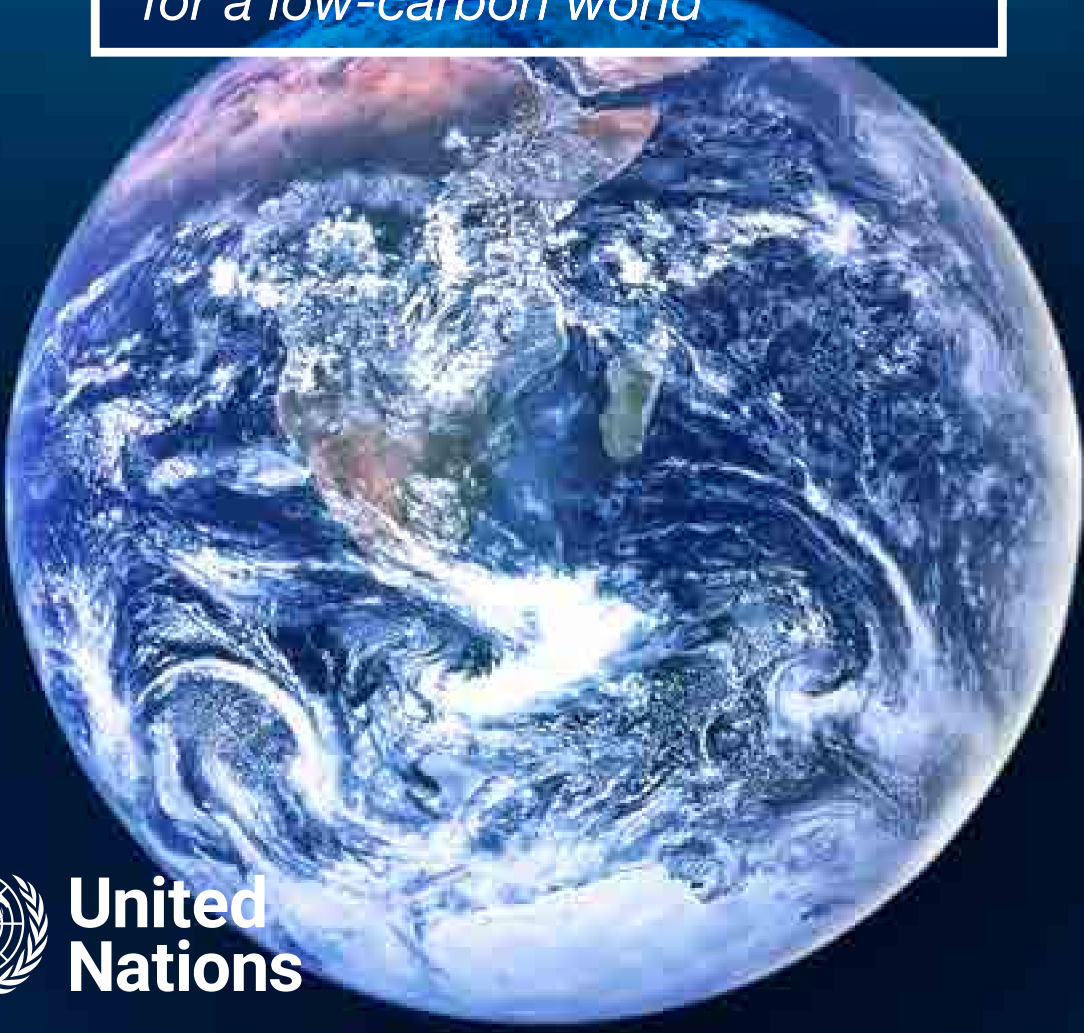
UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT

TECHNOLOGY AND INNOVATION REPORT 2023

Opening green windows

Technological opportunities for a low-carbon world



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NOTE

Within the UNCTAD Division on Technology and Logistics, the Technology and Innovation Policy Research Section carries out policy-oriented analytical work on the impact of innovation and new and emerging technologies on sustainable development, with a particular focus on the opportunities and challenges for developing countries. It is responsible for the *Technology and Innovation Report*, which seeks to address issues in science, technology and innovation that are topical and important for developing countries, and to do so in a comprehensive way with an emphasis on policy-relevant analysis and conclusions. The Technology and Innovation Policy Research Section supports the integration of STI in national development strategies and in building up STI policy-making capacity in developing countries; a major instrument in this area is the programme of Science, Technology and Innovation Policy Reviews.

In this report, the terms country/economy refer, as appropriate, to territories or areas. The designations of country groups are intended solely for statistical or analytical convenience and do not necessarily express a judgement about the stage of development reached by a particular country or area in the development process. Unless otherwise indicated, the major country groupings used in this report follow the classification of the United Nations Statistical Office. These are:

Developed countries: the member countries of the Organisation for Economic Co-operation and Development (OECD) (other than Chile, Mexico, the Republic of Korea and Turkey), plus the European Union member countries that are not OECD members (Bulgaria, Croatia, Cyprus, Lithuania, Malta and Romania), plus Andorra, Liechtenstein, Monaco and San Marino. *Countries with economies in transition* refers to those of South-East Europe and the Commonwealth of Independent States. *Developing economies*, in general, are all the economies that are not specified above. For statistical purposes, the data for China do not include those for the Hong Kong Special Administrative Region of China (Hong Kong, China), Macao Special Administrative Region of China (Macao, China) or Taiwan Province of China. An Excel file with the main country groupings used can be downloaded from UNCTADstat at: http://unctadstat.unctad.org/EN/Classifications.html.

References to sub-Saharan Africa include South Africa unless otherwise indicated.

References in the text to the United States are to the United States of America and those to the United Kingdom are to the United Kingdom of Great Britain and Northern Ireland.

The term “dollar” ($) refers to United States dollar, unless otherwise stated.

The term “billion” signifies 1,000 million.

Annual rates of growth and change refer to compound rates.

Use of a dash (–) between dates representing years, such as 1988–1990, signifies the full period involved, including the initial and final years.

An oblique stroke (/) between two years, such as 2000/01, signifies a fiscal or crop year.

A dot (.) in a table indicates that the item is not applicable.

Two dots (..) in a table indicate that the data are not available, or are not separately reported.

A dash (–) or a zero (0) in a table indicates that the amount is nil or negligible.

Decimals and percentages do not necessarily add up to totals because of rounding.

FOREWORD

The world finds itself trapped in the grip of cascading crises — from global poverty and inequality, to hunger and conflicts — that require collective action to address.

In particular, climate change is a global challenge that calls for global solutions. The battle to keep the 1.5-degree limit alive will be won or lost this decade. We need to act together to close the emissions gap, and transform our energy systems to secure the liveable future required by people and planet alike.

The theme of this year's report – Opening green windows: Technological opportunities for a low-carbon world – reminds us that innovation and frontier technologies can drive the transformative solutions we need.

We need a revolution in renewable energy innovation and technology. Supported by adequate regulations, incentives and investment, renewables provide a clear path to real energy security, affordable power prices and sustainable employment opportunities.

Above all, we must support developing countries as they make the transition to renewable energy.

A renewables revolution means sharing knowledge and technologies with all countries, equally. Currently, the majority of global renewable energy capacity, technology and expertise is housed within a handful of countries. As the world transitions to a net-zero, resilient and just future, we cannot allow developing countries to fall behind.

A renewables revolution also means ensuring that policies and processes are in place to reduce market risk and attract investments to the renewable energy transition across developing countries. Together with international financial institutions and the private sector, developed countries must level the playing field to fast-track renewable energy projects in developing countries.

The fight against climate change is everybody's fight.

By working in solidarity and creating the conditions for the renewables revolution, we can harness the full potential of a just transition for all countries, and pass on a greener, prosperous and more sustainable world to our children and grandchildren.

António Guterres
Secretary-General
United Nations

PREFACE

Developing countries are facing a series of interconnected and cascading crises, including war in Ukraine, the COVID-19 pandemic, the impacts of climate change, and disruptions in geopolitics. To address these challenges, the Technology and Innovation Report (TIR) 2023 focuses on the opportunities presented by the renewable energy revolution in the Global South. These opportunities not only offer the chance to build resilience and mitigate climate disaster, but also to spur economic and technological development, allowing developing countries to "leap" out of the cascade of crisis and move forward.

The report provides a comprehensive picture of green and frontier technologies today, including analyses of their market size, potential for employment creation, and most promising sectors. We cover 17 frontier technologies such as artificial intelligence, Internet of Things, green hydrogen, and electric vehicles. The report estimates that these technologies already represented a $1.5 trillion market in 2020. Thanks to their rapid growth, by 2030 their market value could reach over $9.5 trillion –about three times the current size of the Indian economy.

The report presents a critical assessment of the potential catch-up trajectories in renewable energy technologies in the Global South, sharing lessons from various developing countries in Latin America, Asia, and Africa. The report also presents very original methodology that identifies which are the most complex sectors (requiring more technological capacities) with the lowest carbon footprints. This methodology can help various stakeholders in developing countries in designing a roadmap that selects the greenest paths for economic diversification, while taking advantage of Industry 4.0 to get into specific global value chain (GVC) niches. This TIR's novel research directly addresses one of the four major transformation of the Bridgetown Covenant - Transforming economies through diversification.

This report leaves us with three key messages:

First, developing countries must strategically position themselves to catch the green technological revolution *early*. Access to technologies and knowhow is not enough – timing is especially crucial. Without it, the green revolution will not close but widen global inequalities.

Second, international business-as-usual conditions mean that developing countries cannot on their own take advantage of these green windows of opportunity. Immediate support from the international community is needed to gather enough resources and build the required knowhow. It is also critical that we improve the consistency of the trading system with the Paris Agreement, so that green technology can be effectively transferred to developing nations.

Third, lastly: to address the current technological challenge we need two key things – agency and urgency. The fight against climate change and inequalities is everybody's fight – if we all share the same problem, then we must also share the same tools to solve it. But time is running out. And if this window of opportunity closes, it may well be the last one.

Rebeca Grynspan
Secretary-General
United Nations Conference on Trade and Development

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CONTENTS

BOXES

FIGURES

TABLES

OVERVIEW

1. GREEN WINDOWS OF OPPORTUNITY

In 2023, the world faces severe social and economic challenges. While trying to recover from the COVID-19 pandemic, many countries are now coping with the repercussions of the war in Ukraine, which has not only caused immense suffering but has also heightened geopolitical tensions and created threats to global trade and energy and food security.

The most difficult choices are in developing countries where this conjuncture of crises threatens hard-won development gains. To eliminate poverty, they need diversified and more productive economies to create more and better jobs and boost household incomes. But faster economic growth will demand far more energy which, if sourced from fossil fuels, would send millions of tons of carbon billowing into the atmosphere.

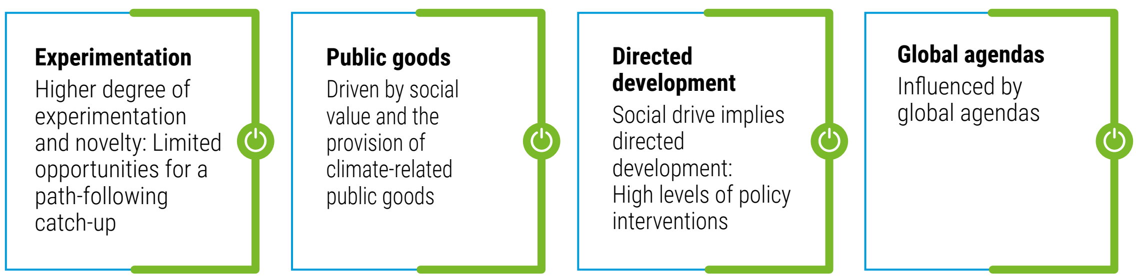
Developing countries need not, however, follow the historical pathways of carbon-fuelled growth – if the global community is committed to equitable social, economic and technological transformations guided by the Sustainable Development Goals.

The 2023 edition of the Technology and Innovation Report focuses specifically on what can be achieved by technological innovation, by opening 'green windows of opportunity'. It does not suggest that these problems will be solved by technology alone, nor that new technology is necessarily beneficial – since the gains for one group can be detrimental for others. But it does argue that innovation and advances in science and technology, if guided by the Sustainable Development Goals, can be used to drive the world along more sustainable and equitable pathways, particularly in the generation and use of energy.

The report is built around the concept of green innovation – creating or introducing new or improved goods and services that leave lighter carbon footprints and open up green windows of opportunity. Developing countries now have opportunities to catch up, reduce poverty, and at the same time help tackle climate change and set the world on a more sustainable course.

For countries aiming to catch up with the more technologically advanced countries, switching green requires more than simple imitation; it demands creative adaptation and innovation. The pathways are likely to differ substantially from those taken by advanced economies. The figure below sets out the four main components of green innovation. The starting point is experimenting with new ideas and technologies and adapting these to local circumstances, values and priorities (Figure 1). To take advantage of these ideas, countries will need the appropriate infrastructure and in the form of public goods – through direct government intervention, supporting the establishment of new green sectors, for example, or introducing regulations such as on air or water pollution. Green innovation is also influenced by global agreements and agendas, rules, and mechanisms, especially those related to climate change, such as the Paris Agreement.

Figure 1
The sequence for opening green windows



Source: UNCTAD.

2. MOVING FAST WITH FRONTIER TECHNOLOGIES

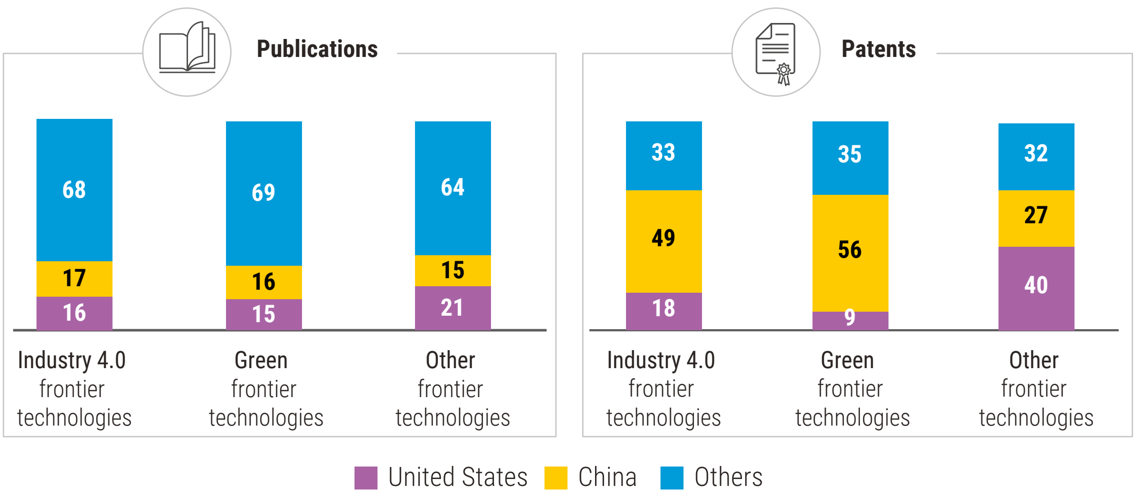
At the leading edge of green innovation are new and rapidly developing technologies that take advantage of digitalization and connectivity. The Report examines 17 of these ‘frontier technologies’ – from artificial intelligence (AI) to green hydrogen to biofuels – highlighting their potential economic benefits and assessing country capabilities to use, adopt, and adapt these innovations.

These technologies have experienced tremendous growth in the last two decades: in 2020 the total market value was $1.5 trillion and by 2030 could reach $9.5 trillion. Around half of the latter is for the Internet of things (IoT) which embraces a vast range of devices across multiple sectors. These technologies are supplied primarily by a few countries, notably the United States, China and countries in Western Europe.

As with previous waves of automation, frontier technologies are both destroying old jobs and creating new ones. Current job expectations may be more pessimistic because of the increasing capacity of AI to mimic human intelligence. Nevertheless, most alarmist scenarios often fail to take into account that not all tasks in a job are automated, and, most importantly, that technology also creates new products, tasks, professions, and economic activities throughout the economy. The net impact on jobs will depend on the final balance between creation and extinction.

For these new technologies, the knowledge landscape is dominated by the United States and China, with a combined 30 per cent share of global publications and almost 70 per cent of patents (Figure 2). Other countries compete in specific categories, notably France, Germany, India, Japan, the Republic of Korea, and the United Kingdom.

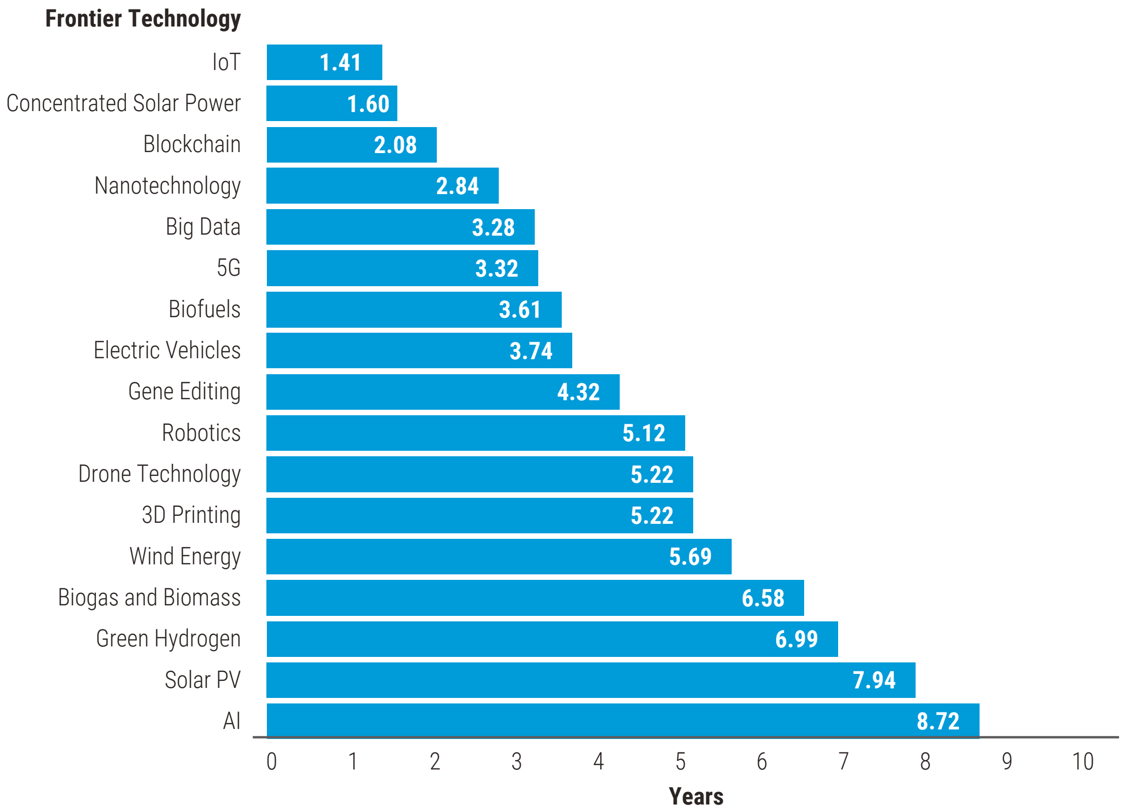
Figure 2
Country share of publications and patents, by frontier technology (percentage)



Source: UNCTAD calculations based on data from Scopus and PatSeer.

All these technologies are at the frontiers of change, but some are more mature than others, as is evident by the record of patents and publications. On the basis of the years in which patents were first sought and the period over which the original patents were subsequently cited, the most mature technology is AI. Most patents for this technology were applied for in 2014 and cite patents on average from 2005, producing a difference of around 9 years. This may seem counterintuitive. But today’s AI patents, such as those for autonomous vehicles and the metaverse, are technologically closer to those for search engines and digital maps, and many of the underlying principles patented in 2005 are still valid.

Figure 3
Patent maturity of frontier technologies



Source: UNCTAD.
Note: For each technology, the number in the bar graph shows the patent maturity, which is the difference between the weighted average patent application year and the weighted average year of the 20 most cited patents between 2000 and 2021.

IoT, on the other hand, is relatively immature, with an average patent application year of 2017 and an average citation date of 2016. This suggests that the dominant design behind IoT innovation is being updated almost yearly, reflecting a technology that is still evolving fast.

For developing countries that need to catch up, the more mature technologies may seem simpler and more affordable options since they demand less research and development. Biomass and solar PV, for example, have well- tested technologies that latecomers can absorb and use with imported machinery from the outside. For solar PV, for example, China initially imported foreign production machinery and benefited from economies of scale. However, these markets may now be more difficult to enter since the incumbents will have developed strong and efficient production processes and are able to trade internationally at more competitive prices.

3. LAYING THE FOUNDATIONS

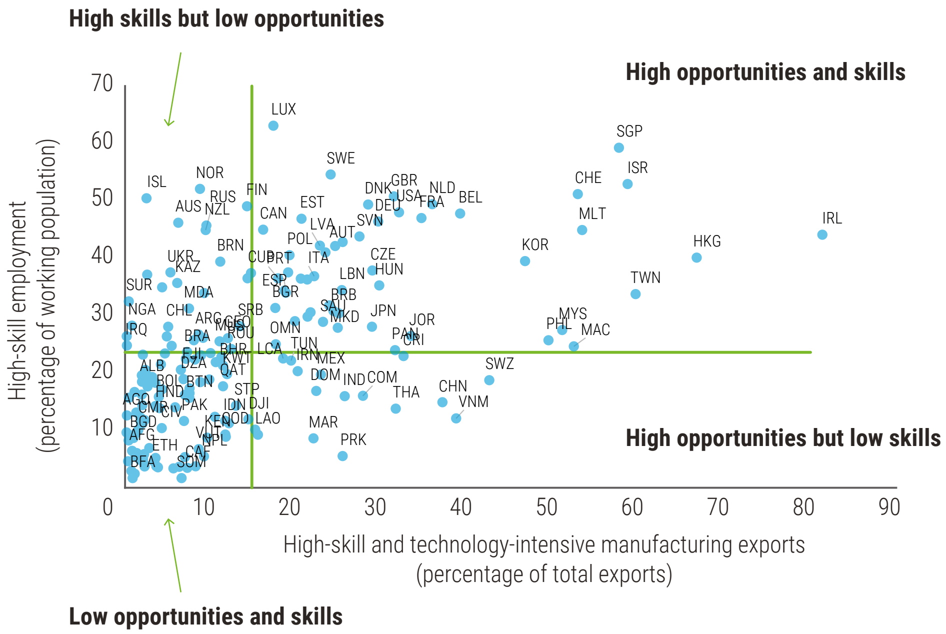
If developing countries are to capture the economic gains associated with new technologies, their firms must have the required capabilities. This includes not just scientific or technical skill, but also the necessary policies, regulations, and infrastructure. To assess national preparedness to equitably use, adopt and adapt frontier technologies, this report presents the 2023 results of the ‘readiness index’ that combines indicators for ICT, skills, R&D, industrial capacity and finance. This ranking for 166 countries is dominated by high-income economies, notably the United States, Sweden, Singapore, Switzerland, and the Netherlands. The second quarter of the list includes emerging economies – notably Brazil, which is ranked at 40, China at 35, India at 46, the Russian Federation at 31, and South Africa at 56. China's lower-than-expected position in the ranking, when compared with its productive and innovative capacities in frontier technologies, is due to urban- rural disparities in Internet coverage and broadband speed. Further behind are countries in Latin America, the Caribbean, and Sub-Saharan Africa, which are the least prepared to use, adopt and adapt frontier technologies and are at risk of missing current windows of opportunity.

Data on individual components of the index highlights areas that need to be improved. Overall, developing countries as a group have lower rankings for their indicators on ICT connectivity and skills. The LDCs, LLDCs, and SIDS rank lower than 100 for all the indicators, with particular weaknesses in ICT infrastructure and research & development.

The countries best placed to move to smart production are those with higher levels of skill and stronger manufacturing industries. The figure below shows the balance between workforce skills and market opportunities – based on high-skill and technology-intensive manufacturing exports as a percentage of total exports, and high-skill employment as a percentage of the working population.

Figure 4

Readiness to benefit from the diffusion of Industry 4.0



Source: UNCTAD (2022). Industry 4.0 for Inclusive Development (United Nations publication, Sales No. E.22.II.D.8, New York and Geneva).

Note: The solid lines represent the global unweighted averages under these two indicators. Data labels use International Organization for Standardization economy codes.

Windows opening and closing

For developing countries and specific renewable energy products, the rapidly changing technological scene offers green windows of opportunity. Countries should take advantage of these now, if possible, since they are likely to close as other countries take over the markets. Otherwise, they may be firmly locked into fossil-fuel pathways, leaving the markets entirely to foreign investors. Much depends on the national preconditions and capacities and willingness to take opportunities and respond strategically as they arise.

Looking at renewable energy technologies, there is significant variability in catch-up trajectories at the sector and country level. The table below considers four scenarios – illustrating which windows have been open, or are within reach, and countries and technologies that have taken advantage of them.

Table 1
Four green window scenarios

Responses / Readiness	Strong	Weak
Strong	**Scenario 1: Windows open** Solar PV, Biomass, CSP – China Bioethanol – Brazil Hydrogen – Chile (potentially)	**Scenario 2: Windows to be open** Solar PV – India Biogas – Bangladesh CSP – Morocco Wind – China
Weak	**Scenario 3: Windows within reach** Biomass – Thailand and Viet Nam Hydrogen – Namibia	**Scenario 4: Windows in the distance** Wind – Kenya Bioenergy –Mexico and Pakistan

Source: UNCTAD.

The best scenario is the one in which strong preconditions are combined with strong responses. For green hydrogen in Chile, for example, the country has adequate preconditions and can show a strong response in development of the technology. Brazil, on the other hand, is in a strong position for biofuel. It has a long history of sugarcane cultivation and from the 1970s started to make significant investments in the technologies, while creating demand, and establishing a supportive framework. With that, the country has managed to catch up and become a global leader both in terms of technology, usage of ethanol, and fuel exports.

However, the lack of strong preconditions does not mean that the window of opportunity is closed. Much depends on the responses at different levels of government and the involvement of various public and private stakeholders. For example, the Thai government addressed weak initial preconditions for biofuel through strong policy responses.

Countries should surpass their initial constraints if they want to reap economic gains. While the opportunities differ greatly from one renewable energy technology to another, there are two main stages for countries switching green. The first is to identify and open windows of opportunity, based on the availability of natural resources, such as favourable wind conditions, and using policies to boost demand and national capacity to use or build the necessary technology. The second is to assess what is needed to sustain the processes. There are also likely to be feedback loops requiring regular adjustments.

