors, including component providers, system developers, researchers, and financiers. The market is also mainly domestic, consisting of a public-funded small pilot and larger demonstration projects. However, the recently formed Chinese CSP industry has also contributed to diffusing the technology outside China. Domestic research institutes and firms have attracted research contracts from foreign entities, including testing and developing next-generation receiver technologies in demonstration-scale projects. Under the flag of the Silk Road fund, Chinese banks have provided substantial amounts of investment to the development of foreign projects. More recently, Chinese firms and research institutes also contribute to defining global project design and equipment standards, helping set quality benchmarks for firms from other countries.[22]

After upgrading to world-class technology, concentrated solar Power in China experienced little further market development. China rapidly caught up in capabilities development and has reached the global knowledge frontier. However, its leadership applies mainly to domestic demonstration projects, with export activity confined to a limited number of engineering, procurement and construction projects in Europe and the Middle East.[23]

3. WIND POWER

Wind energy has been increasingly deployed in developing countries. As an energy source, it is highly dependent on natural conditions, being most conducive at a distance from the equator or in mountainous areas. It can be deployed onshore or offshore, with the latter being more demanding and costly and only recently taken up in countries such as Brazil, India and China. Most lead firms are based in Europe or the US, but a few emerging market multinationals emerged on the global scene from the turn of the century.[24] Most deployed wind turbine technology is grid-connected ‘large’ wind (large turbines in large farms). Still, a concurrent niche is focused on ‘small’ wind,[25] which is often particularly relevant as a complement to solar PV in rural mini-grids.[26]

The overall window of opportunity stems from the increasing policy drive to promote renewables, the changing preference from public and institutional investors and technological developments which sees onshore wind below parity with electricity produced from fossil fuel sources.[27] This window has emerged in upper-middle-income and lower-middle-income countries and, to some extent, also in low-income countries. This section presents empirical evidence from green windows of opportunity and their take up in China, South Africa, Kenya, and Ethiopia.

None of these countries, apart from China, have managed to exploit foreign markets. And there are differences in the degree to which economic activities of domestic wind deployment are localised and the importance of foreign firms mentioned above. There is some, but limited, technological upgrading in upper-middle-income countries. In general, the upgrading process is confined to services in the deployment chain instead of production activities in the manufacturing chain. Overall, there are three broad types of sectoral system responses: active, passive and in-between. China represents the most active system response. South Africa is an in-between case, while Kenya is passive, and Ethiopia is a case of active response despite relatively weak preconditions. These cases present weak preconditions such as the inadequate shape of the sectoral system and the industrial base capacity. Low capacity in the wind sector means that European and Chinese lead firms dominate the GWO, especially in Kenya and South Africa. In Ethiopia, while still in the nascent stages of developing a sectoral system around wind power, certain basic preconditions have been developed, which will be important in subsequent deployment processes.

China

In China, external pressure arising from a commitment to the Kyoto Protocol and, particularly, the Paris Agreement, and domestic pressure to reduce air pollution in megacities such as Beijing is at the root of sector-level opportunities. This has translated into the sector and sometimes regional specific opportunities, often promoted with mission-driven programmes such as the Ride the Wind programme, which was initiated for embryonic sector formation.[28] This programme by China's State Planning Commission, launched in January 1997, specified the first wind target of 1GW to be developed by 2001. The Planning Commission selected a German company, Nordex, as the first foreign partner to develop these projects. The first 400 MW was financed through Chinese and foreign government loans.[29] While the financial underpinnings were typically global and supported by international organizations, in the beginning, the GWO has been internalized, and supported by public finance. However, private sources of investment have been increasingly crowded in with loan guarantees to international investors provided by China Development Bank.[30]

Dai et al.[31] show how recent global wind energy industry transformations have considerable implications for Chinese firms seeking to catch up. The technological frontier has advanced first from onshore to offshore wind turbines and later towards digital systems both at the level of individual turbines and in terms of management of wind farms.[32] These technological shifts open new green windows of opportunity for firms in the industry. The authors find that Chinese turbine firms show differentiated capabilities in responding to technological transformation at the global level, which explains variations in catch-up trajectories. Overall, however, they are not at par with global leaders in digital and hybrid systems. Hain et al.[33] propose a 'market trap' where latecomers remain in a follower position and catch up is aborted, which seems to correspond with the Chinese wind industry. It remains to be seen whether Chinese firms can leverage complementary capabilities in adjacent sectors to integrate advanced software capabilities and make inroads in the 'post-turbine technology regime'.[34]