Pathways to more complex and sustainable production

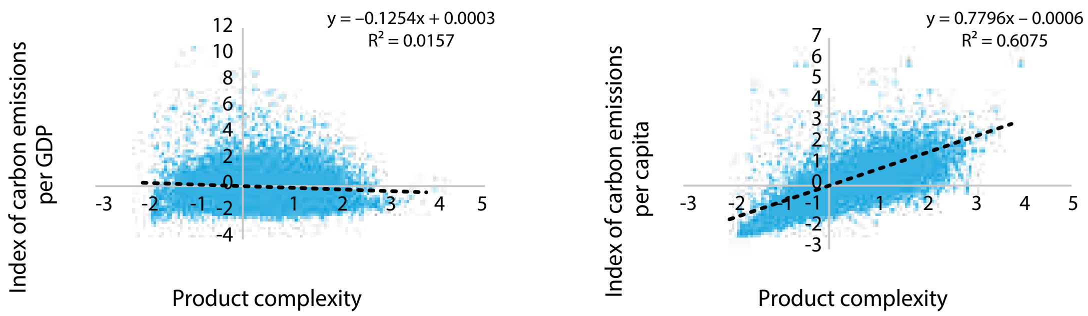
The best direction for developing countries is to switch to products that are more complex,[1] have greater value added and lower carbon footprints.

In most low-income developing countries, economic diversification involves emulating industries in more developed countries – a steady progression that builds on existing industries – it is thus 'path-dependent.' If a country already has the capacity for manufacturing medium and high technology products, it is in a stronger position and can move in a number of directions. But if it is largely producing primary products, it has fewer starting points. If basic technologies need to be learned or transferred from abroad, then innovation is likely to require greater government support. But whatever path they choose for switching green, governments in low and lower-middle-income developing countries have to act fast and decisively; otherwise, they will be left further behind.

Generally, as countries move from agriculture to industry, and to medium and high-tech manufacturing, complexity increases. But this does not necessarily lead to greener production. The less-complex sectors that also have lower carbon footprint include textiles, vegetable products, foodstuffs and footwear. The sectors that are more complex and have higher carbon footprints include chemicals and allied industries, metals and mineral products. However, much will depend on the product mix, because within each industry, one can find products in a range of carbon emissions - from below to above the global average.

To help countries choose greener pathways UNCTAD has produced indices of economic complexity and carbon footprints for 43,000 products exported in international markets. As the product mix becomes more complex and more sophisticated, carbon emissions can fall per unit of GDP, though if more products are being produced for more people total emissions will rise (Figure 5).

Figure 5
Association between carbon footprint and product complexity, 2018

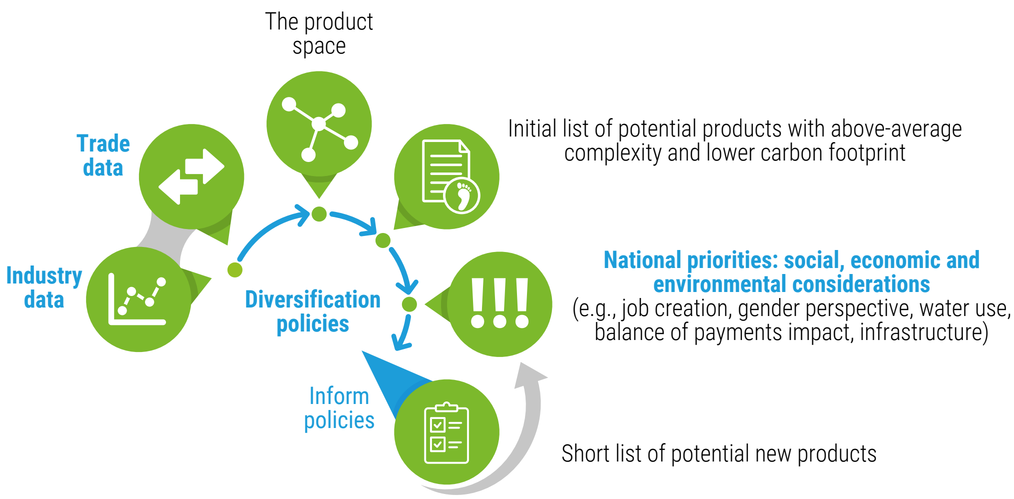


Source: UNCTAD.

For selecting more complex and greener directions, governments should strengthen national capacities for analysing new sectors (Figure 6). This will mean taking stock of the country's existing technological and productive capacities and the availability of natural resource such as wind or agricultural waste. The evaluation can also take advantage of international tools, such as UNCTAD's Catalogue of Diversification Opportunities 2022. They also need to consider how they can fit into global value chains. And as the windows of opportunity open, policymakers should be prepared to adjust their institutional frameworks.

1 More complex products are considered to require higher levels of technology to be produced.

Figure 6
Selecting realistic opportunities for diversification



Source: UNCTAD.
Note: Product space is a network representation of the similarity between products traded in the global market in terms of the technology required for their production.

Twin transitions for global value chains – green and digital

For most countries their capacity for moving to complex and greener products will depend on trade – on how they can fit into global value chains (GVCs). By participating in GVCs, countries can diversify by producing and exporting parts and components of final products or by upgrading existing output to have greater value added.

The greening of GVCs in manufacturing industries is driven by 1) national environmental legislation and trade agreements including environmental provisions, 2) new patterns of demand preferences and consumer behaviours, and 3) new technologies inducing efficiency gains to meet greener demand requirements. These drivers can open green windows of opportunities for firms in latecomer countries involved in GVCs, but seizing these opportunities is not automatic and the failure to do so may leave enterprises worse off than before.

GVCs can become greener through two main routes. The first is by manufacturing the goods used for green production, such as solar PV panels and wind turbines. The second is by greening traditional manufacturing industries, such as food, garments and textiles, leather and shoes, and furniture.

Greening of traditional GVCs can be achieved by switching to digital frontier technologies associated with smart manufacturing – often referred to as Industry 4.0. For example, data collected from online-connected sensors, and from GPS tracking systems, can optimize logistics and significantly reduce carbon emissions.

So far, digital technologies have only diffused slowly in most of developing economies. Manufacturing companies more likely to use Industry 4.0 technologies are found in the more advanced economies. Countries with largely lower-skilled labour are less likely to benefit. There are also differences between companies – in many developing countries, only a minority of larger companies tend to adopt digital technologies; while the majority are still confined to analogue production. To promote the twin transition of green and digital, latecomer countries will need to build digital competency along with the necessary infrastructure and institutions, while building innovation capacity and overcoming financial barriers.

Within value chains, governments can consider targeted policies, such as support for small and medium-size enterprises with finance for new machinery and other requirements for upgrading. They can also create training or technology demonstration centres as well as industrial institutes.

As they upgrade, companies and countries should embed strong social and environmental values. Social upgrading refers to improving the rights and entitlements of workers and their employment. Environmental upgrading refers to a firm's ecological footprint, including its use of natural resources, its emission of greenhouse gases and its impact on biodiversity. These ideals are increasingly being demanded by consumers who are seeking more ethical products, as well as by governments and others who now have more exacting social and environmental standards.

Upgrading value chains can be based on voluntary sustainability standards (VSS) which have emerged mainly through collaboration among NGOs, industry groups or multi-stakeholder groups. By 2020 there were 150 VSS in agriculture, and around 30 for mining and industrial products.

4. PRIORITIES FOR OPENING GREEN WINDOWS

For opening green windows, governments need to assess the current conditions and then strengthen sectoral innovation systems. Much of this happens within 'green industrial policy,' which mainly involves mobilizing the necessary actors and resources and directing how knowledge capacities are upgraded – often amid considerable technological, economic, and political uncertainties.

The report identifies a set of priorities for latecomer countries. They can build digital competency along with the necessary infrastructure and institutions, while strengthening innovation capacity and overcoming financial barriers. This requires collaboration between the private sector and other stakeholders.

A lead agency within government should mobilize resources and convene stakeholders to assess overall state capacity in the areas related to the new technology, as well as the strengths of relevant public agencies, particularly for regulation, extension support systems, and for providing required public services. Overall policy should be mission-oriented – going beyond levelling the playing field to fixing market failures and involving broader programmes of market co-creation and shaping.

In industries where the technology is more mature, as with wind and solar, it may be difficult for latecomers to produce core components. But there can be opportunities further down the value chain related to deployment, such as project development, engineering, procurement and construction.

Governments need to assess at various stages where and how production and innovation should be strengthened and changed. To do so, they can take advantage of UNCTAD's Science, Technology and Innovation Policy reviews which cover the activities of national and local governments, private companies, universities, research institutes, financial institutions, and civil society organizations.

While the options differ from one country and company to another, there are some common priority areas.

Set the direction

Align environmental and industrial policies

Governments need transformational agendas to mitigate climate change, commit to renewable energy production and consumption, electrify rural communities, and increase energy security. Policies that might previously have been developed in separate domains need to be co-created across the energy-environmental and industrial spheres. This requires a whole-of-government approach involving ministries of education, industry, trade, to cultivate design and engineering capabilities and prepare the economy and businesses for responding.

Invest in more complex and greener sectors

The government, the private sector and other stakeholders should develop the capacities and build the institutions to continuously and strategically identify new technologies and sectors for diversification that are more complex and greener. The priority sectors should be supported through vertical policy instruments such as clusters, smart specialization initiatives, pilot and demonstration projects and areas, and the associated finance.

The government and the private sector should also expand financing opportunities for developing and commercializing green technologies. These can include Investment funds for green technology, technical assistance in innovation and technology, and advisory services. To encourage the private sector, both government and donor agencies should come forward as early investors. These activities can be complemented by foreign direct investment.

Build consumer demand

Governments can offer the incentives and infrastructure that help shift consumer demand to encourage recycling and the circular economy. This can be supported by green procurement to create a ripple effect across the rest of the economy.

Build green productive and innovative capacities

Invest in R&D

Nascent green technologies usually require significant investments in R&D. Governments can offer subsidies to build up research, with the collaboration of universities and industry, both domestic and foreign. Public R&D investments are also needed in process improvements and complementary technologies. And when technologies are rapidly evolving, as in the wind industry, this investment will need to be continuous. In the early stages, when the domestic market cannot support a competitive industry, governments can set up technology demonstration projects.

Raise awareness of green technologies

The government, private sector and other stakeholders should create greater awareness of the potential of green technologies. This should start within basic education, along with campaigns to inform the private sector and consumers of the benefits of these technologies and their capacity to reduce carbon footprints. Within firms, technical education and skills development upskill and prepare the manufacturing sector to adopt green technology.

Organized civil society is also important for sensitizing the public about the significance of green technology. Civil society organization can support transfer of knowledge and capacity development activities for farmers and other small businesses. They can also start pilot projects that can be scaled- up by governments. Civil society organizations and the academia can serve as incubators or accelerators for young entrepreneurs interested in starting businesses in green agricultural technologies.

Develop digital infrastructure and skills

As these technologies progress, all countries will need stronger digital infrastructure, in particular high-speed and high-quality Internet connections. This will mean public and private investments in ICT infrastructure along with regulations to foster competition in the telecommunications sector. Governments should also address the connectivity gaps between small and large firms and between urban and rural regions. Some technologies, such as drones, may also need specific regulations.

Skills are needed for adopting existing technologies, for basic use, for adapting these technologies, and finally for creating new ones. For developing countries, it is particularly important to have the capacity to adapt and modify technologies since these are likely to be used in circumstances different from those in which they were originally developed.

Governments should support businesses, including SMEs, to help them build digital skills in areas such as market research, product development, sourcing, production, sales, and after-sales services. Special consideration should be given to women in informal and artisanal small and microenterprises, particularly for entrepreneurs. Countries also need to reduce brain drain, retain skilled professionals, and attract skilled expatriates.

5. INTERNATIONAL COLLABORATION FOR MORE SUSTAINABLE PRODUCTION

In developing countries, opening green windows is unlikely to happen naturally as a result of businesses seeking greater efficiency and profits; it has to be the consequence of deliberate government action.

The least technologically able countries cannot seize green opportunities without the support of the international community and official development assistance. This should be based on equitable partnerships – to build local innovation capabilities and marshal the necessary technologies. Collaboration on innovation not only transfers capital goods and equipment, it also enables people to develop the skills needed to operate and maintain the equipment (know-how) and understand why it is running (know-why). Green technologies typically need more adaptation to local conditions.

Empowering developing countries for switching green thus requires broad and comprehensive development strategies that can deal with multiple tensions and develop partnerships for common public goods.

Cooperation through international trade

Given the extent to which the production and consumption of products related to green technology are traded internationally, much will depend on the conditions on which this trade takes place. Trade rules should, for example, permit developing countries to protect infant green industries through tariffs, subsidies and public procurement – so that they not only meet local demand but reach the economies of scale that make exports more competitive. There should also be requirements for local content though these need to be carefully managed and deliberately sequenced so as to avoid the pitfalls that earlier industrial policies faced in most developing countries.

To support these efforts, the World Trade Organization can review trade rules to make them more consistent with the Paris Agreement. However, member countries can also take steps within existing WTO rules. Countries with larger domestic markets, for example, can subsidize nascent sectors for components for domestic solar and wind energy products. They can thus start producing for import replacement while strengthening capacity for exports, by improving trade facilitation, and ensuring a stable and competitive exchange rates that would have effects similar to those of export subsidies.

The international community should also be innovative and propose new and bold trade mechanisms to support the development of innovation and technological capacity in developing countries for cleaner and more productive production. Developed countries can use development assistance to help countries to emulate the production of more advanced countries. On the demand side, developed countries should open their markets to production from latecomer economies. Identifying the products and countries that should benefit from such a proposal would, however, probably need a new institutional structure. A pilot could be an international programme of guaranteed purchase of tradable green items – such as products, parts and components used for renewable energy.

Reform of intellectual property rights

When the developed economies were producing new products and catching up with Britain after the Industrial revolution, or when a few Asian countries started upgrading their productive and innovative capacities – they were often copying production processes with or without permission. Now the intellectual property rights (IPR) regime is tighter, making it harder for new producers to break in. The international IPR system should be reformed to enable governments in developing countries to manage their systems to support climate action, based on the needs of different sectors and different stages of development. Manufacturers in technologically weak and less diversified countries should be allowed to imitate the production of more technologically advanced economies.

The principle that sustainable development should take precedence over commercial objectives was demonstrated during the COVID-19 crisis. In 2022, the WTO allowed eligible Members until 2027 to produce and supply vaccines without the consent of the patent holder to the extent necessary to address the COVID-19 pandemic. Similarly, flexibilities in the TRIPS Agreement should be given for environmentally-sound technologies to make the trade regime more consistent with climate change agreements.

Partners for green technology

Global efforts should be put in place to accelerate the development and deployment of green technologies under the philosophy of common contributions to common goods. One ground-breaking model for this approach is the Intergovernmental Panel on Climate Change (IPCC). Others are the Paris Agreement of 2015 and the agreements for the Sustainable Development Goals. Even under such an approach, governance mechanisms should be put in place to avoid the North-South divide in knowledge management and ensure that developing countries' views and priorities are fully considered.

There are also successful examples of collective research whose results belong to all participating countries, particularly in natural sciences, including the European Organization for Nuclear Research (CERN), the International Thermonuclear Experimental Reactor (ITER) and the Square Kilometre Array (SKAO) project. Similar collaborations can also shape international cooperation for green innovations that equitably incorporate the views and priorities of developing countries.

Multilateral and open innovation

Most science, technology and innovation efforts are governed at the national level and generally reflect the priorities of developed countries. The international community can offset this bias by shifting research from the national to the multinational level. Such research should be based on open innovation – with all the results available to international experts and knowledge communities. A useful model is the Consultative Group on International Agricultural Research.

Multilateral research can cover the whole value chain, or just a part of it. Research institutions could, for example, bring products or processes close to technology maturity and invite private companies to take care of rapid deployment. Or they might take concepts only to the laboratory stage or to early demonstration projects.

Assessing technologies

Most technologies can have both positive and negative consequences depending on the local context and on how they are used. Each country needs to be able to assess the benefits and dangers of each technology according to their own needs, priorities and concerns. To date, technologies have largely been assessed either from the perspective of the developed countries or emerging economies. UNCTAD is currently carrying out pilot projects involving three African countries to build capacity for technology assessment. What is needed however is a more general multilateral system for assessing new technologies – such as AI and gene editing – based on the opportunities and risks they offer to different types of country. It could also consider how developing countries can be systematically supported to use such technologies.

Regional and South-South cooperation in science, technology and innovation

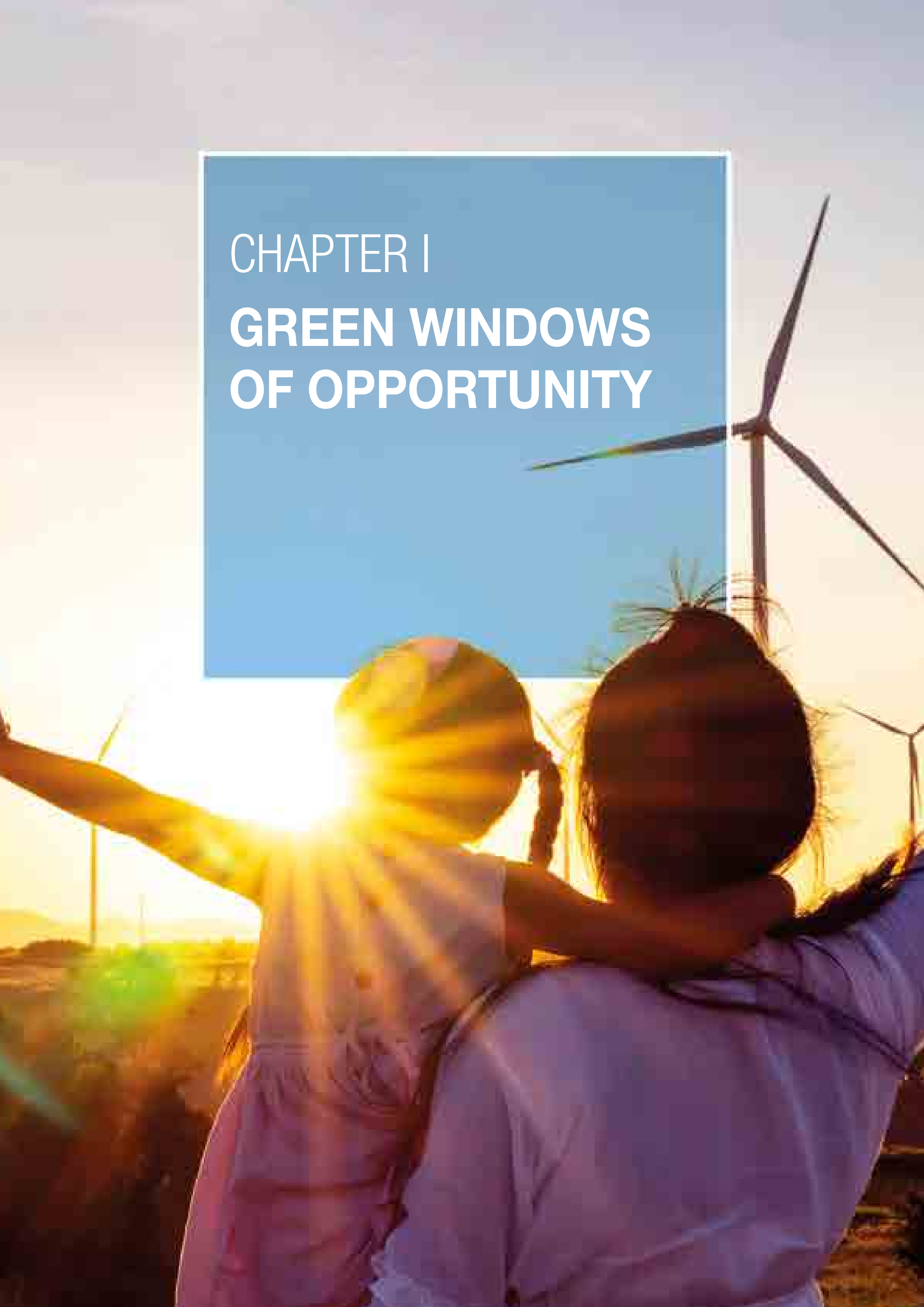
Technological innovations to address the global climate crisis should increasingly be generated at transnational or even global levels. However, cooperation has been limited, even in issues in which countries in the same region often face similar problems. Researchers and investors in the poorer countries have little incentive to cooperate with their regional peers and are more likely to enter research projects with developed countries and emerging economies which can offer access world-class research and laboratories as well as computing power. Moreover, small and vulnerable countries also have limited domestic markets to attract local or international investment in the manufacture of goods related to green innovation. More technologically advanced developing countries should step up and strengthen efforts to promote regional and South-South cooperation for green innovation. Developed countries can support regional centres of excellence for green technologies and innovation – such as the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) and West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

A multilateral challenge fund "Innovations for Our Common Future"

Successful innovation systems create multiple incentives for companies and entrepreneurs to develop their own ideas and transfer them to practice. However, most developing countries lack the financial or management capacities to develop similar incentives. This Report proposes therefore a multilateral challenge fund "Innovations for our common future." Funded by international organizations, donors and international philanthropy the fund would mobilize creative thinking and stimulate innovations that could respond to many global challenges. The next step would be to design a global green innovation competition. The criteria for assessing projects would be the extent to which they incorporate North-South and South-South STI cooperation for green innovation.

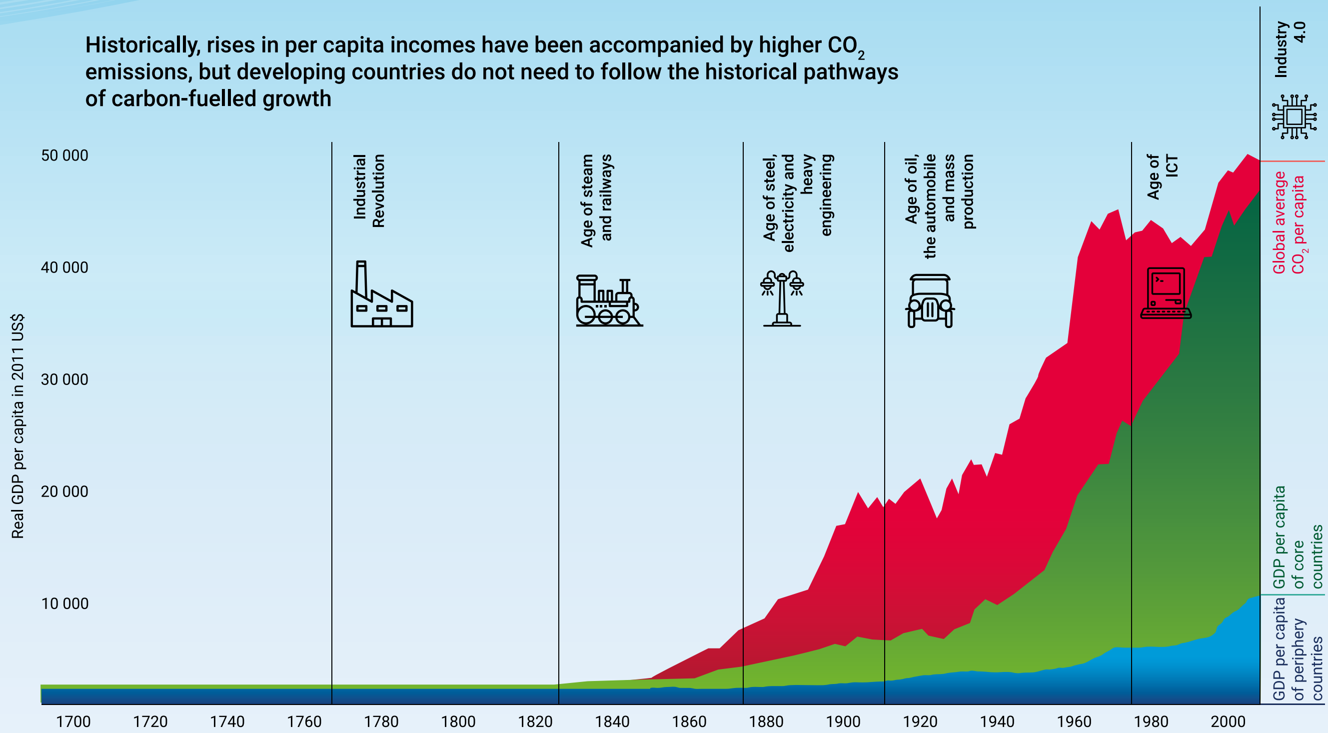
CHAPTER I

GREEN WINDOWS OF OPPORTUNITY



Countries must act now to use green technologies as a driver for sustainable economic development

Historically, rises in per capita incomes have been accompanied by higher CO_2 emissions, but developing countries do not need to follow the historical pathways of carbon-fuelled growth



Green innovation can spur economic and technological development and, at the same time, build resilience and mitigate climate disaster

Green innovation has four key characteristics:

- Higher degree of experimentation – countries have to be innovators. Path-following catch-up is not enough
- Driven by social value and the provision of climate-related public goods
- Direct government intervention
- Influenced by global agendas, rules, and mechanisms related to climate change such as the Paris Agreement

A technological shift based on renewables and digital technologies is happening now, and it creates Green Windows of Opportunities (GWOs)

Time-bounded opportunities that arise from changes in policy, markets, and technologies

National policies are key to open opportunities and build the capacity to take advantage of them

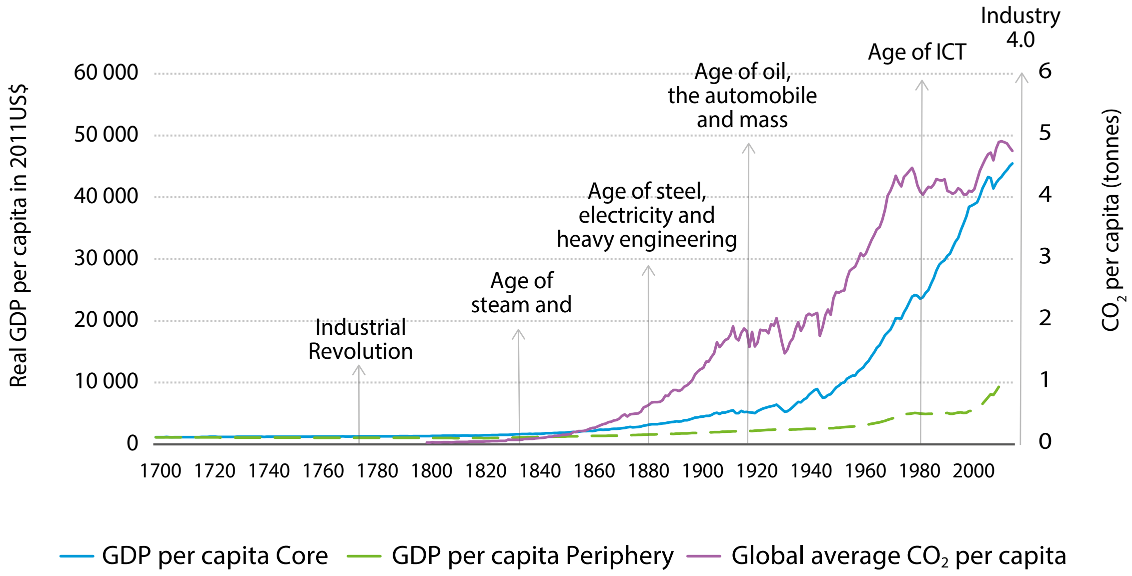
Access to technologies and knowhow is not enough – **TIMING IS ESPECIALLY CRUCIAL. WITHOUT IT, THE GREEN REVOLUTION WILL WIDEN GLOBAL INEQUALITIES**

In 2023, the world faces severe social and economic challenges. While trying to recover from the COVID-19 pandemic, many countries are now coping with the repercussions of the war in Ukraine, which has not only caused immense suffering but has also heightened geopolitical tensions and created threats to global trade, and to energy and food security.

Hovering over this sombre conjuncture is the climate crisis. As indicated in Figure I1, rises in per capita incomes have historically been accompanied by higher CO_2 emissions. Now, governments need to raise the incomes of the poor while also limiting carbon emissions. They must therefore make complex trade-offs between competing policy priorities – between promoting inclusive economic growth and protecting the planet.

Figure I 1

The great divide, rise in CO_2 per capita, and waves of technological change



Notes: "Core" corresponds to Western European countries and Australia, Canada, New Zealand, the United States and Japan. "Periphery" corresponds to the rest of the world.

Source: UNCTAD, based on data from Our World in Data and the Maddison Project Database, version 2018, Bolt et al. (2018), Perez (2002), and Schwab (2013).

The most difficult choices are in developing countries where this conjuncture of crises threatens hard-won development gains. They need more diverse and more productive economies to create more and better jobs, boost household incomes and reduce poverty. But faster economic growth will demand far more energy which, if sourced from fossil fuels, would send millions of tons of carbon billowing into the atmosphere.

Moreover, repeating the historical patterns of growth would further widen inequality. Before the industrial revolution, average incomes at the national level were similar across the world. Subsequently, as highlighted in the *2021 Technology and Innovation Report,* national incomes started to diverge, widening the gap between the developed countries at the core of the world economy and the developing countries at the periphery.[1] A hotter climate will affect everyone – rich and poor. And rising poverty and inequality will further heighten tensions within and between countries.

Developing countries need not, however, follow the historical pathways of carbon-fuelled growth – if the global community is committed to equitable social, economic and technological transformations guided by the Sustainable Development Goals.

This report focuses specifically on technological innovation. It does not suggest that these problems will be solved by technology alone, nor that new technology is necessarily beneficial – since the gains for one group can be detrimental for others. New technologies can destroy habitats, for example, or polarize societies, leaving many people further behind. But it does argue that innovation and advances in science and technology, if guided by the Sustainable Development Goals, can be used to drive the world along more sustainable and equitable pathways, particularly in the generation and use of energy. Developing countries need to open green windows now, at the beginning of the technological transformation, so that they can benefit from technological innovation and have a voice on the direction and pace of change, otherwise they will be once again left behind.

The report is built around the concept of green innovation – creating or introducing new or improved goods and services that leave lighter carbon footprints and open up green windows of opportunity that can help developing countries to catch up, achieve the SDGs, reduce poverty, tackle climate change and set the world on a more sustainable course. In terms of technology, developing countries typically lag behind richer countries. But as latecomers they can profit from earlier experiences, skipping some intermediate stages, and following their own trajectories and paths.[2]

For these transformations, developing countries should also rely on support from the more technologically advanced countries. In the past such assistance has been considered "technology transfer." In practice however, often firms have transferred manufacturing equipment with just enough training to operate it. Technology now needs to be transferred more through innovation cooperation – through equitable partnerships that evolve with changing technological needs and capabilities and with shifts in international political and economic landscapes. This will require new policies for innovation, along with new business models and approaches to financing.[3]

A report on these issues could be very wide in scope. It could, for example, consider how frontier technologies can affect climate change mitigation and adaptation, and how to balance the positive and negative sides of this transformation. Or it could address the impacts of greener products on inequality and elaborate on the important principals of the circular economy.

In the interests of brevity, however, the report focusses primarily on three topics, building on the recommendation of the *Technology and Innovation Report 2021* for developing countries to "adopt frontier technologies while continuing to diversify their production bases by mastering many existing technologies." First, developing renewable energy technologies. Second, applying frontier technologies to greener global value chains. Third, diversifying towards sectors that have lower carbon footprints. These topics are addressed across six chapters:

Chapter I – Green windows of opportunity – Describes the process of catch-up using green windows.

Chapter II – Moving fast with frontier technologies – With a special focus on green technologies and the preparations needed.

Chapter III – Growth powered by renewable energy - Examines the production of renewable energy in developing countries and provides insights on the opportunities for these countries to forge ahead in green sectors and related value chains.

Chapter IV – Twin transitions for global value chains – green and digital – How developing countries can use frontier technologies to go digital and go green.

Chapter V – Pathways to more complex and sustainable production – How developing countries can diversify their economies towards sectors with lower carbon emissions.

Chapter VI – International collaboration for more sustainable production – How international cooperation can transfer technology to and foster innovation in developing countries.

A. GREEN INNOVATION

Green innovation has its roots in the idea of a 'green techno-economic paradigm' first presented 25 years ago by economist Christopher Freeman. A techno-economic paradigm can be defined as a set of "common-sense guidelines for technological and investment decisions as pervasive new technologies mature."[4] A sustainable new techno-economic paradigm involves switching to greener technologies and modes of production.

Typically, each new techno-economic paradigm arises within the existing paradigm and may take 30 to 60 years to fully diffuse.[5] The current information and communications technologies (ICT) paradigm was born the early 1970s. The embryonic green paradigm is also benefitting from advances in ICT but more fully embraces digital technologies.[6]

Once a technological revolution matures, financial capital will explore the opportunities for higher profits, either by extending the paradigm to other countries or by investing in the development of further technologies, creating fresh technological waves.

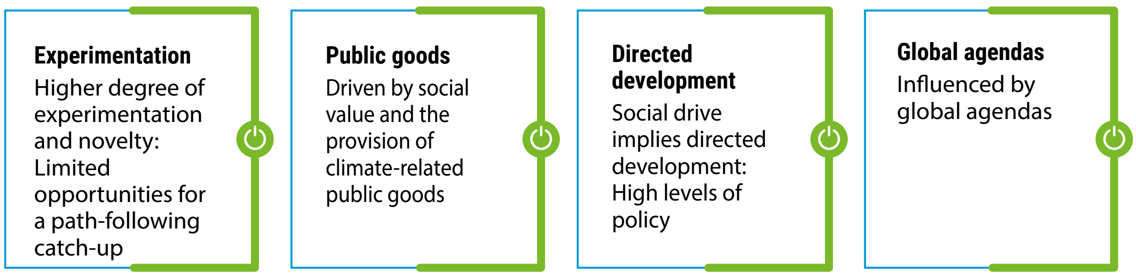
Typically, these waves reach developing countries after a delay – arriving initially in the form of consumer goods as, for example, with the introduction of smartphones and e-commerce. Only later have developing countries applied new technologies to their own production, through investment by multinational companies and later by domestic firms. The outcome is a patchwork of elements of different paradigms at different stages of diffusion in various sectors of the economy.[7]

Developing countries need not, however, wait for new technologies to arrive. They can start to ride the waves of technology in their earlier stages, using these advances to restructure their economies and to grow more rapidly (Box I-1). If they miss the earlier stages of a technological wave there is always the risk of falling irretrievably behind.[8]

Catching up requires more than simple imitation; it demands creative adaptation and innovation. As a result, current catch-up pathways differ substantially from those taken by technologically advanced economies.

Figure I2 illustrates four main components of catch-up based on green innovation. The starting point is experimenting with new ideas and technologies and adapting these to local circumstances, values and priorities (Figure I2). To take advantage of these ideas, they will need the appropriate infrastructure in the form of public goods which often require direct government intervention, supporting the establishment of new green sectors, for example, or introducing regulations such as on air or water pollution.[9] These public goods are freely available to all – they are non-excludable. Green innovation is also influenced by global agendas, rules, and mechanisms, especially, those related to climate change such as the Paris Agreement.

Figure I 2
Catching up with green innovation



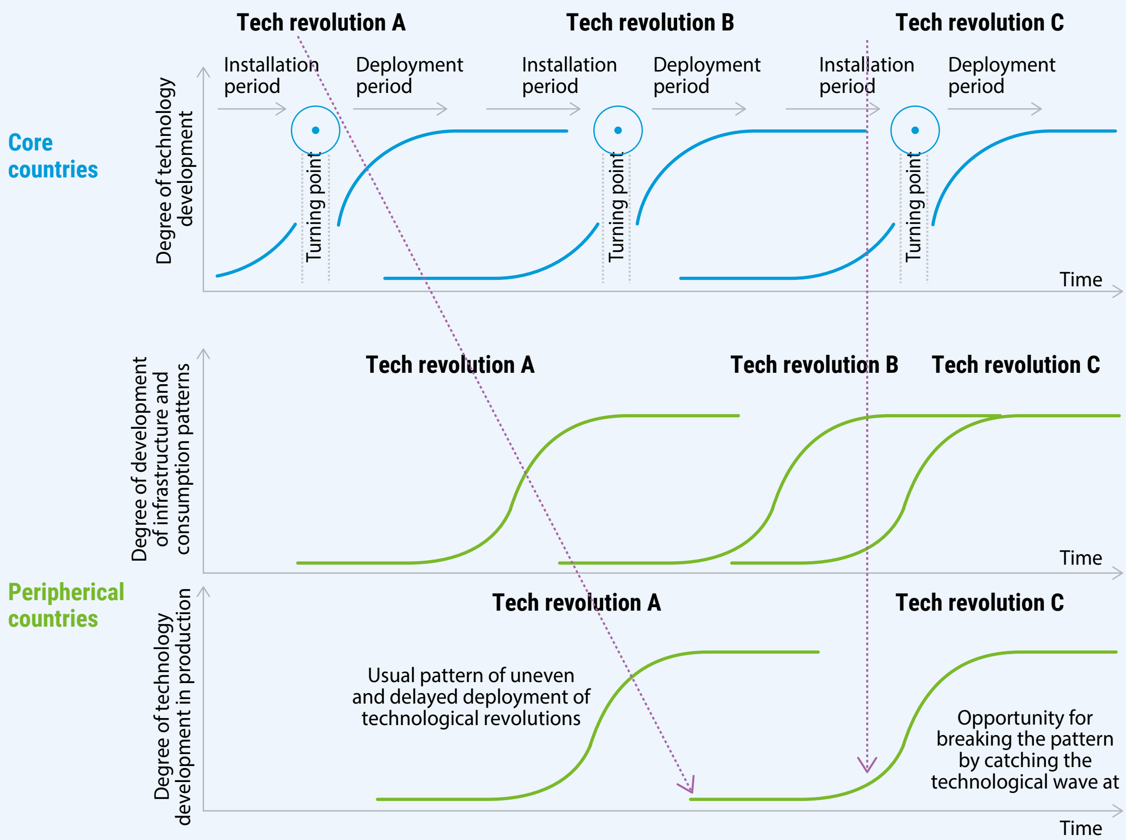
Source: UNCTAD.

Box I 1
Overlapping technological waves

Technological changes can be very uneven and often arrive in overlapping waves. In the chart below, technological paradigm A reaches peripherical countries only when it has already matured in core countries. It first affects infrastructure and consumption patterns and only later is deployed in the production sectors. The pattern is similar for technological revolution B, which has yet to reach the production sectors of peripherical countries.

This pattern can be broken if developing countries take advantage of the emergence of a new technological revolution at its beginning. In technological revolution C, they actively take part in the installation phase – strategically and actively promoting:

a) Changes in domestic consumption pattern towards products related to the new paradigm
b) Installation and diffusion of the required infrastructure, and
c) Diffusion of the new technologies and related innovation in their domestic productive sectors.



Source: UNCTAD.

B. CREATING GREEN WINDOWS

Green windows are time-bounded opportunities that arise from changes in public institutions and policy interventions, markets, and technologies.[10] Previous opportunities have depended largely on external technology[11] or market changes,[12] but green windows of opportunity arise mainly within countries.

Created by public institutions – Green windows of opportunities are often institutional – promoted by public actions and related adjustments to the institutional framework conditions (rules, regulations, policies, etc). In Brazil, for example, the 1973 oil crisis triggered industrial policies to promote the use of biofuels. Similarly, in China in 2006 a renewable energy law stimulated the initial development of the biomass industry,[13] which was supported by solar energy 'missions' such as the Rooftop Subsidy and the Golden Sun Demonstration Programs.[14] In Egypt, the 2014 Renewable Energy Law encouraged the private sector to produce more electricity from renewable resources. In the Philippines, the Renewable Energy Act of 2008 provided incentives for adopting new technologies.[15]

*Created by domestic marke*ts – Governments have been stimulating local demand for green products, for example, by feed-in tariffs aimed at creating competitive parity between green energies and fossil fuels. In India, the "Faster Adoption and Manufacturing of Electric Vehicles" plan stimulates the purchase and the deployment of charging infrastructure.[16] In the Philippines, the Green Public Procurement Roadmap aims to integrate the sustainability criteria in the public procurement process.[17] In China in 2013, the ""Guiding Opinions on Accelerating the Promotion of the Application of New Energy Vehicles" provided purchase subsidies for electric vehicles, supported by the 2015 "Guidelines for Accelerating the Plug-in Electric Vehicle Charging Infrastructure Deployment".[18] Local producers can also consider exports, but many green energy products are not readily tradable.

Created by research and development – Governments can also invest in public R&D programmes. Some examples are the wind offshore demonstration projects in China,[19] the demonstration project on the deployment of solar energy systems in rural health units in the Philippines,[20] and the governmental support for R&D, experimental proof and technology demonstration projects on Clean Energy in India.[21]

Throughout these processes, policymakers have to strike balances. They need to encourage local enterprises by subsidizing products, but if these capabilities are not to remain dormant, they must also stimulate market demand. At the same they must avoid the trap of stimulating green domestic sectors without corresponding investment in technical change, such that firms in developing countries may become market leaders but remain as technology followers.[22] Such institutional-cum-demand windows have been most effective for energy generation as with the use of solar PV in Brazil, China, and India which have large internal markets.

C. ALERT AND READY FOR CHANGE

If developing countries are to catch up, they should be alert to opportunities. This applies both to the policymakers and to firms and supporting institutions, such as universities, research centres, and standards organizations.[23] The firms most likely to be ready and alert are those operating in the same or closely related sectors.[24]

Readiness to seize opportunities has enabled some companies to become national champions. In China for example, this includes Dragon Power in the production of biomass, Suntec for solar PV, and Goldwind for wind technologies. Such firms can then expand to international markets – whether through licensing production overseas or establishing overseas subsidiaries. Goldwin's and Envisions' R&D subsidiaries in Europe, for example, established links with foreign universities and benefited from the recruitment of very experienced engineers.[25] These enterprises also expanded by buying companies in developed countries. For example, Dragon Power's acquisition of a Danish company was crucial for its leadership in the international biomass sector.[26]

In mature sectors, it is relatively easy for firms to acquire world-class technologies, and market success depends more on capital investment in organizational capabilities. In China, for example, following the 2006 renewable energy law, companies licensed core technologies and production plant designs for biomass and wind, mainly from European firms.[27] Similarly, for solar PV production capability they used foreign technologies to manufacture solar panels using globally dominant designs.[28]

In the domestic industry, innovation diffuses from first-movers to followers. In China, a relatively weak intellectual property regime has allowed knowledge to spill over from the leading companies to other domestic firms in related industries.[29]

Within specific sectors there can be intense interactions among lead firms, suppliers, technology providers, and financial institutions.[30] During the more demanding stages of technological upgrading, these contribute to technological deepening, as happened in the Chinese solar PV industry.[31]

Firm-level initiatives need to be supported by national institutions, particular in government and in universities – for example, through public R&D investments in process improvements and the application of complementary technologies.[32] In China, for wind power, university-industry collaboration facilitated the shift from onshore to offshore turbine technologies.[33]

For each of these sectors, the innovation system must continuously adapt to changing market and technological opportunities and take into account the different impacts and influences on men and women.

A key to all of this is smart sequencing. Typically, environmental and energy policies create demand which is then filled through industrial and innovation policies. For instance, the strategy may aim to create a demand through subsidies and price incentives for renewable energy, followed by a subsequent law allocating a share of domestic content for components in wind turbines.[34] Or conversely, in the case of the global shift from combustion engines to electric vehicles, innovation and industrial policies can support domestic design and manufacturing. Transportation policy then encourages domestic diffusion, followed by preparation for exports.[35]

D. CATCH-UP TRAJECTORIES

Catch-up refers to shifts in the balance of economic power between incumbents and latecomers, and can be driven by markets or technologies.

*Market catch-u*p – This can start with government policies that stimulate a domestic market that can be satisfied by local products.[36] In renewable energy this may be quantified and measured as the share of energy generation capacity (in megawatts) sold and installed by domestic producers in the domestic and global markets. In other sectors, such as EV, it can be measured by domestic producers' number of units sold in domestic and global markets. Global market catch-up means achieving internationally competitive quality and prices for green products, such as wind turbines and solar PV panels, and related services. Marketplaces are small for certain pre-competitive, still immature technologies, such as concentrated solar power and green hydrogen.

Technological catch-up – To a significant degree, this relies on capabilities based on pre-existing knowledge and routines and strengthened by user-producer interactions.[37] There is however a distinction between technology that is new-to-the-country and world-class technology at the global knowledge frontier.[38] Both types interact during the latecomer development process since a closer connection to larger and more sophisticated markets may provide critical knowledge for technology improvements.[39] In addition, more robust technological capabilities may increase the competitiveness of national firms in the home and export markets.[40] However, this outcome is not automatic. A certain degree of technological capability attainment may enable domestic market development but may be insufficient for export competitiveness. Conversely, demand-led domestic development may help catch up in production capability, but not technological catch-up, which depends on firm-level advantages provided by access to lead markets.[41]

The next chapter assesses the current state of countries' technological capabilities in Industry 4.0 and green technologies.

1 UNCTAD, 2021a

2 Perez and Soete, 1988; Altenburg et al., 2008; Guennif and Ramani, 2012; Lee, 2019

3 Pandey et al., 2022; Hultman et al., 2012; WEF, 2022; IMF, 2022

4 Freeman, 1992, 1996; see also Kemp and Soete, 1992

5 Perez, 1983

6 Lema et al., 2020

7 Perez and Soete, 1988

8 Perez, 2002

9 Although the current ICT paradigm and the digital economy was very much spurred by public sector programmes and benefited from large investments in the military sector, much less deliberate direction was given by public policies. In fact, the digital economy is to a large extent an unintentional by-product, or positive externality, of investments in the military-industrial complex in the US, even if the state also sought to commercialise the outcomes of these investments. See also Deleidi et al., 2020.

10 Lee and Malerba, 2017

11 Wu and Zhang, 2010

12 Morrison and Rabellotti, 2017

13 Hansen and Hansen, 2020

14 Iizuka, 2015

15 UNCTAD, 2022a, 2022b

16 Press Information Bureau of India, 2022

17 GPPB-TSO, 2017

18 Kalthaus and Sun, 2021

19 Dai et al., 2020

20 UNCTAD, 2022b

21 UNCTAD, 2022c

22 Hain et al., 2020

23 Vértesy, 2017

24 Lee and Malerba, 2017

25 Haakonsson et al., 2020; Lema and Lema, 2012; Fu and Zhang, 2011

26 Hansen and Hansen, 2020

27 Dai et al., 2020; Hansen and Hansen, 2020

28 Binz et al., 2020

29 Hansen and Hansen, 2020

30 Fu, 2015

31 Binz et al., 2020

32 Shubbak, 2019

33 Dai et al., 2020

34 Lema et al., 2013

35 Lema et al (2020) discuss the sequencing of the various elements of GWOs. See also Konda, 2022.

36 Hain et al., 2020

37 This can be measured based on quantitative information (e.g., patent numbers and quality) or qualitative assessments of the distance from the global knowledge frontier in each sector.

38 Altenburg et al., 2008

39 Schmitz, 2007

40 Lee and Malerba, 2017

41 Beise and Rennings, 2005

CHAPTER II

MOVING FAST WITH FRONTIER TECHNOLOGIES

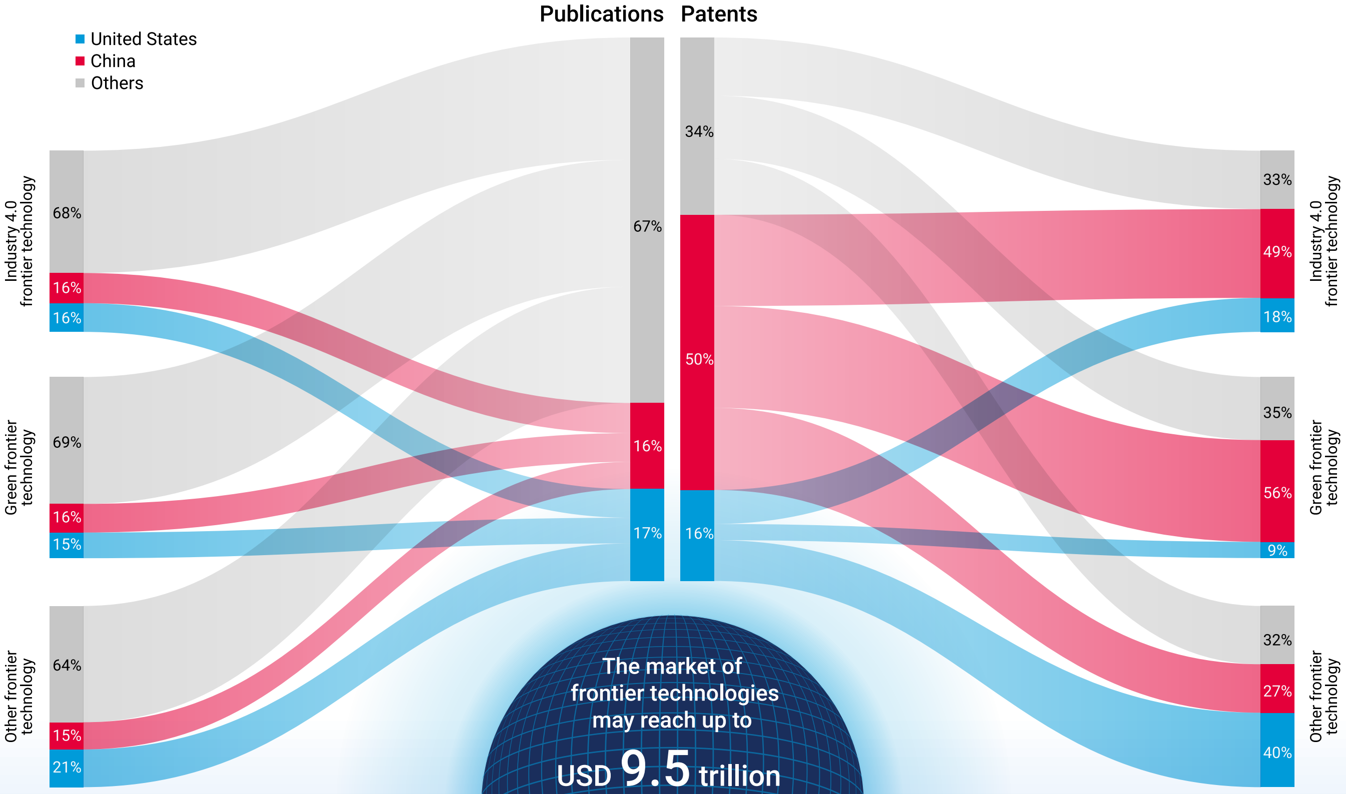
Few have the needed skills to take advantage of frontier technologies, so countries must be proactive to grow with the green transformation

The Technology and Innovation Report 2023 covers 17 technologies divided into three broad categories:

Industry 4.0: artificial intelligence (AI), the Internet of things (IoT), big data, blockchain, 5G, 3D printing, robotics, drones

Green and renewable energy technologies: solar PV, concentrated solar power, biofuels, biogas and biomass, wind energy, green hydrogen, and electric vehicles

Other frontier technologies: nanotech and gene editing



The market of frontier technologies may reach up to

USD **9.5** trillion by **2030**

The trade of these technologies is expanding. For example, the exports of electric vehicles of the top 15 exporter countries jumped from USD 28 billion in 2018 to USD 105 billion in 2021.

There is concentration in terms of suppliers, R&D outputs, and technology presence in developed economies.

Only a handful of countries supply frontier technologies and almost all of them are developed economies

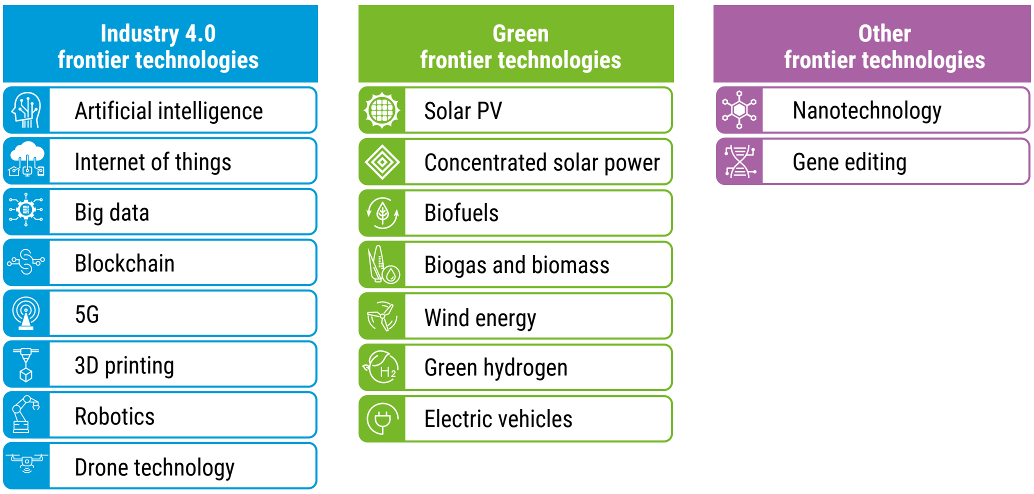
Most publications and patents in frontier technologies are from developed economies and China

There is a limited presence of technologies like EVs in developing economies

This chapter examines frontier technologies – new and rapidly developing technologies that take advantage of digitalization and connectivity – highlighting their potential economic benefits. It also assesses country capabilities to use, adopt, and adapt these innovations.