South Africa

In South Africa, wind deployment targets and a feed-in tariff were introduced to meet wind energy deployment goals with the Integrated Resource Plan (IRP) in 2010. In addition, as mentioned in the section on solar PV, support for a competitive renewable energy auction was introduced in 2011, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). Key in this framework is integrating multiple criteria for procurement, such as support of local firms, including small firms and firms owned by disadvantaged groups. So, while seeking to stimulate at the same time domestic and foreign investments, REIPPPP requires that engineering, procurement and construction contractors (EPCs) have 40 per cent local ownership.[35] South Africa is experimenting with domestic window creation, but as discussed further below, the country is struggling with defining effective supply-side responses.[36]

Morris et al.[37] investigate the wind sectoral system under REIPPPP and examine the effects on the wind energy value chain concerning the localisation of goods and services. They highlight the interplay between energy and industrial policy. They argue that policy failure driven by coal-based vested interests, disrupted system integration and undermined the renewable energy programme which was the cornerstone of the wind GWO. The policy drive was not sufficiently strong and took on a stop-and-go nature. Problems with continuity and predictability of the auction bidding process within energy policy have knock-on effects down the wind energy chain, adversely impacting industrial policy attempts to localise domestic and foreign enterprises. The uncertainty of the policy (stop and go) meant that foreign enterprises could not implement local content requirements as local investment became risky. Local suppliers could not take advantage of new opportunities provided by the policy because banks would not fund investment projects. According to the authors, the South African government failed to prioritise, develop, and embed renewable energy as a sustainable economy strategy within its industrial policy framework.

Kenya

In other countries in sub-Saharan Africa, GWOs are more heavily influenced by international actors. This is shown by Gregersen & Gregersen[38] who compare large scale projects in Kenya and Ethiopia. Systematic frameworks for the evaluation of project proposals are often absent. This means that there are no mechanisms to ensure that projects are not developed on an ad-hoc basis, promoted by specific finance and technology supply consortia. Ad-hoc project approval, while constituting an opportunity for deployment, weakens the bargaining power of governments and typically comes along with informal 'foreign content requirements' tied to external sources of finance. Foreign lead firms and investment consortia, including Chinese groups, tend to take on coordinating roles in the absence of action schemes like the one implemented in South Africa.[39] Demand windows dominate. There is a significant difference in the degree to which windows of opportunity are domestically created (as in China) or are externally provided, e.g., in Kenya.

Given the large multinational involvement in the wind sector in East Africa, Gregersen & Gregersen[40] explore 'learning spaces' in foreign-dominated projects in large scale wind, one European and one Chinese, project. Focusing on how interactions between different stakeholders in wind power megaprojects can lead to the accumulation of technological and managerial capabilities, they show that formalised and tacit knowledge interaction can occur, even in the megaproject setting, but it has limits. In Kenya, the multiplicity of actors involved in the complex infrastructure Lake Turkana Wind Power (LTWP) project involves multiple loops of interactions that could foster local-learning opportunities. Still, such learning largely failed to materialise because of weak pre-existing capabilities among local actors and because no industrial policy was tied to the expansion of wind.[41]

Ethiopia

By contrast, in the Ethiopian case, the government and the Ministry of Water, Irrigation, and Electricity (MoWIE) tied wind projects to industrial development aims by introducing local university consultants to the projects and creating a local pool of experts. This, according to Gregersen & Gregersen,[42] explain that while there was some local learning in both the Kenyan and the Ethiopian cases in the field of operations and maintenance (O&M) as well as some learning about and how to add more renewable energy to the national grid, the Ethiopian Adama case involved different types of learning that did not happen in Kenyan LTWP. Specifically, this was learning about how to design projects. The Government of Ethiopia requested that national universities submit proposals and act as owners' consultants on the project. MoWIE liaised with several universities that could help to meet wider objectives, and, in the process, they gained valuable experience in both government agencies and universities. This is an example of how the government has gone beyond the production system thinking and has involved the knowledge and innovation system, building elements to ensure more local learning in and around the domestic projects. While still with several shortcomings, the Ethiopian government has actively designed the wind projects to guarantee maximum local learning by ensuring that professional users are more involved in the project execution.[43]