As indicated in Figure II-1, the chapter focuses on 17 technologies divided into three broad categories: Industry 4.0, green and renewable energy technologies, and other frontier technologies. Nevertheless, these categories also intersect and overlap. For instance, drones are not classified here as a green frontier technology, though delivery by drone can cut GHG emissions due to their lower energy consumption per package when compared to vehicles.[1] Similarly, nanotechnology can improve the use of renewable sources, for example, by enabling lighter rotor blades for wind turbines.[2]

Figure II 1
Frontier technologies covered in this report



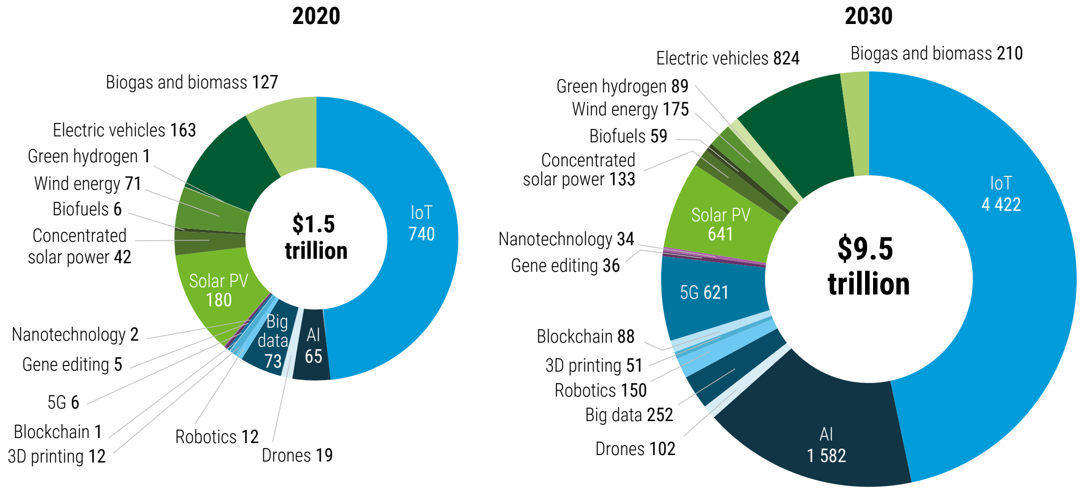
Source: UNCTAD.

These technologies have experienced tremendous growth in the last two decades and will continue to affect economic and social structures, offering possibilities for market growth and a chance for economies to develop their labour markets. In addition, countries that have the required capabilities can enter and develop new sectors like renewable energy sources or EVs, opening green windows to drive their economic growth. Nonetheless, developing economies have to optimize their preparedness and close the gaps for the use, adoption, and adaptation of frontier technologies. The readiness index included in this chapter can help countries do so using an evidence-based approach.

A. TECHNOLOGIES IN THE FAST LANE

Frontier technologies have experienced tremendous growth in the last two decades.[3] In 2020 their market value was $1.5 trillion and by 2030 could reach $9.5 trillion (Figure II-2). For comparison, over this period the global market for smartphones is expected only to double, from $508 billion to $983 billion.[4] But it is important to note that these estimates may be inflated by double counting – for instance, many IoT technologies also involve the deployment of AI and big data.

Figure II 2
Market size estimates of frontier technologies, $ billion



Source: UNCTAD based on various estimates.[5]

Around half the market value of these technologies is for the Intern of things (IoT) which embraces a vast range of devices that are ubiquitous across multiple sectors. Industry 4.0 has accelerated the use of these multiple interconnected devices – from Tesla's automotive factories to Amazon's warehouses to IoT devices in sustainable aquaculture.[6] By 2030, IoT revenues could reach $4.4 trillion.[7]

There is also a rapidly expanding market for AI, which by 2030 might be contributing between $13 trillion and $16 trillion to the global economy.[8] Growth is driven by continued technical improvements in multiple sectors, such as AI-enabled self-programming robots for manufacturing, and AI-based software in financial investment, trading, and loan screening. AI is also improving urban service delivery in smart cities and drone delivery – by directing semi-autonomous vehicles, cars, trucks, and buses, in which drivers are assisted by cameras, radar, and navigation systems.[9]

Between 2020 and 2030, the market revenues for electric vehicles (EVs) could increase from $163 billion to $824 billion. This growth is being driven primarily by demands from consumers who wish to reduce their carbon footprints but are also responding to rising prices for gasoline and diesel that have arisen from geopolitical instability. This demand is now being met by many more suppliers, including companies who previously only produced vehicles with internal combustion engines. Greater competition has reduced prices, encouraging better charging infrastructure, and supportive government regulations and incentives.

The numbers in Figure II-2 are significantly higher than those given in the previous *Technology and Innovation Report*. This is partly because this report adds six more green technologies but also because the use of several technologies accelerated after the COVID-19 pandemic and triggered more rapid digitalization.[10] For the global investment promotion agencies, ICT is now reported as the second most important industry, with technologies like blockchain, big data, 5G, and IoT as the main choices for online activities.[11]

Frontier technologies are supplied primarily from a few countries, notably the United States, China, and countries in Western Europe (Table II-1). The biggest providers of Industry 4.0 technologies are from the United States which is home to major computing platforms that offer a wide range of one-stop, pay-as-you-go services.[12] Companies from China are particularly active in 5G, drone technology, and solar PV. Robotics and green frontier technologies suppliers, on the other hand are more evenly spread among developed economies in Western Europe and East Asia, where companies have benefitted from favourable regulation and rising demand for renewable energy. Only two of the top frontier technology providers are from developing economies, and both are in the renewables sector. Firms in these countries urgently need more government support if they are to operate more effectively close to technological frontiers.

Table II 1
Top frontier technology providers

AI	IoT	Big data	Blockchain	5G
Alphabet	Alphabet	Alphabet	Alibaba	Ericsson
Amazon	Amazon	Amazon Web Services	Amazon Web Services	Huawei (network)
Apple	Cisco	Dell Technologies	IBM	Nokia
IBM	IBM	HP Enterprise	Microsoft	ZTE
Microsoft	Microsoft	IBM	Oracle	Huawei (chip)
	Oracle	Microsoft	SAP	Intel
	PTC	Oracle		MediaTek
	Salesforce	SAP		Qualcomm
	SAP	Splunk		Samsung Electronics
		Teradata		

3D printing	Robotics	Drone technology	Gene editing	Nanotechnology	Solar PV
3D Systems	ABB	3D Robotics	CRISPR Therapeutics	BASF	Jinko Solar
ExOne Company	FANUC	DJI Innovations	Editas Medicine	Apeel Sciences	JA Solar
HP	KUKA	Parrot	Horizon Discovery Group	Agilent	Trina Solar
Stratasys	Mitsubishi Electric	Yuneec	Intellia Therapeutics	Samsung Electronics	Canadian Solar
	Yaskawa	Northrop Grumman	Precision BioSciences	Intel	Hanwa Q cells
	Hanson Robotics	Lockheed Martin	Sangamo Therapeutics		
	Pal Robotics	Boeing			
	Robotis				
	Softbank				
	Alphabet/Waymo				
	Aptiv				
	GM				
	Tesla				

Biofuels	Wind energy	Green hydrogen	Electric vehicles	Concentrated solar power	Biogas and biomass
Archer Daniels Midland	GE Power	Siemens Energy	Tesla	Abengoa Solar	Future Biogas
ALTEN Group	Mitsubishi Heavy Industries	Linde	Ford	Iberolica Group	Air Liquide
Louis Dreyfus	ABB	Toshiba Energy	Hyundai	ENGIE	PlanET Biogas Global
Brasil Bio Fuels	Siemens Gamesa Renewable Energy	Air Liquide	Chevrolet	NextEra Energy Resources	Ameresco
BIOX Corp	Goldwind	Nel ASA	BYD	BrightSource Energy	Quantum Green
Renewable Energy Group	Enercon	Air Products and Chemicals	Volkswagen		Envitech Biogas
Wilmar international		Guangdong Nation-Synergy Hydrogen Power Technologies	Renault-Nissan-Mitsubishi Alliance		Weltec Biopower

Source: UNCTAD based on various sources.

Notes: American companies in dark blue, Chinese companies in orange, others from developed economies in light blue and developing economies in yellow.

Given the multiple overlaps between various technologies, it is difficult to arrive at market sizes. A more accurate way of evaluating each is to project the value they add to the global economy. Some estimates for 5G, for example, suggest that between 2022 and 2030 its economic contribution will increase from $150 billion to $1.3 trillion.[13] Similarly, by 2030 AI could be adding $13 trillion to global economic output – 1.2 per cent of global GDP, while IoT could be adding between $5.5 trillion and $12.6 trillion.[14] Finally, blockchain is estimated to generate $176 billion of value by 2025 and $3.1 trillion by 2030.[15]

1. CREATION AND EXTINCTION OF JOBS

As with previous waves of automation, frontier technologies have both destroyed old jobs and created new ones.[16] Current job expectations may be more pessimistic because of the increasing capacity of AI to mimic human intelligence and recent job cuts by some big technology companies, nevertheless the alarmist scenarios often fail to take fully into account that not all tasks in a job are automated, and, most importantly, that technology also creates new products, tasks, professions, and economic activities throughout the economy.[17] The net impact on jobs will depend on the final balance between creation and extinction.[18]

Industry 4.0 frontier technologies

AI – A study in the United States using data on online job vacancies found that between 2010 and 2019 demand for AI skills rose sharply across most industries and occupations. The highest demand was in IT occupations, followed by architecture, engineering, scientific and management occupations.[19]

Big data – There is a booming demand for data scientists in the United States. Between 2020 and 2030 there are expected to be 7,100 job openings, with annual job growth projected at 15 per cent or higher.[20]

Blockchain – Between 2020 and 2021, on Indeed.com the number of postings for blockchain jobs doubled.[21] Blockchain developers continue to be remunerated well, with an estimated annual income in the United States of $136,000, in Asia of $87,500 and in Europe of $73,300. The five biggest blockchain employers are Deloitte, IBM, Accenture, Cisco, and Collins Aerospace.[22]

Drones – Between 2020 and 2040, in Australia, on average drones are expected to support 5,500 full-time job equivalents per annum.[23] Meanwhile between 2013 and 2025 the United States should add more than 100,000 drone-related jobs. The top three drone job locations are the United States, China, and France.[24]

5G – Between 2022 and 2034, around 4.6 million 5G-related jobs will be created in the United States, driven largely by employment in agriculture, construction, utilities, manufacturing, transportation and warehousing, education, healthcare, and government.[25] By 2035, the global 5G value chain is expected to support 22 million jobs.[26]

3D printing – Additive manufacturing is demanding more skilled professionals, such as engineers, software developers, material scientists and a wide range of business support functions including sales, marketing, and other specialists. In the United States, it is estimated that 3D printing will add between three and five million new skilled jobs in the next decade.[27]

IoT – The growth of IoT has led to skills shortages. According to one study, between July 2021 and April 2022 the number of online job ads that included IoT increased by one-third.[28] LinkedIn data suggest more than 13,000 IoT-related job openings in the United States.[29]

Robotics – Job growth in robotics is more modest. In the United States, in 2016 there were 132,500 robotics engineers and the job market for this professional type is expected to grow by 6.4 per cent between 2016 and 2026.[30] Robotics careers include robotics engineers, software developers, technicians, sales engineers, and operators.[31]

Green frontier technologies

Biofuels – Worldwide, the liquid biofuel market employs an estimated 2,411,000 people.[32] Although biofuel jobs declined between 4 and 5 per cent in the United States in 2020 because of the Covid-19 pandemic, the demand for workers is projected to rebound.[33]

Biogas and biomass – Job markets will keep growing. Biomass is estimated to create 73 permanent full-time direct jobs per 100MW of installation capacity. Solid biomass employs around 765,000 individuals worldwide, while biogas employs approximately 339,000 people.[34]

Solar PV – Solar PV is the largest contributor to employment among the renewable energy industries, accounting for almost four million jobs worldwide.[35] Solar energy jobs are set to grow rapidly but there is little evidence of solar hiring boom. Growth in the solar energy sector has been slowed by political and industry turbulence due to regulatory uncertainty and the bankruptcy and layoffs of big companies due to lower prices and shifts in the technology, making old ones obsolete.[36]

Concentrated solar power – Worldwide, the concentrated solar power industry has created an estimated 32,000 jobs.[37] In the best-case scenario, concentrated solar projects could create 100,000 to 130,000 new jobs by 2025. Of these, 45,000 would be permanent roles in operations and maintenance.[38]

Wind energy – The job market is expected to experience rapid growth. Wind energy currently employs an estimated 1,254,000 people worldwide,[39] and another 3.3 million direct jobs are expected to be created by 2025 as a result of additional 470GW of wind capacity.[40]

Green hydrogen – Between 2030 and 2050, green hydrogen is expected to create as many as two million jobs, through investments in electrolysers and other green hydrogen infrastructure.[41]

Electric vehicles – Electrifying the transportation industry is expected to result in net job growth. In Europe by 2030 around 200,000 permanent jobs could be created to provide EV infrastructure – for battery manufacturing, charger manufacturing, installation of the chargers, grid connections, and charge point operations.[42] Likewise, by 2035 globally there could be more than two million net jobs.[43]

Other frontier technologies

Nanotechnology – The nanotechnology job market is expected to expand 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.[44]

Gene editing – Labour demand in gene editing is expected to soar, especially in developed countries. In the United Kingdom, an estimated 18,000 new jobs will be added between 2017 and 2035,[45] while in the United States, medical scientists and biomedical engineers together are expected to add 22,500 jobs between 2021 and 2031.[46]

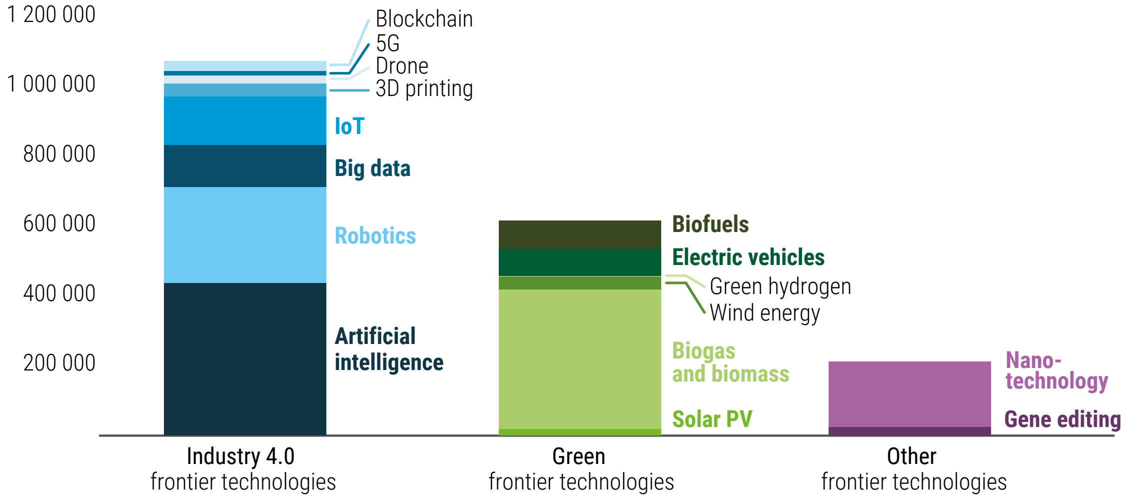
2. KNOWLEDGE ON FRONTIER TECHNOLOGIES

Over the past two decades, frontier technologies have generated increasing interest amongst academics and innovators. The number of associated publications and patents has soared (Figure II-3 and Figure II-4). Particularly high volumes are evident in Industry 4.0 – for AI, 438,619 publications and 214,365 patents; for robotics, 276,027 publications and 122,940 patents; and for IoT, 139,805 publications and 147,906 patents. In green frontier technologies in 2000-2021: for electric vehicles 79,732 publications and 206,049 patents; and for wind energy 37,514 publications and 58,134 patents.

The knowledge landscape is dominated by the United States and China with a combined 30 per cent share of global publications and almost 70 per cent of patents (Figure II-5, Figure II-6, and Box II-1). Other countries compete in specific categories, notably India, the Republic of Korea, Germany, the United Kingdom, France, and Japan.

Figure II 3

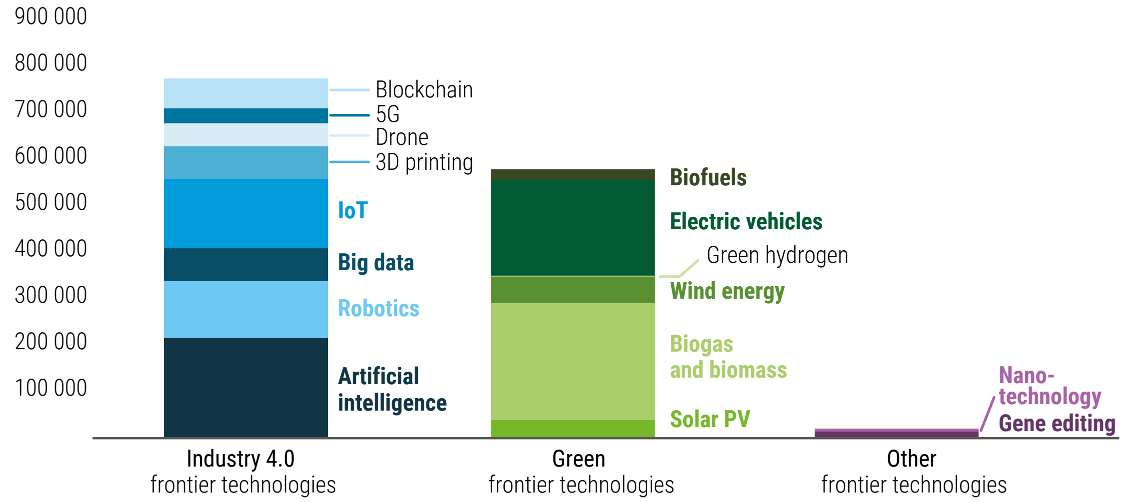
Number of publications on frontier technologies, 2000 – 2021



Source: UNCTAD calculations based on data from Scopus.

Figure II 4

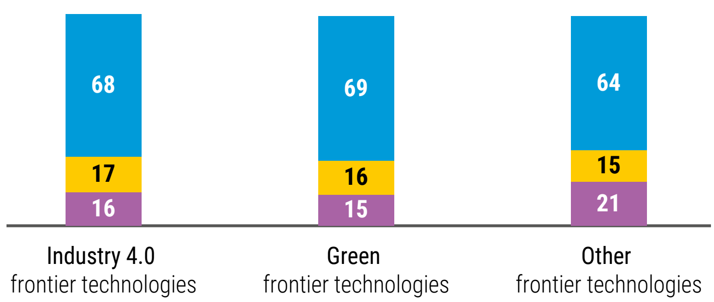
Number of patents for frontier technologies, 2000 – 2021



Source: UNCTAD calculations based on data from PatSeer.

Figure II 5

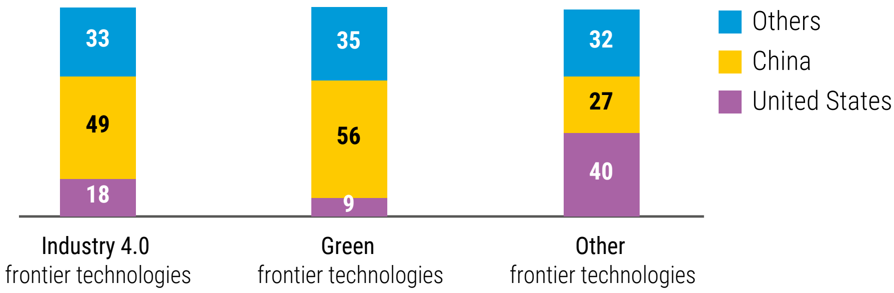
Country share of publications, by frontier technology



Source: UNCTAD calculations based on data from Scopus.

Figure II 6

Country share of patents, by frontier technology



Source: UNCTAD calculations based on data from PatSeer.

Box II 1

China and the United States dominate patents on frontier technologies

For 14 of the 17 categories of frontier technology, the United States and China are the two largest sources of published research and are always in the top three. They are also the top sources of patent assignees in nine and make up two of the top three in seven categories. China is absent only in concentrated solar power – which is the smallest of the categories.

Over the period 2000-2021, China has been particularly dominant in Industry 4.0 and green frontier technologies, accounting for approximately half of all patents. China produced a total of 536,115 patented technologies, which included IoT (100,958 patents), AI (71,055 patents) and big data (62,063 patents). Over the same period, the United States, generated 169,447 patents, which includes robotics (49,318 patents), AI (43,193 patents) and electric vehicles (19,523 patents).

China places technological development as a priority. In the 14th five-year plan, for example, it aims to reach an average annual growth rate of 20 per cent of the number of robots, form a group of leading enterprises that are internationally competitive, build industrial clusters, and double the intensity of robots in manufacturing.[47] According to a study, the country is the leader in granted patents in robotics considering the period between 2005 and 2019, accounting for 35 per cent of the total. Others in the top of this ranking are Japan, the Republic of Korea and the United States.[48]

The gap between China and the United States in patent is even wider in green frontier technologies. China has 56 per cent of overall patents for these innovations, and the United States only 9 per cent. Over the past two decades, firms in China created 33,066 patents for wind energy while firms in the United States generated just 2,963 patents. In solar panels, China created 31,365 patents, while the United States generated 1,586. China's domination reflects the priority status given since 2012 to green technologies in its patent examination system, as well as the determination of policymakers to create a hospitable environment for green innovation.

Source: UNCTAD.

The data shown here highlights the concentration of knowledge creation for these frontier technologies. The accumulated knowledge in countries such as the United States, China, India, and United Kingdom needs to be shared with countries in the Global South, especially LDCs, LLDCs, and SIDS, through international cooperation and multilateral forums and initiatives. Key indicators for the frontier technologies covered in this report are shown in Table II-2. Detailed information is presented in Annex A.

Table II 2
Key indicators

Category:	AI	IoT	Big data	Blockchain	3D printing	Robotics	Drones	5G
Publications	438 619	139 805	119 555	27 964	36 367	276 027	23 526	13 045
Patents	214 365	147 906	72 184	63 767	70 799	122 940	48 613	32 412
Price	Video/speech analysis AI : $36,000-56,000 Intelligent recommendation engine: $20,000-$35,000	ECG monitors: $3,000-$4,000 Energy management system: from $27,000	Data warehouse (cloud storage): ~$359,951/year Data warehouse (on-premises storage): ~$372,279/year	NFT marketplace: $50,000-$130,000 Decentralized Autonomous Organization (DAO): $3,500-$20,000 Cryptocurrency exchange app: $50,000-$100,000	Entry-level 3D printer: $100+ Industrial 3D printer: $10,000+	$50,000 - $150,000 for industrial robot	Commercial drone: $2000+ Military drone: $800,000 to $400 million	$60-70+/monthly for unlimited US 5G network access
Market size	$65 billion (2020) $1,582 billion (2030)	$740 billion (2020) $4,422 billion (2030)	$73 billion (2020) $252 billion (2030)	$1 billion (2020) $88 billion (2030)	$12 billion (2020) $51 billion (2030)	$12 billion (2020) $150 billion (2030)	$19 billion (2020) $102 billion (2030)	$6 billion (2020) $621 billion (2030)
Major providers	Alphabet, Amazon, IBM, Microsoft, Alibaba and Tencent	Accenture, TCS, IBM, EY, Capgemini, HCL and Cognizant	Amazon, Microsoft, IBM, Google, Oracle, SAP and HP	Alibaba, Amazon, IBM, Microsoft, Oracle and SAP	Stratasys, 3D Systems, Materialise NV, EOS GmbH and General Electric	ABB, Fanuc, KUKA, and Yaskawa (industrial robotics), Alphabet/Waymo, Aptiv, GM, Tesla (autonomous vehicles)	3D Robotics, DJI Innovations, Parrot, Yuneec (commercial) Boeing, Lockheed Martin, Northrop Grumman (military)	Ericsson, Huawei, Nokia, ZTE, Samsung, and NEC
Major users	Retail, banking, discrete manufacturing	Manufacturing, home, healthcare and finance	Banking, discrete manufacturing and professional services	Banking, process manufacturing and discrete manufacturing	Discrete manufacturing, healthcare and education	Discrete manufacturing, process manufacturing and resource industry	Utilities, construction and discrete manufacturing	Mobile operators, industrial automation, manufacturing

Category:	Gene editing	Nano-technology	Solar PV	Wind energy	Green hydrogen	Electric vehicles	Biofuels	Biogas and biomass	Concentrated solar power
Publications	24 802	186 827	19 875	37 514	802	79 732	74,801	400,062	3,195
Patents	13 970	6 175	38 425	58 134	58	206 049	22,325	251,251	1,101
Price	$373,000 to $2.1 million for human genome editing therapies	$80 for 1mg gold nanoparticles	$2.94/watt	$0.053/kWh (onshore) $0.115/kWh (offshore)	$2.5-6/kg H2	$46,526 (average transaction)	Cellulosic ethanol: $4/gge HEFA: $3.70/gge	$0.030 to $0.140/kWh	$ 0.108/kWh
Market size	$5 billion (2020) $36 billion (2030)	$2 billion (2020) $34 billion (2030)	$180 billion (2020) $641 billion (2030)	$71 billion (2020) $175 billion (2030)	$1 billion (2020) $89 billion (2030)	$163 billion (2020) $824 billion (2030)	$6 billion (2020) $59 billion (2030)	$127 billion (2020) $210 billion (2030)	$42 billion (2020) $133 billion (2030)
Major providers	CRISPR Therapeutics, Editas Medicine, Horizon Discovery Group, Intellia Therapeutics, Precision BioSciences, Sangamo Therapeutics	BASF, Apeel Sciences, Agilent, Samsung Electronics, Intel	Trina, Canadian Solar, Jinko, Hanwha Q-Cell, SunPower	Vestas, Siemens Gamesa, Goldwind, GE, and Envision	Air Liquide, Air Products and Chemicals, Engie, Green Hydrogen Systems, Siemens, Toshiba, Tianjin Mainland Hydrogen Equipment	Tesla, Renault–Nissan–Mitsubishi Alliance, Volkswagen, BYD, Kia and Hyundai	Cosan, Verbio, ALTEN Group, Archer Daniels Midland, Argent Energy UK, REG, Cargill, Louis Dreyfus, and Wilmar International	Future Biogas, Air Liquide, PlanET Biogas Global, Ameresco, Quantum Green, Envitech Biogas, and Weltec Biopower	Abengoa Solar, S.A., Ibereolica Group, ENGIE, NextEra Energy Resources, and BrightSource Energy
Major users	Pharma-biotech, academia, agrigenomic	Medicine, manufacturing and energy	Residential, commercial and utilities	Agricultural, residential, utilities, industrial	Heavy industry, transportation, heating and power generation	Transportation, e-commerce, delivery	Transportation, heating and electricity generation	Industrial, transportation, residential and electric power generation	Industrial, commercial and residential

Source: See Annex A.