4. ELECTRIC VEHICLES

EVs have started to diffuse in large volumes worldwide, but only to a limited extent in developing countries when it comes to passenger cars. Countries like India, Indonesia and Brazil possess the infrastructure to support two-wheeler electric vehicles. Still, they do not have policies for a full-scale transition to electric-run transportation comparable to those, for instance, in Europe.[44] Electric mobility offers ideal opportunities to create synergies with other technologies discussed in this report and for the broader phasing-in of renewables to the transport sector. Electric vehicles create new demand for electricity that can be supplied by wind, solar, biomass and other renewable sources. In addition to benefits such as reducing carbon emissions and air pollution, electric mobility could also play an essential role in providing decentralised storage for variable renewable electricity sources. This section explores the empirical evidence of green windows related to EVs sector in China, India, Brazil, and South Africa.

The energy demand-side of the techno-economic paradigm shift is still in the stage of the open-ended search for effective green solutions in many areas. There are relatively clearer paths forward in the transportation sector: with the increasing technological maturity and price reduction of battery-electric vehicles, electromobility is now a key viable option – along with some alternative but still less certain solutions such as biofuels and hydrogen.

It is not yet clear how this transition from combustion engines to electric vehicles will affect the position of emerging markets in the global automotive sector. It could increase entry barriers and make the competition more demanding or decrease them and provide new competitive advantages. Much will depend on the speed of the transition from conventional cars to EVs, the global geography and the knock-on effects on global value chains. In principle, the opportunity is significant because EVs are simpler, with fewer parts, compared to traditional cars. Traditionally, the automotive sector has been dominated by relatively small numbers of global lead firms that have developed region-specific car models and supply chains, with differentiated industrial structures as a result.[45] Consequently, the automotive industries in Brazil, China, India and South Africa differ widely. Each has widely different prerequisites for gaining or losing from the green transformation of the automotive sector. Apart from imports of complete electrical vehicles, there is still relatively little globalisation of production, which is spurred by protectionist measures such as import duties.

China

Technological windows dominate following the techno-economic paradigm shift from combustion engines to electric vehicles in the automotive industry. But Chinese intervention in the EV sector can be seen as creating a green window for domestic take-off by stimulating the demand side and speeding up deployment. Konda shows the role of two distinct policy phases during sector formation. The goals for deployment set in the first period had not been achieved by 2012, and so the Government introduced a new plan for the next eight years which was more comprehensive and paid more attention to developing capabilities, not just to deployment.[46]

In 2009, China began mass production in the EV sector without any novel technical knowledge.[47] Despite the subsidies that were made available, customers did not demand EVs in the following years, mostly owing to their shortcomings compared with internal combustion engine vehicles. In 2010, the battery technology was not satisfactory as the manufacturing cost per kWh was between 3,400 and 5,000 yuan, and this presented a large proportion of the total EV costs. Battery life was between three and five years or circa 160,000 kilometres, making EVs much less of an economic proposition than conventional vehicles.[48] By February 2014, battery production cost had decreased to around 3,150 yuan per kWh, which was still much higher than the 2,000 planned for 2015. The core technology was thus immature until recently. Hence the government had to address all aspects of the ecosystem. The policies evolved from traditional green industrial towards broader policies that enable catching up by combining climate and economic goals. The first creates a demand for a technological solution that is still economically less efficient than dirtier solutions. The second enables knowledge transfer and creation, and the third boosts production to fulfil the demand. The case shows that strategies and initiatives that respond to initial green window opportunities based on building basic production capacity were insufficient for upgrading and deepening technological capabilities.[49]

In general, advanced OECD economies dominate the EV sector. Emerging economies are mainly making inroads in non-passenger cars, such as two-wheelers, three-wheelers and buses. China had surpassed the United States in EV stock, with 32 per cent of the global share and 44 per cent of worldwide annual sales in 2016.[50] The country is seeing some exports, but still at a low level. Some technological upgrading has occurred, but there is still uncertainty regarding global competitiveness and markets for low-cost EVs. For domestic deployment especially in China, ambitious strategies have spurred a high degree of domestic market sales.

India

In India, the government started the path toward electro-mobility with the 'National Electric Mobility Mission Plan 2020' (NEMMP2020) in 2013. The plan provided a roadmap to achieve sales of 6-7 million EVs in 2020, among which 400,000 units of e-passenger cars. In 2015, the government supported the plan with the "Faster Adoption and Manufacturing of Electric Vehicles" (FAME) scheme, which transitioned in its second phase (FAME-II) two years later. FAME-II ends in 2022 and includes stimulation for the purchase and the deployment of charging infrastructure.