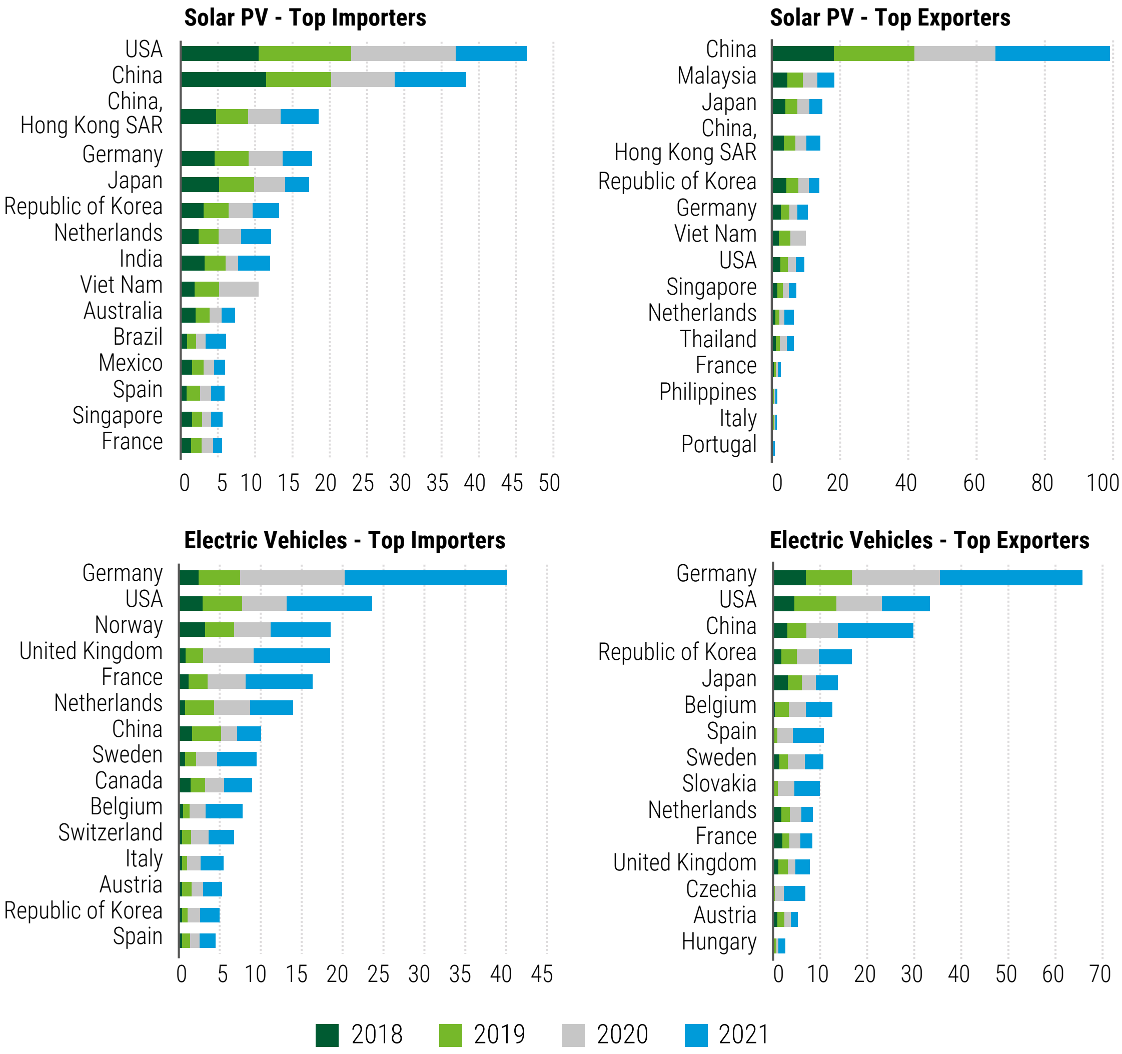
Notes: Publication and patent data are from the period 2000-2021. Market size data are rounded.

3. TRADE EXPANSION

One of the main channels for innovation transfer is trade. This can happen through the imports of capital goods as well as contact with export markets which favours learning-by doing and increases the scope for imitation.[49] Figure II-7 illustrates the increases in trade for solar PV and electric vehicles. For example, the exports of electric vehicles of the top 15 exporter countries jumped from $ 28 billion in 2018 to $ 105 billion in 2021. Considering green technologies, total exports of developed economies jumped from around $ 60 billion in 2018 to over $ 156 billion in 2021, while imports went from $ 89 billion to $ 188 billion. In the same period, exports of developing countries increased from $ 57 billion to $ 75 billion, while imports jumped from $ 48 billion to 63 billion.

Figure II 7

Technology imports and exports by top countries, 2018-2021 ($ billions)



Source: UNCTAD.

Note: Viet Nam's values for 2021 were not available. Imports and exports of solar PV refer to "Photosensitive photovoltaic LED semiconductor devices" classified under HS 854140, "Polysilicon" classified under HS 280461 and "Luminaires and lighting fittings: Photovoltaic, designed for use solely with light-emitting diode (LED) light sources" classified under HS 940541. Imports and exports of electric vehicles refers to electric motorcycles classified under HS 871160, electric cars classified under HS 870380, electric tractors/trucks classified under HS 870124 and hybrid cars classified under HS 870360 and HS 870370. All values represented are in current USD.

Among the developing countries, trade is greater for solar PV, following the drop in prices between 2010 and 2015, with an average reduction of 65 per cent in the expense of employing utility-scale solar PV.[50] Market expansion has translated into further efficiency-led cost reductions, opening up more options for developing countries.

Developing countries have less trade in EVs than in solar PV. This could reflect the fact that the former is a less mature technology, as explored in greater levels of detail in Chapter 3. In general, more immature technologies require greater efforts in terms of science and R&D, which tends to be lower in developing economies, as shown previously. There are also cost and infrastructure-related barriers to the broader EV adoption in developing economies. In addition, for oil-reliant countries, EV trade has been limited by the political economy of fossil fuels and the transition to renewables needs a nuanced approach that balances sustainability with economic stability and poverty alleviation.[51]

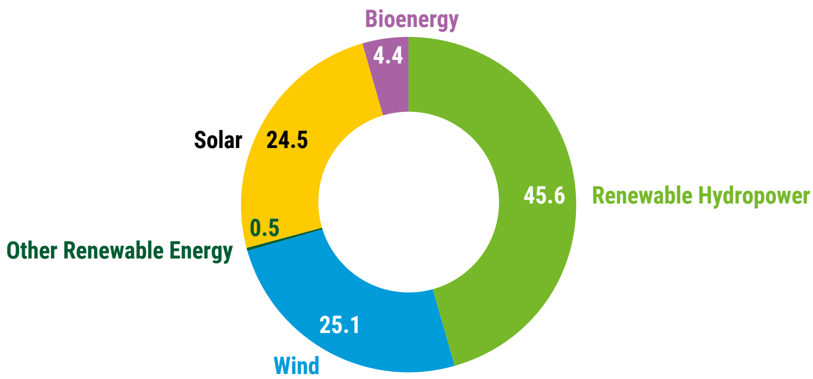
B. THE EXPANSION OF GREEN FRONTIER TECHNOLOGIES

Economies that depend on fossil fuel imports will need to move towards renewable energy sources that allow for greater energy autonomy and self-sufficiency, especially given the recent increase in energy prices due to geopolitical events. These same forces also push the faster adoption of electrified transport than previously anticipated.

As indicated in Figure II-8, installed capacity of renewable energy is dominated by wind and solar.[52]

Figure II 8

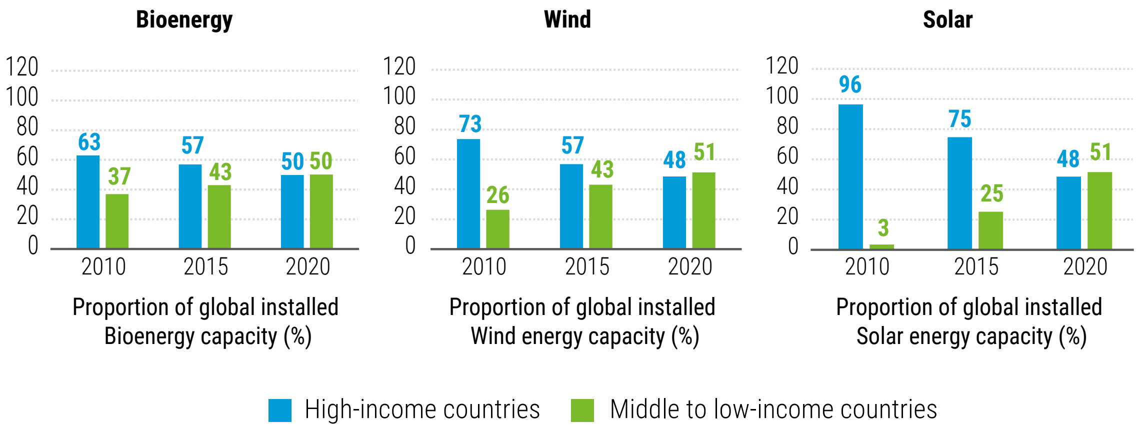
Installed renewable energy capacity, 2020 (percentage of world total)



Source: UNCTAD based on IRENASTAT (2021).

Figure II-9 compares the positions for country groups for bioenergy, solar PV, and wind.[53] Between 2010 and 2020, the installed capacity for all three sources increased in middle- and low-income countries which now host over 50 per cent of total installed capacity – with a notable growth in the share for solar energy, which grew from 3 to 51 per cent.

Figure II 9
Installed renewable energy capacity by regions (percentage of world total)

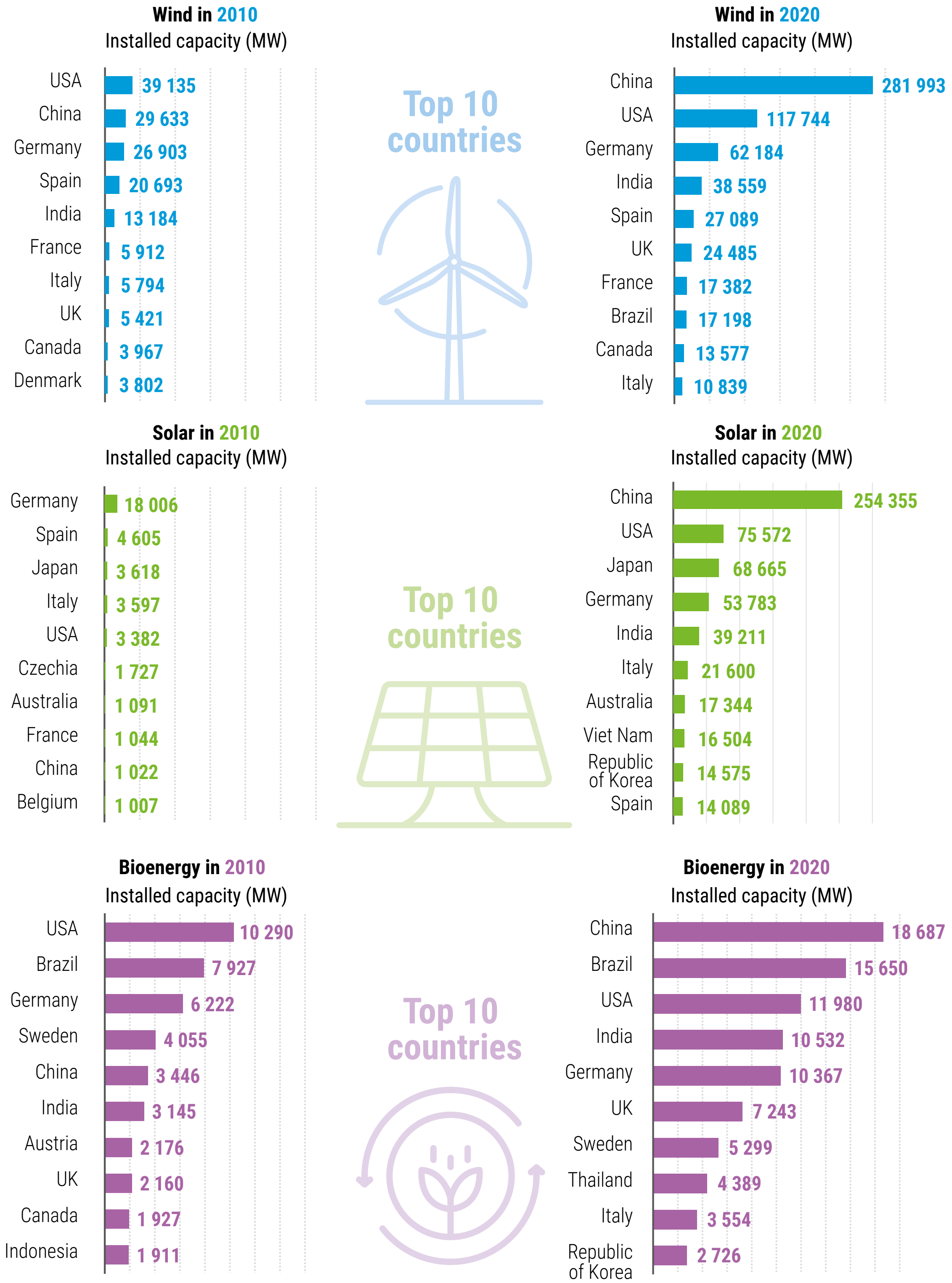


Source: UNCTAD based on IRENASTAT (2021).

These expansions are mainly driven by China, which is now the leading country globally, and is being joined by lower-middle-income countries such as Viet Nam and India, and upper-middle-income countries like Brazil and Thailand. With Africa possessing the world's greatest renewable energy capacity potential, estimated to reach 310GW by 2030, there is scope for significant progress if encouraged by public policy. Figure II-10 shows the distribution of installed capacity for bioenergy, solar and wind, indicating the increasing participation of developing economies. Given political will, there is scope for significant progress, with the prospect of greater energy security and many new jobs.[54]

Figure II 10

Top 10 countries in renewable energy sectors according to installed capacity (MW), 2010 and 2020



Source: UNCTAD based on IRENASTAT (2021).

As EV and green hydrogen are the most recent markets, they are examined in greater detail in the following sections.

1. GREEN HYDROGEN

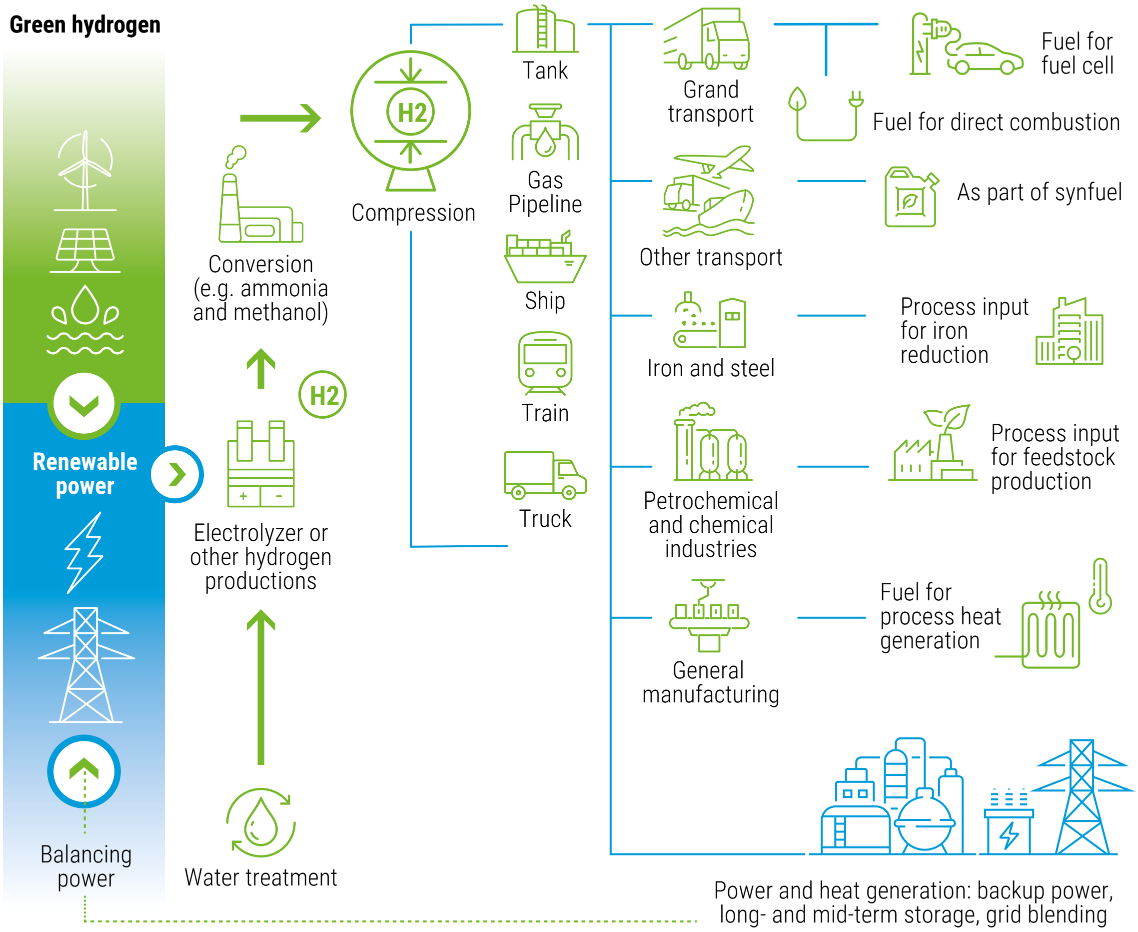
Green hydrogen, also called clean hydrogen, refers to hydrogen produced through the electrolysis of water, using energy sourced from renewables. When used as a fuel, hydrogen releases nearly three times as much energy as the same weight of gasoline and nearly seven times than the same weight of coal.[55]

Green hydrogen has a number of advantages and is gaining momentum. It can be stored for long periods and unlike solar or wind can be provided more easily and flexibly to meet consumer demand. Nonetheless, the market is still incipient, and represents only four per cent of global hydrogen production.[56]

Green hydrogen can be used for vehicle fuel, petroleum refining, metal processing, fertilizer production, and food processing. Hydrogen also represents the 'missing piece' in the energy transition because it can be employed in hard-to-abate sectors such as cement and steel that cannot use electricity from intermittent supplies from solar or wind. Moreover, green hydrogen can be converted to feedstock and to chemicals such as ammonia and methanol, which are easier to store and transport than regular electricity (Figure II-11).[57]

Figure II 11

The value chain of green hydrogen from inputs to production to final use



Source: UNCTAD.

Nevertheless, green hydrogen faces a number of barriers, notably cost and the immaturity of the technologies, many of which are not ready for widescale commercialization, as for example with gas turbines. There is also significant energy loss along the production chain, making the process more energy intensive. There are fears regarding the availability of renewable energy to meet the needs of increasing green hydrogen production as this sector's demand for renewable energy could reach 21,000 MW by 2050, which is almost as much electricity as is produced globally today. There are also uncertainties about regulation and infrastructure.[58] Most of these barriers are not structural, and could in principle be mitigated by innovation, which might, for instance, improve the energy efficiency of green hydrogen. At the same time, increasing prices for fossil fuels could make green hydrogen more competitive for certain uses. Furthermore, much of the world's existing natural gas infrastructure can be converted for use with hydrogen,[59] and there are efforts to establish regulations and standards (Box II-2).[60] Carbon pricing will also have an effect.

Developing economies could become net exporters of green hydrogen. Europe is expected to be unable to satisfy its own demand as it will exceed the ceiling of its renewable energy production capacity and may thus become a net importer, mainly from Africa and the Middle East which have the highest technical potential (Table II-3).[61] Nonetheless, this potential is no guarantee of successful production, and countries must foster the necessary framework and infrastructure.

Table II 3

Technical potential for producing green hydrogen at less than $1.50/kg (in exajoules) by 2050

Sub-Saharan Africa	Middle East	North America	South America	Oceania	Asia	Europe
2 715	2 023	1 314	1 114	1 272	960	88

Source: IRENA (2022).

Box II 2
Green hydrogen standards and regulations

A global certification system is an important step to the commercialization of green hydrogen, signalling compliance with regulation and production criteria, and allowing consumers to differentiate green hydrogen from grey hydrogen (produced with fossil fuels) and blue hydrogen (produced with natural gas). This opens the possibility of companies acquiring this hydrogen and willing to pay a premium for clean sources. There are several green hydrogen standards already in place:[62]

- *TÜV Süd* – Has a green hydrogen standard for the transport and the industrial sectors (CMS 70), basing it on European legislation.
- *ISCC PLUS* – ICC is a multistakeholder initiative recognized by the EU, which offers voluntary certification, ISCC PLUS, for bio-based and recycled raw materials for all markets and sectors not regulated as transportation fuels under the European Renewable Energy Directive or Fuel Quality Directive.
- *Zero Carbon Certification Scheme* – Launched in 2020 for hydrogen and its derivatives by the Smart Energy Council, an Australian NGO.

However, the criteria in these standards vary substantially, which creates difficulties in harmonising them to constitute a global certification system.[63]

Governments have also been enacting regulations and strategies and plans. Examples include:

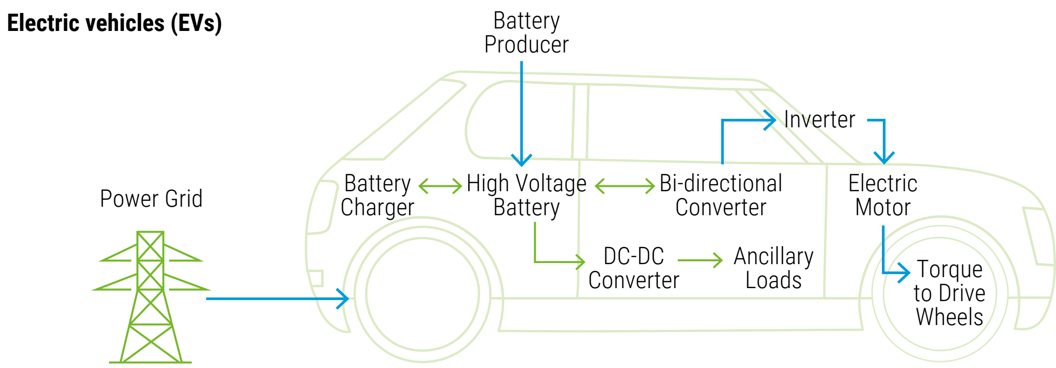
- *Renewable Energy Directive II* – Launched in 2022 by the EU, this considers renewable fuels of non-biological origin as those produced based on renewable energy (wind, solar, geothermal, ambient energy tide, wave or other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas) as electricity sources for production. It adds that the renewable energy source has to come in operation after or at the same time as the unit generating the fuel and is either not connected to the grid or connected but providing evidence that the electricity was supplied without decreasing the electricity in the grid.[64]
- *Low Carbon Fuel Standard* – Launched in 2011 by the state of California, in the United States, this allows three possible ways to produce renewable hydrogen: (i) through electrolysis using renewable energy, (ii) via catalytic cracking or steam methane reforming based on biomethane, or (iii) through the thermochemical conversion of biomass.[65]
- *Inflation Reduction Act* – Implemented in 2022 by the United States, this seeks to stimulate the production of clean hydrogen through tax credits – increasing the benefits as emissions decrease – and considering GHG emissions throughout the lifecycle. Clean hydrogen is defined according to emissions thresholds, with the highest benefit being for production that emits less than 0.45 kg of CO_2 per kg of hydrogen.[66]

Source: UNCTAD.

2. ELECTRIC VEHICLES

The technology employed in EVs present different benefits. EVs use one or more electric motors for propulsion. They can be powered by a collector system, with electricity from extra-vehicular sources, or autonomously from a battery, and will have an electric motor, inverter, boost converter, and an on-board charger (Figure II-12).

Figure II 12
Main components of an electric vehicle

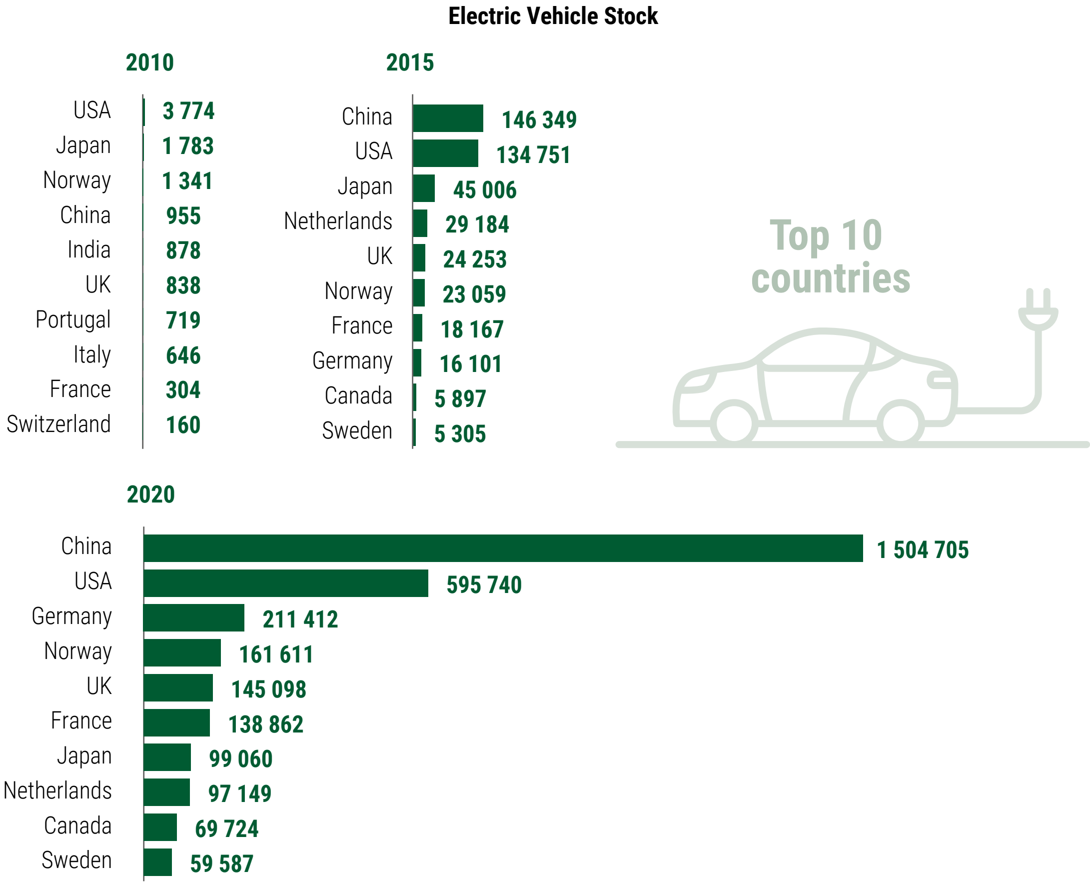


Source: UNCTAD.