The FAME policy encourages manufacturers to use batteries with advanced chemistry—lithium—instead of environmentally less-friendly lead-acid variants. The EV policy in India is spread among three levels of authority—national, state, city—and most laws and regulations are placed at the state or city level. Aside from the FAME scheme, India supports the automobile industry with the "Make in India" program, which stimulates FDI through the offer of several incentives to foreign investor like tax exemption and concession and subsidy, provides tax incentives for R&D, and with the "Phased Manufacturing program" (PMP). The PMP has reduced a "basic custom duty" (BCD) in 2017 (between 0 - 25 per cent) for electric vehicles, assemblies, and EV parts to support electro-mobility development. In 2020, BCD started gradually increasing (10 – 50 per cent) to stimulate domestic manufacturing.[51] India's auto component sector is growing faster than the sector of complete vehicles and exports a quarter of the production. In the last three years, it attracted high investments from domestic and foreign entities, e.g., Japan Bank for International Cooperation ($1 billion), Toyota Kirloskar Motors ($272.81 million) for EV components. The electrification of the automobile sector allows establishing a new battery sector and interconnects with the existing IT sector. According to the Indian Energy Storage Alliance, the battery market potential was $580 million in 2019. It is forecasted to grow to $14.9 billion by 2027. Currently, India is dependent on importing lithium, but the newly discovered lithium resources in 2020 could enable faster development of the sector.[52] In electric two and three-wheelers, the battery cost presents up to half of the vehicle's price. Thus, the government allowed manufacturers to sell vehicles without batteries and encouraged the development of different battery swapping services.[53]

In this country, responses to the existence of green windows in the EVs sector are mainly confined to national flagship automotive firms with a weak innovation system formation.

South Africa

Green windows depend on natural resources for battery production. In South Africa, increasing global use of EVs provides the country with special opportunities to explore a competitive advantage in the lithium-ion batteries value chain.[54]

In 2013, the government in South Africa introduced the 'Automotive Production and Development Programme',[55] which did not specifically address the EV sector but the whole automobile industry. The policy's four pillars—import duty, production incentives, assembly allowance, investment scheme—managed to keep the industry stable but had not improved its global position. In the middle of the previous decade, a policy targeting increasing pollution by road transportation (GTS 2018 – 50) was implemented. It stimulates domestic production, R&D, and consumption of alternatives to vehicles on internal combustion. At the end of the APDP period, the government updated it with the South African Automotive Masterplan (SAAM 2021-2035), with the primary goal to address the decreasing local content in the automobile industry (from 46.6 per cent in 2012 to 38.7 per cent in 2016). Despite policy emphasis on the importance of EVs in the future, it does not make special provisions.[56] Overall, the EV development has explicit support in the policies related to cleaner transportation, mainly with penalizing dirtier solutions—Environmental CO_2 levy— but not in the manufacturing.[57] South Africa has established battery production and recycling, mainly lead-acid type.[58] The country is also rich in some required raw materials—manganese (78 per cent of the world's resources), nickel, calcium fluoride, titanium, aluminium, copper, and iron. The government plans that an existing industry will also cover electric vehicles' batteries and supports it under the 'The Technology and Human Resources for Industry Programme', which involves the University of the Western Cape, the uYilo eMobility Programme, the Council for Scientific and Industrial Research, and Zellow Technology.[59] The first lithium-ion mega-factory—The MegaMillion Energy Company—plans to start a manufacturing plant in 2022.[60] South Africa is an important automotive hub, especially for spare parts. The stable position in GVC could be upgraded by the development of the electric vehicle sector, however, slower adoption of new technologies poses a threat to losing the GVC position.

For South Africa, the insertion into automotive GVCs means that the techno-economic paradigm shift could make significant parts of the domestic supply chain obsolete because many locally produced components are no longer needed.

Brazil

Brazil introduced the first policy for cleaner transportation in 1986 (PROCONVE) to address rising pollution in the urban and intense-production areas. In early 2000, the Government introduced several incentives for R&D, and a decade later for building the charging infrastructure. Looking at the policies supporting domestic production, the Government introduced four incentives in the last decade. Starting in 2011 with the national development bank (BNDES) Fundo project and two years later with "Inovar Auto" covering the period from 2013 to 2017, which was later replaced with the current "Rota 2030 program". Brazil is rich in natural resources needed for EV batteries production, having the third biggest reserves of graphite and nickel, and the seventh of lithium.[61] Despite having 8 per cent of global lithium reserves, Brazil only accounts for 0.7 per cent of world production, thus lithium has to be imported.[62] The country also has existing low-voltage battery production of industrial and stationary batteries, based on local knowledge. However, there is a lack of connection between scientific research and production.[63] Moreover, Brazil has some existing lead-acid batteries manufacturers (e.g., Moura Group) and it is involved in the R&D and development of lithium batteries. Finally, the Brazilian company Pxis (a collaboration between CODEMGE and Oxis Energy) is planning to establish the first mass-production plan of lithium-sulphur batteries, which in the laboratory stage have overperformed the current lithium batteries.[64]

In the country, the success of the locally produced flex-fuel engine and bioethanol industry makes the innovation system path-dependent, and there are vested interests in keeping the focus on bioethanol. Insufficient response means that other regional hubs close to lead markets may be better positioned to take advantage of green windows in this industry.

1 Hansen and Hansen, 2020

2 A waste-to-energy plant is a waste management facility that combusts waste to produce electricity.

3 Hansen and Hansen, 2020

4 According to IRENA, in 2020 in the biogas sub technology the leading country in terms of installed capacity is Germany with 7500 MW and Thailand ranks 7th with 550 MW (IRENA, 2022d).

5 Suwanasri et al., 2015

6 The Biogas Technology Research Centre of King Mongkut's University of Technology Thon- buri (KMUTT) is one of the partners of this UN project in Nigeria (UNFCCC, 2021).

7 The two main institutions involved in training and technical advice and consultancy to the domestic companies are BIOTEC, the national center for genetic engineering and biotechnology established by the Minister of Science Technology and Energy, and KMUTT, a national technological university (see Footnote 13)

8 Suwanasri et al., 2015

9 Reinauer and Hansen, 2021

10 Yaqoob et al., 2021

11 E. J. Ordoñez-Frías et al., 2020

12 International Climate Initiative, 2022

13 Chowdhury et al., 2020

14 The "Biogas Partnership Program" ended in 2019 and supported national biogas programs in Ethiopia, Kenya, the United Republic of Tanzania, Uganda, and Burkina Faso (Africa Biogas Partnership Program - Supporting biogas programs in Africa, 2019). The Biogas for a Better Life initiative was launched in 2007 in Nairobi with the aim to install 2 million biogas plants by 2020 (Nes and Nhete, 2007).

15 Scarlat et al., 2018

16 Data are from https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Country-Rankings

17 https://www.cif.org/

18 World Bank, 2016

19 World Bank, 2016

20 Choukri et al., 2017

21 Gosens et al., 2020

22 Gosens et al., 2020

23 Gosens et al., 2020

24 Lema et al., 2013; Lewis, 2007.

25 Wandera et al., 2021

26 Johannsen et al., 2020

27 IRENA, 2021d

28 Dai et al., 2020

29 IRENA, 2013

30 Upstream, 2021

31 Dai et al., 2020

32 Digital and hybrid technologies are integrated in smart energy systems. Technology comprises digital solutions (SaaS, IoT, and AI) for wind turbines and various up and downstream technologies as well as energy storage (Dai et al., 2020)

33 Hain et al., 2020

34 Dai et al., 2020

35 Matsuo and Schmidt, 2019

36 Morris et al., 2022

37 Morris et al., 2022

38 Gregersen and Gregersen, 2021

39 Lema et al., 2021

40 Gregersen and Gregersen, 2021

41 Gregersen, 2020

42 Gregersen and Gregersen, 2021

43 Lema, Bhamidipati, et al., 2021

44 TRT Magazine, 2022

45 Sturgeon et al., 2008

46 Konda, 2022

47 Hain et al., 2020

48 World Bank, 2011

49 Konda, 2022

50 IEA, 2019

51 DPIIT, 2020

52 Sasi, 2021

53 The Economic Times, 2020

54 Montmasson- Clair et al., 2021

55 Automotive Production and Development Programme, 2021

56 Barnes et al., 2018

57 Smart Energy International, 2020

58 Automotive or car battery is a rechargeable battery used to start a motor vehicle and not batteries for EVs

59 Raw and Radmore, 2020

[60] TMEC, 2020

[61] Statista, 2022b

[62] Elétricos no horizonte, 2019

[63] Consoni et al., 2019

[64] Elétricos no horizonte, 2019

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