As energy-consuming technologies, EVs create new demands for electricity that can be supplied by renewables. In addition to the benefits of this shift, such as reducing carbon dioxide 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. However, the market expansion for this technology might require infrastructure adaptations to enable sufficient power stations. For example, in Europe, the current system is considered to be able to cope with the complete replacement of the car fleet for EVs.[67] But this is not necessarily the case in other regions. In terms of diffusion, electric cars are less common in developing than in developed economies. In 2010, only two developing economies were among the top ten countries in terms of EV stock.

By 2015, China had managed to reach first position in this ranking, but India had dropped out. India, Indonesia, and Brazil have demonstrated that while low- and middle-income countries can support two-wheeler EVs, they may not yet have policies for a full-scale transition to electricity-powered transportation.[68] This is a missed opportunity to generate growth in other sectors. Electric mobility offers great opportunities to create synergies with other technologies particularly by increasing the demand for renewable energy. EVs can also provide decentralized storage for variable sources of renewable electricity through their batteries.

Figure II 13
Top ten countries: electric vehicles stock 2010-2020



Source: International Energy Agency (IEA) – Global EV Data Explorer (2022).

C. READY TO ACT

If developing countries are to capture the economic gains associated with new technologies, their firms must have the required capabilities to enter new and growing sectors while their governments need to establish the necessary policies, regulations, and infrastructure to support them. To assess national preparedness to equitably use, adopt and adapt frontier technologies, this report presents the 2022 readiness index that combines indicators for ICT, skills, R&D, industrial capacity and finance (Table II-4).

The readiness index ranking is dominated by high-income economies, notably the United States, Sweden, Singapore, Switzerland, and the Netherlands. Emerging economies are primarily found in the second quarter of the list – notably Brazil is ranked at 40, China at 35, India at 46, the Russian Federation at 31, and South Africa at 56.

Table II 4

Readiness towards the use, adoption and adaptation of frontier technologies, selected countries

	Rank in 2022	Rank in 2021	Movement in rank	ICT ranking	Skills ranking	R&D ranking	Industry ranking	Finance ranking
Top 10								
United States of America	1	1	–	11	18	2	16	2
Sweden	2	4	▲	6	2	16	11	18
Singapore	3	5	▲	7	8	17	4	17
Switzerland	4	2	▼	21	13	12	5	5
Netherlands	5	6	▲	4	9	15	10	31
Republic of Korea	6	7	▲	15	26	3	9	7
Germany	7	9	▲	24	17	5	12	40
Finland	8	17	▲	22	5	21	20	30
China, Hong Kong SAR	9	15	▲	9	23	29	2	1
Belgium	10	11	▲	13	4	23	19	48
Selected transition and developing economies								
Russian Federation	31	27	▼	43	32	13	54	69
China	35	25	▼	117	92	1	8	4
Brazil	40	41	▲	50	55	18	51	57
India	46	43	▼	95	109	4	22	75
South Africa	56	54	▼	71	77	36	67	25

Source: UNCTAD (see the complete table in Annex B).

Countries in Latin America, the Caribbean, and Sub-Saharan Africa are the least ready to use, adopt, or adapt to frontier technologies and are at risk of missing current technological opportunities.

Compared to the initial index in 2021, there are several economies with notable changes in their 2023 rank. Finland and China, Hong Kong SAR, for example, increased their position significantly due to increases in their human capital, notably the increase of high-skill employment.

Furthermore, among the emerging economies, Brazil was able to improve its position despite slower industrial activities, due to increase in ICT development. Meanwhile, China's lower-than-expected position in the ranking when compared with its productive and innovative capacity in frontier technologies is due to urban-rural disparities in Internet coverage and broadband speeds (Box II-3).

Box II 3
Download speeds in China

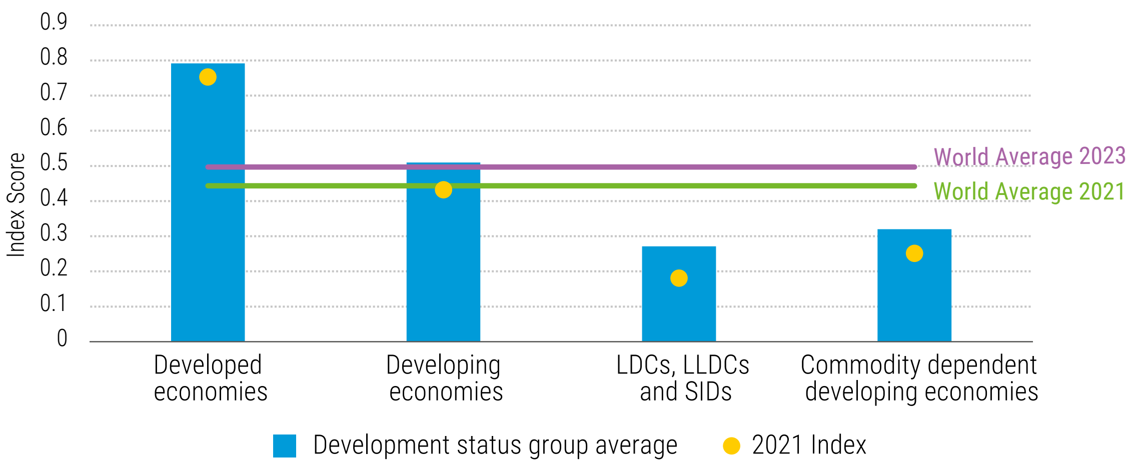
China's position in the 2022 Index can be partially explained by its changing position in the ICT ranking. In the 2022 Index, China had an ICT rank of 117, compared to its ICT rank of 99 in the 2021 Index. This change was largely driven by China's mean download speed (Mbps), which was slower relative to its peers according to data collected from M-Lab. Some reasons for this might include:

- The wide urban-rural disparities in Internet access, with Internet coverage comparable to Portugal and Poland in urban areas and similar to Cambodia and Côte d'Ivoire in rural areas.[69] There are also stark differences in broadband penetration and Internet speed across the different provinces in China. According to a 2021 report by the Chinese organization Broadband Development Alliance, provinces in the West continue to experience much lower Internet speeds than Eastern provinces. This might drive down average broadband speeds in China.
- China's system of Internet firewalls decreases the network performance and download speed of content from many non-Chinese sites.[70] Internet speed is negatively affected as incoming and outgoing traffic is routed through a limited number of access points which increases latency, while Deep Packet Inspection is used to monitor the Internet which might cause packet loss.[71] As a result, while Internet speeds might be significantly higher for accessing content hosted on in-country servers, poorer performance might be reported if downloads were attempted from sites behind firewalls.
- Internet speeds decreased during lockdowns globally, with China experiencing the highest percentage loss in speed (52 per cent) of all the countries studied.[72] One explanation for this is that lockdowns generate Internet congestion due to higher online traffic as people increasingly work and study from home.[73] If this were the case, given that lockdowns persisted in China through 2021 while they were lifted in other parts of the world,[74] China might have experienced relatively lower Internet speeds in 2021. However, it should be noted that a variety of Internet speed rankings exist apart from M-Lab, including Ookla, SpeedTestNet.io, and BandwidthPlace.com. These rankings adopt different methodologies and assumptions in calculating broadband speed, leading to a range of estimations of the Internet speed of any given country.

Source: UNCTAD.

Since 2021, the overall value of the index has increased by 14 per cent, from 0.44 to 0.50 points. For developed economies the average is 0.80 points; for developing economies 0.50 points; for LDCs, LLDCs, and SIDS 0.28 points; and for commodity-dependent economies 0.32 points. The gaps between these groups are wide, but they are starting to narrow.

Figure II 14
Average index score by development status



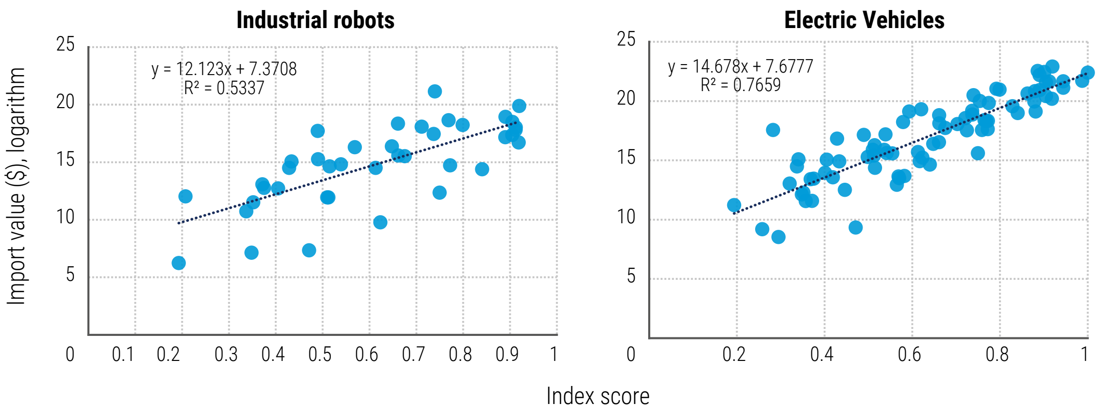
Source: UNCTAD.

Having low index scores suggests a lack of the foundational capacity to take full advantage of green windows. Countries with a lower readiness index will face greater challenges as they seek to revitalize their transport systems, shifting away from fossil fuels and reducing CO_2 emissions in line with Paris Agreement Nationally Determined Contributions. The EVs market, for instance, shows a strong correlation between a country's readiness index and the total value of imports of electric vehicles (Figure II-15). Developed economies with very high index values have advanced infrastructure and highly skilled populations, as well as access to the finance to purchase EVs (Figure II-16).

It is important to note that there is no causal relationship between the index and trade activities. In other words, achieving a higher index does not necessarily lead to an increase in trade activities as measured by import, or vice versa. Robotics that are commonly used in industry 4.0, for instance, have a positive and significant correlation between the index value and imports of the goods (see Figure II-15). However, for the last five years, the imports of this industrial robots have been constantly higher in developing than in the developed economies (see Figure II-16). It is interesting to note that the COVID-19 pandemic has affected the global distribution which caused a slowing down of the import of industrial robots in 2020 before picking up again in 2021.

Figure II 15

Correlation between the index score and the adoption of selected frontier technologies, 2021

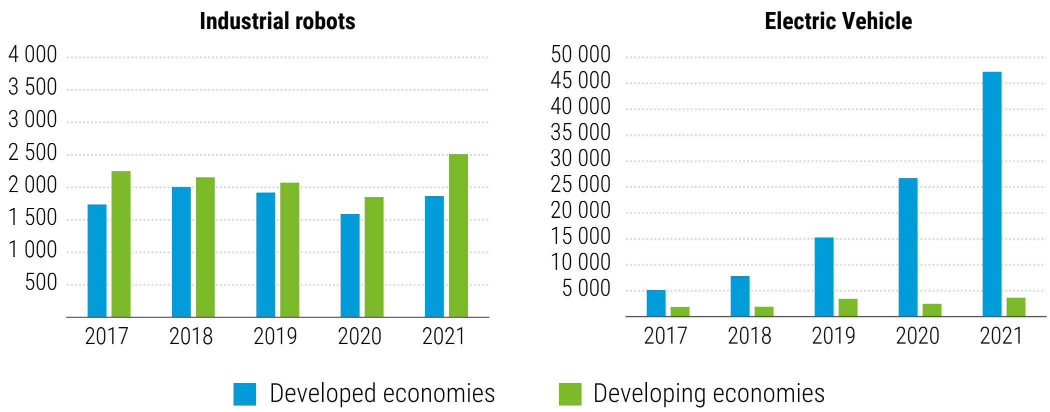


Source: UNCTAD based on data from UN COMTRADE and IRENA, 2022.

Notes. Import of electric vehicles refer to "Vehicles, with only electric motor for propulsion" classified under HS 870380. Import of industrial robots refer to "Machinery and mechanical appliances: industrial robots, n.e.c. or included" under HS code 847950. The correlation in the three graphs is statistically significant at 0.01 level (p <,001).

Figure II 16

Import value of selected frontier technologies ($ millions)

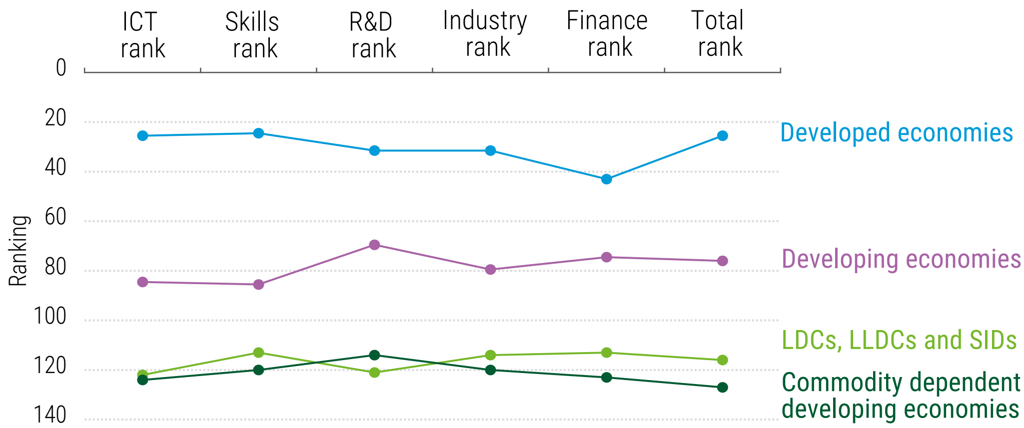


Source: UNCTAD based on data from UN COMTRADE.

The index highlights areas that need to be improved to enable greater use, adoption, and adaptation of frontier technologies. Overall, developing countries as a group, and even the top five developing countries, have lower rankings for ICT connectivity and skills (Figure II-17). LDCs, LLDCs, and SIDS rank lower than 100 in all the building blocks, with particular deficiencies in ICT infrastructure and in research & development.

Figure II 17

Average index ranking by building block (selected country groupings)



Source: UNCTAD.

The readiness index highlights areas in which countries need to improve – to place themselves better in the race to develop new sectors and establish themselves as leaders. However, a high value for the readiness index does not necessarily mean the country will be able to open the green windows for frontier technologies, as this also requires appropriate policies and investments.[75] The following chapter shows how this has been working out in practice for green industries in developing countries.

[1] Rodrigues et al., 2022

[2] Ahmadi et al., 2019; Zang, 2011; Hussein, 2015

[3] UNCTAD, 2021a

[4] Persistence Market Research, 2022

[5] Data estimates from Chui et al., 2021; Precedence Research, 2022a; Allied Market Research, 2022a; Research and Markets, 2021; Valuates Reports, 2022; Lux Research, 2021; Precedence Research, 2021; Allied Market Research, 2021c; Allied Market Research, 2021a; Prophecy Marketing Insights, 2022; Next Move Strategy Consulting 2020; Allied Market Research, 2021b; Precedence Research, 2022c; Precedence Research, 2022d; Allied Market Research, 2022c; Precedence Research, 2022b; Allied Market Research, 2022b

[6] Abraham et al., 2021; Buntz, 2020

[7] Froese, 2018; Lueth, 2018

[8] McKinsey & Company, 2018; PwC, 2017a

[9] West and Allen, 2018

[10] Amankwah-Amoah et al., 2021; UNCTAD, 2021c; McKinsey & Company, 2020a

[11] UNCTAD, 2021b

[12] UNCTAD, 2021c

[13] PwC, 2021

[14] McKinsey & Company, 2018; Chui et al., 2021

[15] Kandaswamy et al., 2018.

[16] Frey and Osborne, 2017; McKinsey Global Institute, 2017; PwC, 2018; Maddison, 2001

[17] For example of empirical and theoretical research supporting the labour-friendly nature of frontier technology product innovation, see Vivarelli, 2014; Dosi et al., 2021; Barbieri et al., 2020; Vivarelli, 2022; Damioli et al., 2022. Frontiers technologies may also have adverse labor market impacts; in this respect, see for example Montobbio et al., 2022; UNCTAD, 2021a. See also Forbes, 2022a

[18] UNCTAD, 2021a

[19] Alekseeva et al., 2021

[20] Bright Outlook, 2022

[21] Konkel, 2021

[22] The Blockchain Academy, 2021

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

[24] Radovic, 2019

[25] Mandel and Long, 2020

[26] Campbell et al., 2017

[27] Kearney, 2017

[28] Hasan, 2022

[29] Hiter, 2021

[30] CareerExplorer, 2020a

[31] Grad School Hub, 2020

[32] IRENA, 2021a

[33] U. S. Department of Energy, 2021

[34] IRENA, 2021a; Ravillard et al., 2021

[35] IRENA, 2021a

[36] Chamberlain, 2018 and 2017

[37] IRENA, 2021a

[38] Sooriyaarachchi et al., 2015

[39] IRENA, 2021a

[40] Global Wind Energy Council, 2021

[41] IRENA, 2021a

[42] Pek et al., 2018

[43] UC Berkeley and GridLab, 2021

[44] CareerExplorer, 2020a

[45] Thompson, 2017

[46] Bureau of Labor Statistics, U.S. Department of Labor, 2019a

[47] Ministry of Industry and Information Technology of the People's Republic of China, 2021

[48] Konaev and Abdulla, 2021

[49] Hoppe, 2005

[50] IEA, 2016

[51] Dioha et al., 2022

[52] Annex C shows that renewable hydropower represents an important share of the total installed capacity. The industry is not included in the present study for several reasons. There is an ongoing discussion about how "green" the hydropower sector really is. The proponents of the hydropower sector argue that it is a renewable, low carbon energy technology that is crucial for mitigating climate change. However, hydropower opponents argue that large hydropower has large-scale and irreversible environmental impacts including ecosystem destruction, geomorphological changes, hydrological changes, impacts on aquatic species, habitat, and biodiversity loss. Besides, it is an industry characterized by large economies of scale and fully dominated by China, where about half of the world's large dams are based. For an interesting account of how China has gained market and technological leadership in the sector see Zhou et al., 2021. See also Hamilton et al., 2020.

[53] Based on the World Bank classification.

54 African Development Bank, 2019; Nasirov et al., 2021

55 Skyllas-Kazacos, 2010

56 IRENA, 2020

57 IRENA, 2022a

58 IRENA, 2022a

59 UNIDO, 2022

60 German Energy Agency/World Energy Council, 2022

61 van Renssen, 2020

62 German Energy Agency/World Energy Council, 2022

63 German Energy Agency/World Energy Council, 2022

64 EU, 2018

65 German Energy Agency/World Energy Council, 2022

66 US Congress, 2022

67 Slednev et al., 2022

68 TRT Magazine, 2022

69 UNCTAD, 2021a

70 Normile, 2017

71 Schmitz, 2022; Geerts, 2018

72 M-Lab, 2022

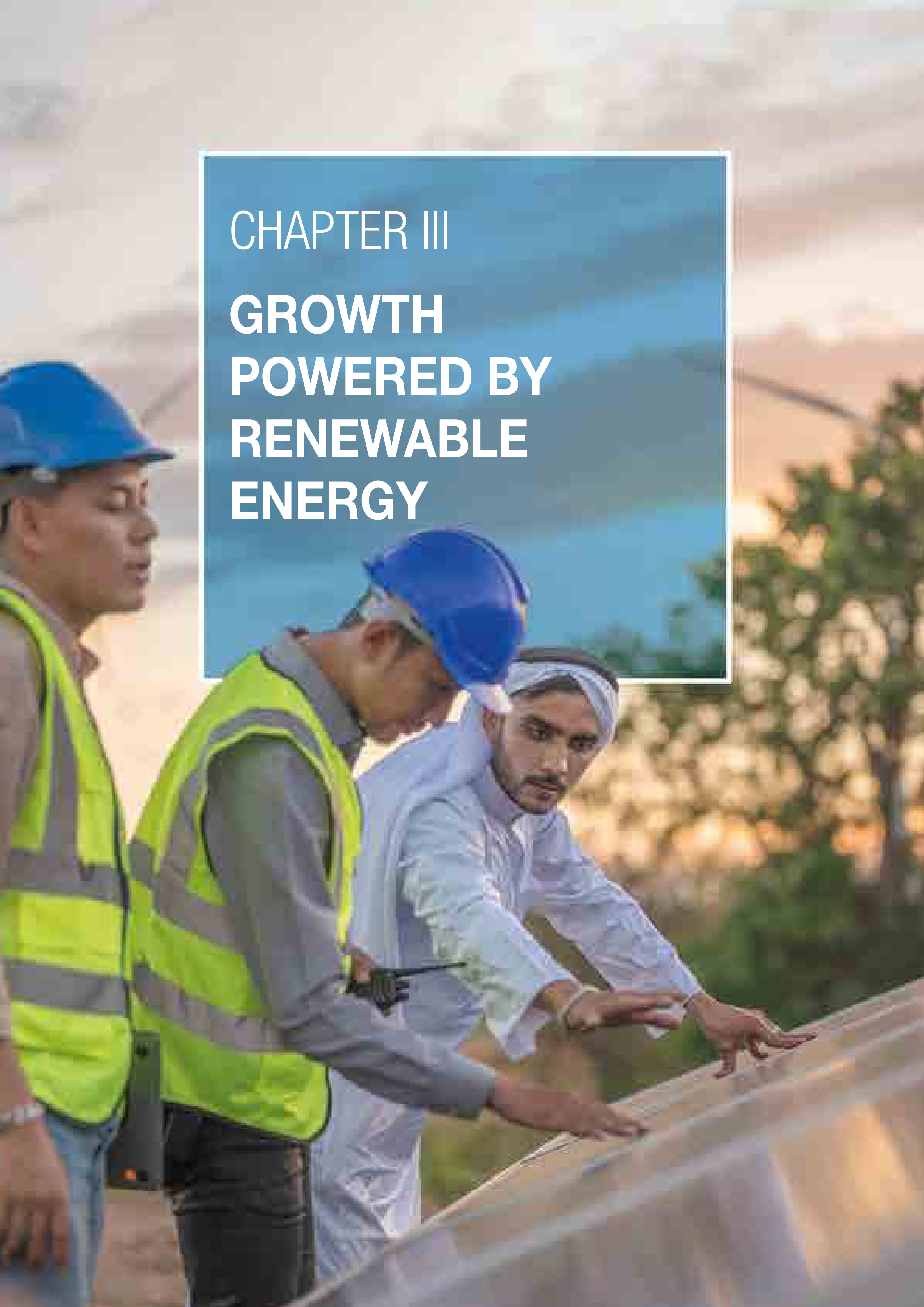
73 World Bank, 2020; Basso et al., 2020

74 *Financial Times*, 2022

75 *Brookings*, 2021

CHAPTER III

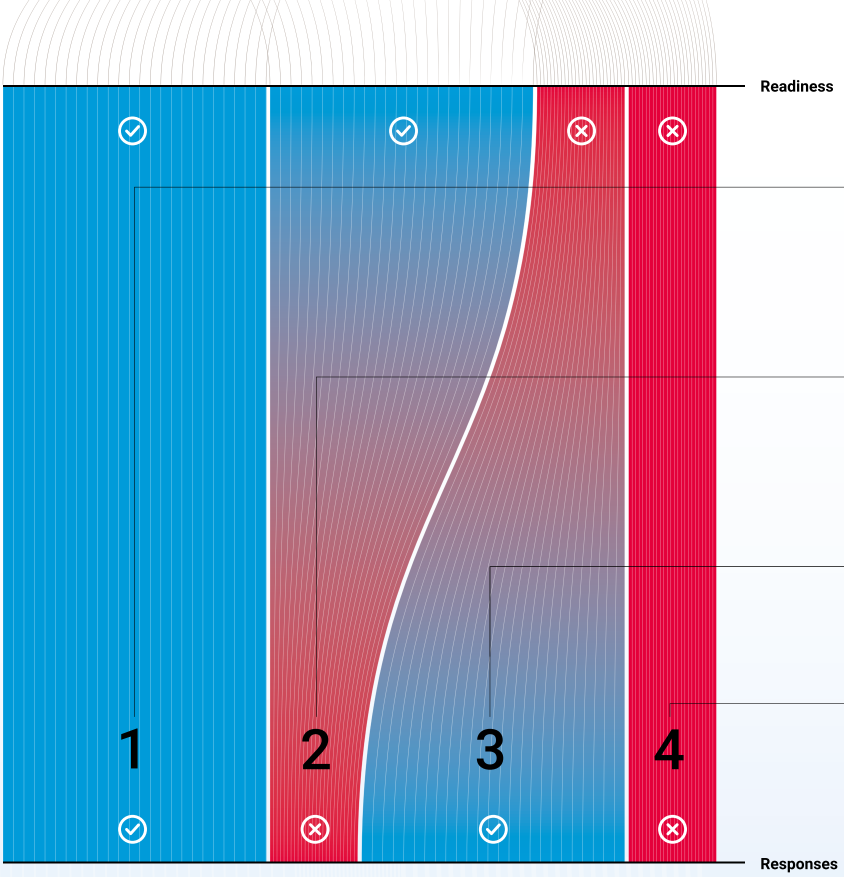
GROWTH POWERED BY RENEWABLE ENERGY



Combining strong initial conditions and strong responses make up the best scenario to seize GWOs but weak conditions can be compensated by strong efforts

There is no unique way of catching up but it does not happen without strong government effort.

The initial conditions in a sector do not make seizing its GWOs automatic or impossible - they are influenced by government action



Scenario:

Windows open
Solar PV, Biomass, CSP: China
Bioethanol: Brazil
Hydrogen: Chile *(potentially)*

Windows to be open
Solar PV: India
Biogas: Bangladesh
CSP: Morocco
Wind: China

Windows within reach
Biomass: Thailand and Viet Nam
Hydrogen: Namibia

Windows in the distance
Wind: Kenya
Bioenergy: Mexico and Pakistan

The maturity and tradability levels of technologies affect GWOs

- **Immature technologies** require stronger initial conditions in science and R&D
- **Mature technologies** tend to entail more market competition
- **Tradability** involves different dimensions that influence the competitive dynamics and modes of technological learning

Benefiting from GWO requires opening and augmenting them and enhancing relevant capabilities

Countries have employed policies like human capital attraction, government-created demand, and local content requirement to create and take up GWOs

GWOs develop over time, so the strategies and initiatives need to adapt

This chapter examines developing country experiences in producing, distributing, and using renewable energy technologies – bioenergy, solar and wind energy, and green hydrogen. The depth and speed of latecomer development vary according to sector. Mature sectors such as biomass or solar PV have readily available technologies and can provide a relatively fast track to boosting economic activities. But new technologies such as green hydrogen, concentrated solar power (CSP), or electric vehicles are more demanding in terms of developing new technological capabilities and require significant investment in innovation systems.

In most countries the speed of development is driven by national ambitions to generate economic growth, mitigate climate change, transform energy production and consumption, electrify rural communities, or increase energy security. As the same time, there are international and global pressures to diffuse green investments and establish promising new markets.

Each country needs to identify opportunities in specific stages of the value chain and orient research and development as well as education and training to build domestic capacity; even the more mature technologies that are easily imported can be adapted to the local context. Some countries start with natural advantages such high levels solar radiation, but these do not automatically offer opportunities for latecomer development. The key to generating growth through the green transition is to foster the necessary capabilities and respond to opportunities as they arise.[1, 2]

A. OPENING GREEN WINDOWS IN DEVELOPING COUNTRIES

The presence of Green Windows of Opportunity – favourable but time-bounded conditions for latecomer development associated with sustainable transformation (Chapter 1) – is specific of each technology and its characteristics depends on the related institutional, market, or technological changes. The following sections examine the experiences of some developing countries in producing, distributing, and using renewable energy technologies: bioenergy, solar and wind energy, green hydrogen, and electric mobility. Additional cases, in bioenergy, concentrated solar power, wind energy, and electric vehicles are presented in Annex C.

1. SOLAR PV

China

China has 254 GW of installed capacity in solar PV.[3] It has established this world-leading position by supporting a domestic production and innovation system that combines public and private business actors as well as by supporting and regulating research institutions (Box III-1). The 2006 Renewable Energy Law encouraged Chinese firms and research institutes to collaborate with foreign partners which enabled them to enter international markets. A key programme was the Thousand Talents Plan aimed at recruiting global experts and attracting the return of prominent Chinese researchers in PV cell technologies.[4, 5]

Local firms, universities, and industry associations[6] engaged in a progressive catch-up across the whole PV industry, starting from portable lightning devices, then moving to solar PV panels and ultimately creating a domestic cell and wafer industry with the technological capabilities to produce polysilicon, previously imported from the United States. China also started producing power devices such as inverters.[7]

Overseas sales suffered a setback with the 2008 financial crisis. Germany and several other countries reduced their PV subsidy programmes, which caused a considerable drop in demand and, consequently, prices. In reaction, the Chinese Government boosted domestic demand, through for example, the Concession Programme for Large-Scale Solar PV Power Plants, the Solar Rooftop Subsidy Programme, and the Golden Sun Demonstration Programme, offering subsidies of up to 70 per cent of total investment.[8] In this period the sector also benefited from intense interactions among leading firms.

Box III 1

How China came to dominate the global PV market

The 2008 financial crisis was a blow to China's overseas PV exports. After that, the State sought to transform local demand and supply of its PV sector. Supported by national policies, the PV industry promoted cooperation across the value chain and intensified technological innovation. In 2013, two leading enterprises agreed to procure each other's products. Yingli agreed to purchase silicon materials and wafers from GCL-Poly Energy while GCL-Poly Energy procured components and modules from Yingli to construct solar PV stations.

Later, five state-owned enterprises collaborated on attracting investment, project management, integrated construction, R&D, training, hardware maintenance, and setting the standards. With the support of the Central Bank, the industry partnership gained collective advantages globally along the whole value chain.

In the Talatan area of Gonghe county in northwestern China, thanks to the Concession Program for Large Scale Solar PV Power Plants, herds of sheep scamper through the blue 'forest' of solar PV panels and graze in the pasture below. The solar panels not only collect sunshine they bring water to the soil underneath from monthly washing, producing quality forage for livestock farming.

Meanwhile Qiejuntai, a villager in Gonghe county, now makes a living from both the solar industry and husbandry, obtaining an income of over 10,000 euros each year.[9] According to China Global Television Network, as of the end of 2020, 100,000 villages across China had installed PV power stations, generating 18.65 million KW of electricity and bringing an annual income of about 27,000 euros to each village.[10]

Source: UNCTAD based on Xinhua News Agency, 2020 (http://www.xinhuanet.com/nzzt/135/) and CGTN, 2021.

Mexico

To build local demand for solar PV, the Government carried out a national auction, through which successful bidders were awarded contracts, or power-purchasing agreements that guaranteed the price per unit of electricity generated.[11, 12] In the Mexican approach, these clean energy auctions are technology-neutral, meaning that all clean energy sources compete. The competition is based on offered price and is driven by free-market cost competition, with no explicit aim of developing a domestic renewable energy industry. This auction design attracted large foreign developers and specialized vertically integrated renewable energy companies, but it offered limited scope for developing domestic capabilities across the value chain.

South Africa

South Africa has developed the Renewable Energy Independent Power Producer Procurement Program. As in Mexico, this is market-based with government purchasing renewable energy through a reverse auction system. In this case, however, the auctions are technology-specific and there are additional regulatory requirements to foster black economic empowerment, create jobs, include local content, and have 70 per cent community ownership.

This produced a different outcome.[13] The auction attracted a diverse set of international and local project developers, and the local content requirements engaged national engineering, procurement, and construction companies. However, technological upgrade was restricted by an initial shortage of semi- and skilled workers, combined with local content requirements.[14] In addition, the regulations were not well enforced, and loopholes enabled foreign developers simply to use warehouses in South Africa rather than set up production plants.

India

Instead of building up a domestic manufacturing capacity, the Indian national programme prioritized cheaper prices that would maximize installed capacity. It attracted large projects offering low tariffs and incentivised energy developers to rely on cheaper imports of solar cells and panels. In general, limited emphasis has been devoted to R&D and building up domestic and production capabilities. When local content requirements were introduced, there was insufficient domestic capacity to fulfil the supply[15].

In 2018, under pressure from domestic manufacturers, the Government introduced a safeguard duty against solar cell imports from China and Malaysia. However, this forced developers to buy more expensive panels and slowed down the bidding process – while offering few benefits to domestic manufacturers. If the manufacture of cells and panels is now out of reach, there are still opportunities in the service stages of the value chain and for manufacturing other components.[16]

Viet Nam

Viet Nam has rapidly expanded its solar energy installed capacity and is considered more successful than other ASEAN countries like Malaysia and Indonesia.[17] In 2015, the Government launched the National Strategy on Renewable Energy Development and followed this in 2020 by a Party's Resolution on the Orientation for National Energy Development. Measures included a feed-in-tariff, temporary tax exemptions for solar developers, and tariff exemptions for imported equipment. Viet Nam also has a favourable environment for foreign direct investment, and no local content requirements. These measures attracted foreign developers and created a large domestic market. In 2020, Viet Nam was the world's eighth largest market in terms of installed capacity. However, this did not build domestic production or technological capacity (Box III-2).

Box III 2
The Mekong 'power delta' with the sun

Countries in the Mekong Delta have relied in the past for electricity on hydropower. However, output has been affected by lower rainfall and less runoff,[18] as well as unsustainable upstream dam construction and farming patterns. Solar power is a promising alternative that takes advantage of the natural conditions. Solar power stations are being built in barren land, on farmlands, or on the river in Viet Nam, Thailand, and Cambodia.

Viet Nam – In southwestern Viet Nam, at the foot of Cam Mountain, in 275 hectares of barren land the domestic private sector has invested heavily in solar electricity and is expected to produce 400 million kWh. Together with eco-tourism, the solar business drives the local economy by creating jobs.[19] Because the existing publicly managed grid network has been unable to keep pace, the local provincial government has invested in a 500kV transmission line connecting An Giang with O Mon in Can Tho, the largest city along the Mekong Delta, in the 2021-2025 period.[20]

On farmlands in north-western Viet Nam in Sơn La Province, for example, a 100-square-metre solar-powered dry-house processes 1.5 tons of fresh bamboo shoots every three days and produces 120-150kg of dried product.[21] The availability of rooftop solar power avoids the need to burn firewood and thus enables farmers to receive higher incomes with less time, energy, forest degradation, and air pollution.

Viet Nam also has South-East Asia's first floating solar power generating system. Floating solar power projects (i.e., solar panels installed on the surface of reservoirs, industrial ponds, lakes or near-coastal areas), can re-use reservoirs built originally for hydro power and existing transmission infrastructure, increasing supply with almost no marginal costs.[22] The Da Mi project is operated by a national power company, Vietnam Electricity, using a feed-in-tariff of $9.35 per kilowatt-hour.

Cambodia –After failures in a few solar power projects,[23] the Government is nevertheless determined to exploit the solar potential.[24] It has recently approved a 60 MW solar farm in Kampong Chhnang Province, the first part of a 100-MW National Solar Park, as well as a 60-MW farm in Pursat.[25]

Thailand – In 2021, At Sirindhorn Dam in Ubon Ratchathani province, Thailand, the world's largest hydro floating solar farm went online in November 2021.[26]

Source: UNCTAD.

Kenya

In Sub-Saharan Africa, there is a rapidly growing solar PV market. More recently, the initiative has been taken by private companies facilitated by international finance. Domestic solar PV firms have been able to face up to international competition and have established themselves in different market segments, having moved from standalone installations to larger-scale plants; from distribution to installation; and from government tenders and donor projects to commercial contracts.[27] This could make Kenya a global hub for clean energy companies, particularly in small-scale decentralized energy generation and consumption. In some cases, upgrading has been the result of strategic networking with international actors and of investments in national capacities and skills.

Nevertheless, domestic companies continue to face significant challenges in the areas of finance, skills and policy, which prevent them gaining larger shares of the growing domestic market. To develop a well-functioning and coordinated domestic solar PV industry, they will need closer collaboration between the industry players and supporting institutions, such as the commercial banks, the training and academic institutions, the ministries and various public bodies.[28]

Ethiopia

The country has enormous potential in solar energy which could be used to privatize and decentralize the electric power sector through off-grid and mini-grid technologies.

Iran

Thanks to government commitment, solar PV is taking an increasing share of renewable energy production, but local industrial capacity remains very limited. Some factories are assembling the modules using imported raw materials – though there are plans to exploit the country's silica resources. At present the country does not have clear and implemented regulations and incentives to attract investment and encourage R&D.[29]

2. BIOFUELS

A wide range of biomaterials can be combusted to produce heat, converted to electricity, or processed into biofuels – ranging from agricultural and forestry residues, solid and liquid organic wastes – including municipal solid waste, sewage, and animal manure. Some crops can also be cultivated specially for energy, such as corn and soybeans (Figure III-1).

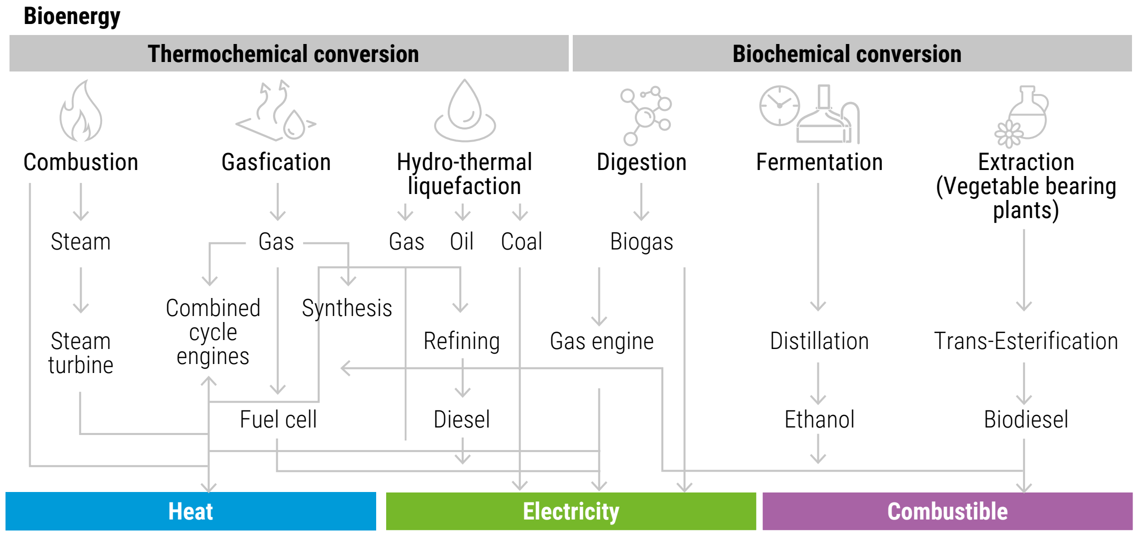
Liquid biofuels are convenient renewable substitutes for internal combustion engines running on gasoline, diesel or kerosene for use in road, sea and air transport. Apart from direct combustion, adequate energy utilization of biomaterials is also possible through high-temperature and pressure gasification, hydrothermal liquefaction converting biomass into crude-like oil, biochemical digestion, fermentation, and extraction (Figure III-1).

Bioethanol and biodiesel have opened opportunities within climate change strategies in a range of developing countries. This switch is particularly significant in countries with the potential for sugarcane production and other crops that do not compete directly with food production.[30]

While Brazil and other countries, such as Australia, developed biofuel industries based on sugar cane, many developing countries during the 2010s experimented with oil from palm or from the seed of the jatropha tree which can produce biodiesel or jet fuel. Jatropha has several favourable properties such as high yield and low water and fertilizer requirements, as well as high resistance to pests and the ability to thrive on marginal land without competing with food crops. After the turn of the millennium, many investors, governments, and NGOs highlighted jatropha as a promising opportunity.

According to multiple authors,[31] jatropha strategies have largely feel short from expected results. Countries like Mexico, India, China, Ethiopia, Mozambique, the United Republic of Tanzania, and Ghana did not meet their expectations regarding investments in this crop to use it as biofuel input to reap economic benefits consequent social gains like reduced poverty.[32] Governments and private investors adopted a "wait-and-see" stance, expecting that technological and land-use problems could be resolved but there were unexpected complexities, and most investment projects fell far short of initial prospects.[33]

Figure III 1
Processes for producing bioenergy



Source: UNCTAD.

Brazil

Brazil's success with bioethanol largely stems from government policy.[34] Experimentation with bioethanol started in the 1930s, but the current programme was largely a response to the oil crisis of the 1970s when OPEC placed an embargo on petroleum. The government has taken institutional efforts to increase the attractivity of the industry and develop the sector. Such efforts include for example the Sugarcane-based ethanol fuel program and the RenovaBio - Green Certificates for the production.

Brazil gradually developed its production system and knowledge base. The government also incentivised investments through programmes like BNDES' Climate Fund. As such, the country developed what became the most successful biofuel industry in the world so far. Since 1980, Brazil has reduced the far, cost of producing bioethanol by 88 per cent.[35] For comparison the United States has a long history of bioethanol production based on corn. But over the same period has reduced the cost by 60 per cent. Today, Brazil is the world leader both in terms of technology and usage of ethanol. Moreover, there is significant, yet unrealised, export potential[36] and Brazil has become the leading supplier of biofuels technology for the developed world.[37] There are also potential forward linkages. Brazil has for example, invented a flex-fuel engine for cars, enabling alternation between traditional and bioethanol-based fuels.[38]

Through its wide-ranging biofuel policy frameworks, Brazil has successfully stimulated both demand and supply,[39] and promoted learning by building productive and technological capacities of the private sector, research and development institutions and other related stakeholders.[40] Technologically it is now a leader in first-generation liquid biofuels and is pioneering new technology – drawing on first-generation capabilities to compete in the second-generation arena.

Today Brazil has around 30 per cent of the global market for ethanol. It has the largest fleet of flexible-fuel vehicles and fully supplies local gas stations where unblended fuel ethanol competes directly with gasoline. In addition, the country exports to a number of countries including the United States, the Republic of Korea, and the Netherlands.

In future, however, without a change in its innovation system Brazil may be unable upgrade to second-generation bioethanol based on food waste and crop residues which do not compete with food production.[41] The focus is still largely on sugarcane and Brazil's federal institutions are less committed to future technologies. At the federal level this is linked with the discovery of offshore petroleum reserves. If it does not respond to global technology changes, Brazil may thus experience a 'technological discontinuity trap'.[42]

Ghana

Ghana has focused on producing biofuels using jatropha. In 2006, to increase domestic demand the Strategic National Energy Plan and National Biofuel Strategy in 2006 enforced blends of gasoline and biodiesel at 5 per cent by 2010, and 10 per cent by 2015.[43] The National Jatropha Plantation Initiative has established 53 districts across the country to start pilot plantations on low-fertility agricultural land where they would not compete with food production.[44] The projects were strongly supported by NGOs and local 'jatropha champions.' Supported by GTZ, UNIDO, and UNDP, key firms and individuals made efforts to show-case jatropha biodiesel. Production also offered carbon credits through the clean development mechanism.[45]

However, the results fell far short of expectations. This was due to low yields and difficulties in ramping up production. Public R&D support was weak, with relatively little sharing of learning and a lack of the technical and managerial information needed to enter international markets.[46]

Ethiopia

The increasing number of sugar factories and the vast land suitable for growing feedstocks offer considerable potential for biofuels which could serve as alternative fuels for transport and cooking services. The country has been producing bioethanol from biomass for decades, but it supplies less than one per cent of power through this source.[47] Taking advantage of its potential for biofuel production would allow Ethiopia to decrease its dependence on fuel imports, and the country could explore difference sources such as sugarcane and jatropha. Nonetheless, there is a need to reform policies to provide greater support.[48]

The United Republic of Tanzania

Tanzania's sectoral system of innovation is unresolved.[49] By 2005 the system comprised a few loosely connected 'experiments' involving around 30 different actors in a grassroots-based organizational model. The system then evolved to a profit-driven model through which thousands of smallholder out-growers supplied jatropha seeds to a firm owning a centralized oil-processing facility.[50] In addition, transnational corporations established large plantations to export jatropha seeds to the West for processing. As in Ghana, initiatives were linked to foreign commercial investors or aid donors.[51]

India

India had an ambitious jatropha biodiesel development programme but many policy changes were not implemented, and production fell short of capacity. Public institutes did not carry out sufficient research on increasing yields, resulting in short-duration crops. A better approach would be to shift from jatropha to an approach using multiple types of feedstocks or inputs instead of jatropha alone, with a better system of incentives both at the feedstock and biodiesel production stages, and augmenting the efforts in research and development for increasing the yield from the feedstock. [52]

3. GREEN HYDROGEN

Hydrogen for energy can be produced in a number of ways, typically classified as black, brown, grey or green depending on the source of energy employed in its production. Black hydrogen uses coal or lignite as a source of energy, while grey hydrogen is created from natural gas, or methane, using steam methane reformation.[53] Green hydrogen, on the other hand, is made by electrolyzing water using electricity from renewable energy sources, such as solar or wind power (see Chapter 2 for a discussion of the status of green hydrogen).

Green hydrogen can reduce dependence on oil price volatility and supply disruptions, as well as lowering energy costs.[54] Since 2019, a number of European states have developed hydrogen strategies, including Austria, Denmark, France, Germany, Italy, the Netherlands, Norway, Portugal, the United Kingdome and Spain, as well as in Australia and Canada.

However, the most attractive sites for producing green hydrogen are in countries with abundant solar and wind resources – particularly in Africa, Southern Asia and the Western regions of South America.[55] There have been a number of initiatives in Brazil, Chile, Uruguay, Viet Nam, Türkiye, Morocco, Namibia and South Africa.[56] Most have relatively small domestic markets, but since green hydrogen can be transported over long distances by boat these countries can become significant exporters. For this, however they will need to improve their techno-institutional capacity and invest in electrolysers and infrastructure for storage and transportation.

Chile

Chile has ambitious climate targets with the expectation that, by 2030, 70 per cent of the power grid will use energy from renewable sources – capitalizing on solar in the north of Chile and wind in the south. In 2020 the Government published a three-phase Green Hydrogen Strategy. The first phase, starting from 2025, will mainly target the domestic market, replacing grey hydrogen for heavy and long-distance transportation. The second stage from 2030 extends local use along with exports. The third, long-term stage after 2035 anticipates opening new markets both domestic well and international.[57] However, Chile is a long way from markets in Asia and Europe. To overcome shipping costs exporters will need to produce hydrogen at a low-cost.[58]

Most of the impetus and coordination has come from the State which has helped lower barriers and reduced regulatory, financial, and technical risks. Private actors, academia and business associations can collaborate with the Government to invest in capabilities, technologies, businesses, and projects for both domestic and export markets. The plan includes:

- *Funds* – For supporting companies, and national and international consortiums to invest in scalable and replicable green projects.
- *Pricing* – A roadmap for pricing of fossil fuel emissions to level the playing field.
- *Regulations and standards* – To be clear and stable throughout the value chain to ensure safety and give certainty to investors.
- *Community participation* – Early and transparent involvement of local communities in green hydrogen-related projects.
- *Innovation system* – An R&D system involving industry, academia and technological centres.

Since 2017, Chile has had micro-grids powered by green hydrogen, providing 24-hour clean energy without requiring diesel-based power backup systems. Developed by the Italian company, Enel, these systems can be on-grid or off-grid and moved to locations such as small community camps.[59] The Chilean National Development Agency (CORFO) has six new pilot projects selected with the involvement of international investors.

Brazil

In 2021, the Ministry of Mining and Energy presented a baseline Hydrogen Strategy, which called for national stakeholders to "embrace the opportunities for the development of various technologies for the production and use of hydrogen, including green hydrogen, in which it can be very competitive."[60] Several states have initiatives to kickstart production – taking advantage of their renewable energy capacity and port infrastructure. The state of Ceará for example, is developing a green hydrogen hub at the port of Pecém which connects solar and wind energy parks and an export processing zone. Pecém port is a joint venture between the State of Ceará and the Port of Rotterdam Authority – a link that could facilitate entry to European markets.[61] By October 2022, the State Government had signed 22 memoranda of understanding with companies from several countries: two of these, from Australia and United States, have moved to the pre-contract phase. Other initiatives are in the states of Bahia and Pernambuco.

China

China is the world's largest producer of hydrogen, but most of this is from coal. For green hydrogen, China lags behind advanced countries in key technologies for storage and transport, though these can be expected to emerge in the future.[62] China's policies for developing hydrogen date back to the 10th Five Year Plan (2001-2005).

In 2021, China launched a mega-project in Inner Mongolia to build a cluster of plants that will use solar and wind energy to produce 66,900 tons of green hydrogen a year.[63] A further project is the Renewable Hydrogen 100 Initiative, launched by the China Hydrogen Alliance which includes China Energy Corporation and several companies from the energy, transportation and metallurgical industries, along with universities and research centres. The aim is to install electrolysers to produce100 GW of hydrogen by 2030.[64]

China is also at the centre of the UNIDO Global Programme for Green Energy in Industry, through the International Hydrogen Energy Centre in Beijing which will operate as a knowledge partner by supporting research and development.[65]

South Africa

In September 2021, South Africa approved a Hydrogen Society Roadmap aiming to achieve competitive domestic production by 2030 (Box III-3). Three green hydrogen hubs have been identified in South Africa's 'hydrogen valley'.[66] The Johannesburg hub will primarily produce for industry. The Durban hub will produce for vehicles, as well as for port activities and oil refining. The Limpopo hub will produce for the mining sector. South Africa's Department of Science and Innovation points out that the country needs to identify the potential for green hydrogen in different sectors, scale up the number of electrolyzers and invest in the necessary transportation and storage systems.[67]

Box III 3
Green hydrogen is a game-changer in South Africa

Since 2007, people in South Africa have become accustomed to blackouts due to load shedding,[68] when the electricity demand exceeds the available supply.[69] In 2020, according to the Council for Scientific and Industrial Research of South Africa, the country spent 859 hours load shedding. During the decade from 2009 to 2019, the total economic cost of load shedding was estimated at ZAR338 billion (around 20 billion euros).[70] Demand for electricity has continued to outgrow supply. The state-owned Eskom is also heavily reliant on coal-power plants.

Green hydrogen could be a game-changer. The national Government is seeking a just transition by intensifying public-private cooperation through its Hydrogen Society Roadmap. The initial project, CoalCO_2-X, is in the eastern province of Mpumalanga, where flue gas in coal-fired power stations is stripped of pollutants and mixed with green ammonia to be converted into fertilizer.

To embark on the project, the Department of Science and Innovation of the national Government granted ZAR50 million (around €3 million).[71] In June 2021, the private-equity-owned energy producer Sasol and the state-owned financier Industrial Development Corporation, secured joint funding for the feasibility study.[72] More private- and public-sector investment is expected to follow.

In the local private sector, Mitochondria Energy Systems is developing bespoke fuel-cell technology in cooperation with the Austrian engineering consortium AVL, Co-funded by two state-owned financial institutions, the Industrial Development Corporation of South Africa and the Development Bank of Southern Africa Fuel cell systems could be a source of cleaner energy in industry and for combined heat and power.[73]

Source: UNCTAD.

Namibia

Namibia could produce low-cost renewable energy on a large scale and, given the limited national demand, most of this can be exported.[74] The Harambee Prosperity Plan Green identifies green hydrogen as a transformative strategic industry.[75] The Government has launched the Southern Corridor Development

Initiative and established a Green Hydrogen Council supported by a Technical Committee to collect and coordinate projects and infrastructures. These will include plans for both green hydrogen and ammonia, with wind, solar electrolysis and desalination assets, a wind blade manufacturing plant and adequate port facilities.

The Namibia Green Hydrogen Association provides a platform for public-private interactions. In January 2022 the President announced that the first bid to produce 300,000 tons of green hydrogen and ammonia per year had been won by Hyphen Hydrogen Energy.[76]

Namibia has established international cooperations to support hydrogen production. It established a partnership with Germany to identify suitable sites for green hydrogen production. This is part of the H2Atlas-Africa project, which will carry out research on green hydrogen production in arid areas using desalinated water. [77] To build domestic knowledge this also includes exchange programmes for researchers and experts, and scholarships for Namibian students. The country also signed agreements with Belgium and Rotterdam (Netherlands). These international agreements encompass funding, but Namibia is also considering options like green or sustainable bonds to achieve the necessary value for the projects.[78]

Morocco

The Middle East and North Africa region has an abundance of solar and wind power and has considerable potential for supplying green hydrogen demand to countries in the European Union – transporting it through existing gas pipelines.[79] In Morocco, the German Moroccan Energy Partnership will include technical support for the elaboration of a roadmap for local production and for exports to Europe and elsewhere.[80]

Oman

Oman has the advantages of consistent daytime sunlight and strong winds at night, so is starting to invest in green hydrogen. One of the world's largest plants is being planned by a consortium which includes the state-owned oil and gas company OQ, the Hong Kong SAR China-based renewable hydrogen developer InterContinental Energy, and the Kuwait-based energy investor Enertech. Most of the output will be exported as hydrogen or as ammonia, which is easier to store and ship, to Europe.[81]

Africa

The Africa Hydrogen Partnership Trade Association (AHP) is a non-profit company incorporated in Mauritius, which enables member companies to exchange knowledge on economic, technical, and other relevant social topics, including the treatment of political, legal and tax issues, as well as to lobby with governments and administrative bodies with one voice.[82] One of the AHP projects is the issuing of Green African Hydrogen Bonds to collect low-cost, long-term financial capital, creating mutually beneficial opportunities for African governments and financial institutions.[83]

B. GREEN WINDOWS OF OPPORTUNITY

This section considers the extent to which countries are in a position to take advantage of green windows of opportunity and how they have responded. Some countries may have the conditions to develop such technologies but unless they respond strategically to seize these opportunities, they may be firmly locked into fossil-fuel pathways, leaving foreign investors to capture the arising markets. Other countries may wish to take these opportunities but lack the necessary conditions, especially in terms of industrial capacity and sectoral system capabilities that are relevant to a given green technology.

Table III-1 considers four scenarios in terms of preconditions and responses – though is this necessarily a simplification. There are many grey areas and overlaps between weak and strong conditions.

Table III 1

Four green window scenarios

Preconditions \ Responses	Strong	Weak
Strong	**Scenario 1:** **Windows open** Solar PV, Biomass, CSP – China Bioethanol – Brazil Hydrogen – Chile (potentially)	**Scenario 2:** **Windows to be open** Solar PV – India Biogas – Bangladesh CSP – Morocco Wind – China
Weak	**Scenario 3:** **Windows within reach** Biomass – Thailand and Viet Nam Hydrogen – Namibia	**Scenario 4:** **Windows in the distance** Wind – Kenya Bioenergy –Mexico and Pakistan

Source: UNCTAD.

1. SCENARIO 1 – WINDOWS OPEN

China – The best scenario for seizing these economic opportunities is where strong preconditions are combined with strong responses. This is evidently the case for China which has large internal markets for green technologies and a diverse industrial structure. It also has design and engineering capabilities for biomass plant construction[84] and scientific knowledge in solar PV as well as R&D in nascent technologies such as CSP.[85, 86] Regarding responses, there have been efforts in several sectors to co-design environmental and industrial policies. Many initiatives have been put in place to diffuse knowledge among firms and knowledge institutions such as government stimulation of knowledge spillovers, with loose enforcement of property rights and diffusion through state-owned design institutes.

Brazil – Over many years, Brazil has built the preconditions to take up opportunities in green sectors. It has extensive sugar and ethanol processing plants and the technological learning linked to these sectors. Technology suppliers and research institutions have cooperated in sugarcane-related technology development. Private firms also responded to these opportunities by establishing collaborative consortia to develop cars with flex-fuel systems (i.e., engines that run on a combination of gasoline and methanol or ethanol).[87] Although driven initially by the local market, Brazil has been moving to a leadership position in the global market.[88]

Chile – Another case that can combine of adequate preconditions with strong responses is the development of the green hydrogen industry in Chile. The country has a relatively well-developed production system, and a tradition of public investments in sustainable industrial development.

Table III 2
Examples of opening green windows

China: Electric vehicle	Brazil: Ethanol
Green industrial policy, infrastructure, subsidies, public procurement etc.	Incentives have been in place since the 1970s; technological learning from innovation policies
Strong response by both existing OEMs and pure players (experimentation and many failures)	Response from the private sector, which created passenger cars with the flex-fuel system
New and important competitive advantages for leadership in battery technology, software integration electric buses	Leadership in the global market

Source: UNCTAD.

2. SCENARIO 2 – WINDOWS TO BE OPEN

A combination of strong preconditions with insufficient responses translates into possible opportunities that have not be taken up yet. This is the scenario in which many developing economies find themselves:

India – The National Solar Mission prioritized low-cost deployment above stimulating local manufacturing. This has resulted in a high dependency on imports. Insufficient attention was paid to training, promotion of linkages to relevant stages of the value chain and to R&D to boost competitiveness. This illustrates the importance of carefully designing and complementing domestic market stimulation to avoid insufficient protection of domestic investments.[89]

Bangladesh – An existing system of R&D organizations involving biomass energy has not been complemented with appropriate incentives to encourage biogas plant installations. Also, very little has been done to increase awareness among farmers about the potential of waste management.[90]

Morocco – Concentrated solar power has been promoted through strong political commitment towards solar energy. Thanks to an initial productive base, a few domestic companies have begun displaying some capabilities.[91] Nonetheless, by 2015, the practical opportunities for local manufacturing of solar energy inputs and components were still restricted because of a limited capacity in promoting technology and knowledge transfer.[92]

China – China had the heavy industry capabilities needed to manufacture and install wind turbines and strong university-industry linkages.[93] However, compared with its success in solar PV, China has been unable to achieve market leadership. Green windows develop over time, and strategies and initiatives need to adapt to continue to be effective. Those based on building basic production capacity may be insufficient for subsequently upgrading and deepening technological capabilities, especially when technologies are evolving. In the Chinese wind sector, there were good preconditions. However, it was unable to follow the successful pathway of other green sectors, such as solar PV. This would have required the integration of 'smart systems' for turbine and wind farm management which the Chinese wind industry could not deliver.[94]

Table III 3
Examples of windows to be open

China: Wind	South Africa: Electric vehicle
Driven by international and domestic environmental policy	Rich in key natural resources used in automotive and EV production and key auto hub
Active industrial policy (e.g. LCRs from 2005)	No response by the foreign OEMs for locating EV production in SA
Active approach by firm: licensing and co-design	Small market and mainly private mainly infrastructure solutions
Catching up close to frontier in 2010	Real risk of falling behind
Now falling behind in post-turbine technology due to insufficient IS response	

Source: UNCTAD.

3. SCENARIO 3 – WINDOWS WITHIN REACH

Some countries have weak preconditions but are nevertheless taking active steps to reach for the windows:

Thailand – For biogas, the Government has offered subsidies, tax incentives, and mandatory purchasing of electricity generated. This has encouraged private investors and a co-evolutionary pattern with shifts within and across learning mechanisms.[95]

Viet Nam – Viet Nam has the opportunity to generate biomass energy from rice husks. Private actors, including some foreign investors such as Decathlon, and public actors, including domestic research and development institutions, are developing a dynamic sectoral system.[96]

Ethiopia – Despite little experience in this area, the wind industry has grown through major projects. The Government is building key elements to ensure more local learning in and around projects. While still with several shortcomings, the Ethiopian Government has taken an active role in designing projects to ensure maximum local learning, by ensuring that professional users are more involved in project execution.[97]

Namibia – The Namibia Green Hydrogen Association has been created to provide a platform for private actors and government-business interactions. Namibia has also established a critical partnership with Germany, characterized by intense R&D interactions and collaborations to identify suitable sites for producing and training professionals specialized in this new industry.

Table III 4
Examples of windows within reach

Ethiopia: Wind	Thailand: Biogas
Wind part of energy policy and planning	Subsidies, tax incentives, mandatory biogas purchase
Active role in designing wind projects to guarantee maximum local learning, by ensuring the involvement of professional users in the execution of projects	Favourable conditions for private investments
Still limited industrial outcome but local learning secured	Strong response and learning by domestic firms

Source: UNCTAD.

4. SCENARIO 4 – WINDOWS IN THE DISTANCE

Weak preconditions and responses provide a meagre scenario for seizing green windows as shown in the examples here.

Kenya – Relatively weak starting points have impeded large-scale wind development. Insufficient strategies to ensure local embeddedness and to learn from projects resulted in a lack of success to seize opportunities for learning and supply chain development.[98, 99] Projects such as the Lake Turkana Wind Power Project should be more deeply integrated, with strategies for strengthening sectoral systems of production and innovation.[100] These could include initiatives regarding the training and certification of engineers and technicians and research programmes in universities.

Mexico – The country has vast potential for bioenergy but has weak regulations and a lack of technical competencies limits awareness of the potential.[101] As a result there has not been sufficient public and private investment to upgrade bioenergy technology.

Pakistan – The story in the bioenergy industry is similar to that of Mexico, with a lack of capabilities and effort.[102]

Table III 5

Examples of distant windows

Kenya: Wind	Mexico and Pakistan: Bioenergy
Driven largely by global finance and support	Lack of technical capabilities
Ad-hoc project approval with no industrial conditionalities attached	Little policy attention and weak regulation lead to insufficient investment
Virtually zero local content and learning	Lack of sufficient stimulus to develop the sector
Small number of local jobs in O&M	

Source: UNCTAD.

C. MATURITY AND TRADABILITY OF GREEN TECHNOLOGIES

As in Table III-6, Green technologies can be analysed in terms of their maturity and tradability. The distinction between mature versus immature technologies is explained by the existence and development of different socio-technical configurations, including infrastructure, regulations, market and technical standards, maintenance networks and user practices. The development of low-maturity (or immature) technologies requires significant policymaking efforts, including large R&D investments, market creation support, and technical standards.[103]

Tradability varies with the energy source. Electricity is difficult to trade over very long distances, whereas liquid fuels such as bioethanol or green hydrogen in the form of ammonia are easier to transport. More importantly, the underlying energy production technology also has variable tradability. At one end of the spectrum, hydropower technology needs to be almost fully produced at the point of energy generation and consumption. At the other end of the spectrum, electric vehicles are highly tradeable and can be produced far from the point of consumption.

Table III 6
Maturity and tradability of different sustainable industries

Technological maturity / Tradability	High	Medium	Low
High	Solar PV; Biofuels	Electric Vehicles	Green hydrogen
Medium			Concentrated solar power
Low	Bioenergy (excl. Biofuels)	Wind	

Source: UNCTAD.

1. TECHNOLOGICAL MATURITY

Mature technologies are fully developed with stable, dominant designs – along with the infrastructure, regulations, market and technical standards, maintenance networks and user practices.[104] The automobile sector, for example, has high maturity for one dominant design of petrol and diesel cars, and is now arriving at medium maturity for the design of electric or hydrogen vehicles. Wind also has medium maturity – for onshore wind turbines and second-generation offshore turbines.

There is not, however, a unique and straightforward way of measuring technological maturity. One way is through considering the year the patent was applied for, and also the dates of other patents that it cites – which is here is termed the average 'citation date'. [105] Mature technologies are likely to have patents dating back many years. Thus, the gap between these applications can be taken as a measure of maturity in years. For example, a patent for a new technology in 2016 might cite patents from 2014, 2010, and 2006. The average year of citation would be (2014+2010+2006)/3= 2010. The maturity of the patent would be 2016 minus 2010, and thus six years.[106]

This report has calculated the average year of patent for each major technology, and for the top-20 most cited patents the average citation date. For AI, for example, on average, most patents were applied for in 2014 and cite patents on average from 2005, producing a difference of 8.72 years. The same calculations have been carried out for 15 frontier technologies (Figure III-2).

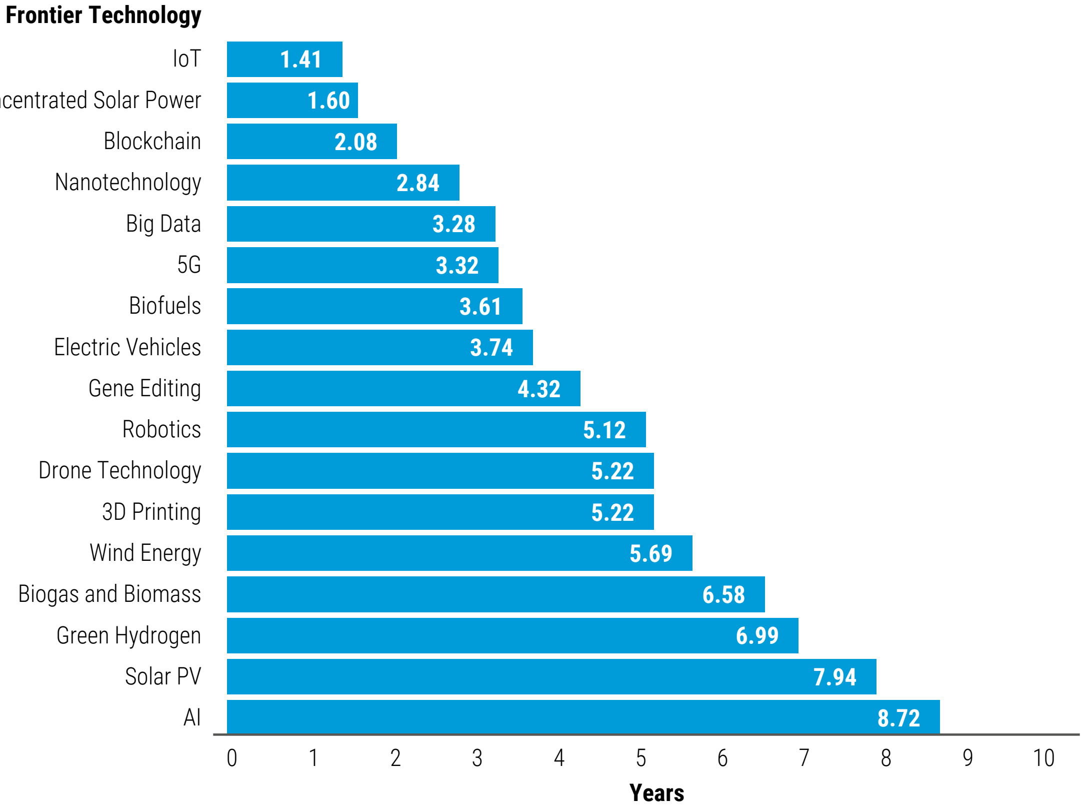
By this measurement, AI is a mature technology as, on average, most patents were applied for in 2014 but cited patents from 2005 (and thus a difference of 8.72 years between average applications and forward citations). This may seem counter intuitive. But today's AI patents, such as those for autonomous vehicles and the metaverse, are technologically close to those for search engines and digital maps, and many of the underlying principles patented in 2005 are still valid.[107]

IoT, on the other hand is relatively immature, with an average patent application year of 2017 and an average citation date of 2016. This suggests that the dominant design behind IoT innovation is being updated every 1.4 years, reflecting a technology that is still evolving fast.

However, this methodology does create anomalies. Not all technologies are as mature as suggested by this measure. For green hydrogen, for example, progress over this period has been slowed by a lack of research in the past. Nonetheless, its pace is now picking up. Between 2020 and 2021 the number of applications jumped from 6 to 31.

Developing countries should take into consideration the level of maturity when deciding which frontier technologies to switch to. Immature sectors offer open opportunities that latecomers can use to disrupt the industry. However, these sectors are also more difficult to operate in since they require greater initial efforts in science and R&D that are only within the capacity of strong domestic systems, such as China for CSP and in Brazil for bioethanol. Mature technologies may demand less R&D, but they also present

Figure III 2
Patent maturity of frontier technologies



Source: UNCTAD.

Note: For each technology, the number in the bar graph shows the patent maturity, which is the difference between the weighted average patent application year and the weighted average year of the 20 most cited patents between 2000 and 2021.

potential barriers in terms of strong and efficient production processes and tradability that may deter new competitors.[108] Moreover, in such a setting, countries must be able to acquire technologies and adapt them to local circumstances.

Biomass and solar PV have mature technologies that latecomers can absorb and use with machinery from the outside. For example, in the case of solar PV, China was able to take advantage of the green window as it could import foreign production machinery and benefit from economies of scale. It required entrepreneurial dynamism in the private sector and state support on the supply side. In India, on the other hand, with weaker manufacturing capability, the sector did not develop as expected because of the inability to manage localization issues.

2. TRADABILITY

Like technological maturity, tradability is not easy to assess in a rapid appraisal. This is because tradability relates to at least three aspects of innovation – of capital equipment; of the technology itself and the processes needed to use it; and of energy being produced. An indication of the extent of the tradability of green technologies is indicated in Table III-7.

Tradability influences competitive dynamics as well as modes of learning. Sectors with high tradability may need a degree of market protection, and careful design and implementation strategies to boost demand.[109] Taking advantage of high tradability in capital equipment, however, requires strong capacities in related production domains. In the case of low tradability, learning may initially occur through FDI.

For example, for wind, where turbines can be traded, although at high transportation costs, Kenya was able to use FDI to import turbine technology. However, combined with the relatively small market size, the lack of preconditions in the private sector – in particular the capacity in heavy-industry and electrical engineering – have meant that the opportunity is still distant. In China, such preconditions were in place and enabled the catching up for required domestic deployment. Through dynamic localization, FDI was replaced or took on a new role over time. Low tradability offers a degree of natural protection in the home market. For technologies with low tradability and low maturity, countries can take advantage if they have the necessary R&D capabilities and the capacity to supply components. For CSP, China was able to open the window, while Morocco with a relatively weak supply base and limited R&D capability missed this opportunity.

Table III 7

Three dimensions of tradability

Dimensions of tradability	Capital equipment and inputs	Energy generation technology	Green energy outputs
Bioethanol	*Medium* (Distillery equipment)	*Low* (Ethanol distillery)	*High* (Ethanol)
Biogas (a)	*Low* (Heavy-duty machinery)	*Low* (Biogas plant, e.g., waste to energy)	*High* (Gas)
Biogas (b)	*High* (Anaerobic digestion equipment)	*Low* (Biogas digester)	*High* (Gas)
Biomass	*Low* (Equipment)	*Low* (Direct-fired biomass plant)	*Medium* (Electricity)
Solar PV	*High* (Industrial robots, assembly line designs)	*High* (Solar PV Panels)	*Medium* (Electricity)
CSP	*Low* (Heavy duty machinery)	*Low* (Solar farm)	*Medium* (Electricity)
Wind power	*Low* (Heavy duty machinery, steel)	*Medium* (Wind turbines)	*Medium* (Electricity)
Green Hydrogen	*Medium* (Electrolysis equipment)	*Low* (Conversion facility)	*High* (Ammonia)

Source: UNCTAD.

D. REQUIREMENTS FOR OPENING GREEN WINDOWS

Opening green windows in developing countries requires government activities at different levels – national and local – and the involvement of various public and private stakeholders. Overall policies to open and take advantage of these windows should be mission-oriented – going beyond levelling the playing field to fixing market failures and involving broader programmes of market co-creation and shaping (Box III-4).[110]

While the opportunities differ from one technology to another, benefitting from them involves two main stages.[111] The first to identify and open windows of opportunity. The second is to assess what is needed and to sustain the processes. However, the stages will often overlap. Some assessment must be done before the decision to invest otherwise the window may be missed. There are also likely to be feedback loops requiring regular adjustments.

Box III 4
Mission-oriented policymaking

Mission-oriented policies require foresight to identify future opportunities, recognize the conditions needed to take advantage of these opportunities, and how to overcome possible weaknesses and challenges in the national systems of innovation. This diagnosis should be the basis for new strategies, establishing organizations and institutions, and facilitating linkages in the innovation system. Mission-oriented policy making for a greener economy should:

a) Be well defined with clear intermediate goals and deliverables as well as embedded processes of monitoring and accountability.

b) Include R&D projects to account for possible failures which should be accepted as learning experiences.

c) Ensure investment across different sectors and involving different private and public actors.

d) Engage a wide range of public institutions, with a clear division of labour and well-defined responsibilities for coordinating and monitoring.

Source: UNCTAD based on Mazzucato, 2018.

1. IDENTIFY AND SWITCH

This can be a complex task since policymakers often have to make decisions over long time periods based on incomplete information and in the face of emerging developments. They need to identify the potential of particular windows in terms of the availability of natural resources, such as favourable wind conditions or the availability of agricultural waste, and also the national capacity to use or build the necessary technology.

Align environmental and energy, STI and industrial policies

For this purpose, policies that would previously have been developed in separate domains need to be co-created across the energy-environmental and industrial spheres. For example, initiatives to facilitate a green energy system, such as auctions or feed-in tariffs, should be aligned with industrial policy and measures to build local capacity for production and innovation.[112] This, however, is not always an easy endeavour, so it might require active effort to avoid conflicts (Box III-5).

In Thailand, for example, the Ministry of Energy developed environmental legislation but also encouraged factories to invest in biogas production and combined this with policies to strengthen the sectoral innovation system. At the same time, a network of other actors such as the Ministry of Science and Technology, was researching and developing biogas technology and setting up demonstration programmes. Also, the Board of Investment under the office of the Prime Minister, introduced tax incentives to attract private investors. Various research centres and universities established training programmes to build domestic capacity for setting up and maintaining the installed systems.[113]

Box III 5

Political economy challenges of renewable energy sectors

The development of green sectors entails political economy challenges. First, managing the incentives created is key to achieving the desired results. Due to market and coordination failures, governments must deploy incentive measures to stimulate investments in these sectors. However, adequate state-business relations (SBRs) are required to establish the necessary information exchange to implement and succeed with such incentive policies. Second, policies enacted by different governmental bodies influence the industrial development of green sectors – especially, renewable energy sources. However, different governmental bodies often have different priorities, which might create tensions between policies. Therefore, ensuring their alignment through intragovernmental coordination is necessary.

Links between the state and the private sector are important channels to improve information flows[114] so that the government manages to get the relevant information and the transfer of publicly produced knowledge.[115] However, this cannot occur in state capture by the private sector. The state bureaucracy must be able to retain its independence to adapt and withdraw incentive measures if they are not achieving its goals or are no longer necessary.[116] In Germany, for example, the institutionalization pattern of SBRs in the automotive industry created barriers for new firms and groups to engage with the State. Consequently, incumbent firms that invested in carbon-intensive vehicle technologies successfully delayed the introduction of further policies to incentivize EVs in the 2000s. Meanwhile, in the United States, the mode of SBR in this sector allowed for the participation of different stakeholders, including those with environmental-friendly agendas, which favoured the enactment of regulations incentivizing EVs.[117]

A second political economy challenge comes from the intersection of different policy domains. Sustainable development is a cross-cutting issue and relevant policies are spread across a wide range of government organizations. For example, energy, industrial[118], environmental[119], trade and competition[120] policies influence innovation in the renewable energy sector, as well as their interaction.[121] So, promoting the coordination of different governmental bodies is key to mitigating the risks of contradicting policies and facilitating the exploration of synergies between them. For example, policies to improve the competitiveness and capabilities of renewable energy producers and their inputs suppliers favour the deployment of renewable energies if they have a decreasing effect on prices, while energy policies can stabilize and expand the domestic market for these sources, reducing the uncertainties and risks that investors face.[122] In the opposite case, a lack of alignment between policies undermines their effect. For instance, in Germany, the wind energy sector faced financial issues created by the lack of coordination between incentive policies and the adaptation of the infrastructure,[123] while in Brazil the development bank attached national content requirements to the offer of interest rates lower than the market rate for solar energy projects and promoted the construction of domestic industry, but the trade policy made it cheaper to import the final panels than their separate parts to assemble it in the country.[124]

Notwithstanding the need for policy alignment, different government organisations often have distinct priorities. In the renewable energy sector, there might be a trade-off between ensuring faster and cheaper deployment of projects and developing a national industry since the latter entails additional costs (at least temporarily).[125] This trade-off reflects a contradiction inherent to industrial policies targeting green sectors. One way of measuring its success is to analyse the amount of clean energy produced; another way focuses on traditional industrial policy measures, like jobs created and the international competitiveness of supported industries, among others. However, the fastest way of expanding renewable energy production is to rely on imported goods and suppliers, which conflicts with the creation of domestic industries.[126] Consequently, the priority level given to each of these goals leads to different policy designs and, thus, different industrial outcomes.[127] In South Africa, for example, while the National Treasury prioritises energy deployment at a low cost, the Department of Trade and Industry (DTI) emphasises the development of local manufacturing and job creation. The DTI is responsible for drafting local content requirements, but the National Treasury governs the Renewable Energy Independent Power Producers' Procurement Programme (RE IPPPP). This results in some missed opportunities to push forward the national industry. The fourth round of RE IPPPP did not, for instance, include any requirement for the local lamination of solar PV modules as a bidding requirement, which could have resulted in job creation and spin-off activities that benefited local industries.[128]

Source: UNCTAD.

Select and adapt to local circumstances

Policy instruments need to be selected according to the intended goal. In sectors characterized by domestic market opportunities, the selection of policy instruments for market stimulation, for example, through feed-in tariffs or national auction systems, needs to be carefully designed and implemented.

Policies also need to be adapted to local needs. Box III-6 describes two renewable energy support mechanisms: feed-in-tariffs and auctions, showing their advantages and disadvantages.

The Mexican and South African national auctions for renewable energy show how they can work differently in diverse contexts. In Mexico, for example, the priority was low-cost deployment, while in South Africa the objective was to establish a domestic renewable energy value chain. This led to different micro level policies and produced different outcomes.[129]

Box III 6

Renewable energy support mechanisms

Feed-in tariffs

These are fixed electricity prices paid to renewable energy (RE) producers for each unit of energy produced and injected into the electricity grid. The feed-in-tariff (FIT) usually varies between technologies to reflect the differences in generation costs as well as between the size of installed capacity, reflecting the higher generation costs of small- and medium-scale RE projects. A third differentiation is according RE resource quality, such as the average wind speed at different project locations. The FIT for is higher for sites with lower RE potential.

FITs are relatively simple policy instruments that can be fine-tuned to different policy objectives – such as innovation, climate protection, and regional development. For investors, FITs combined with long-term contracts guaranteed by the government, provide transparency, predictability and security, and therefore contribute to reducing investment risks and financing costs.

The main challenge with FITs is to define levels of remuneration that are neither too low to be attractive for investors nor too high as to result in over-paying. This requires good information on project costs along with effective monitoring.

Auctions and tendering schemes

These are competitive mechanisms for allocating financial support to RE projects, usually based on the cost of electricity production. Public authorities are responsible for preparing the tender documents, the publication of the tender, the evaluation of the bids and the selection of the winning bids. They specify the capacity (kW) or the electricity generation (kWh). They can also specify the technology such as solar PV or wind energy, or they can be technologically neutral. Sometimes they indicate the location. Project developers can then submit a bid, outlining their proposal and stating the price per unit of electricity they will be able to realize.

Auctions and tendering schemes stimulate competition between different operators, locations and technologies, reveal the actual costs of RE technologies, and prevent overcompensation.

Auctions can help control the development of renewable energy projects because they require public authorities to define the required additions to capacity. This enables central planning and coordination of renewable energy development.

However, for the bidders, there are certain costs and risks – which also tend to discourage the involvement of small and medium investors and can lead to more expensive offers.

The main difference between FITs and auctions is the mechanism for price discovery. In FITs, the price is fixed by the policymakers. In auctions, the industry determines the price through competitive bidding. If a country lacks experience and does not have cost data available, auctions are a useful way of discovering the true cost of the technology. However, for auctions to be successful, they need to be competitive, which means there needs to be enough interest amongst project developers.

Source: UNCTAD based on energypedia.info.

Combine policy instruments

Policymakers will need to use a combination of measures. In China, for example, creating the domestic market for solar energy was combined with subsidies for developers of off-grid and grid-connected projects, covering up to 70 per cent of the costs of installations as part of the Golden Sun Demonstration Program. There were also public investments in grid infrastructure and in poverty alleviation programs of installation of solar PV panels for poor households.[130] There was also mandatory purchasing of electricity generated from renewable energy.

Find the finance

For building up solar PV production the China Development Bank and other state and commercial banks provided credit to PV producers when most Western solar manufacturers had difficulty accessing credit due to the financial crisis.[131]

Other developing countries will be unable to finance renewable energy projects from national sources, but they should be able to get concessional external finance. Morocco, for example, identified CSP as the best option, and for CSP installations was supported by the Climate Investment Fund, the World Bank, the African Development Bank and other EU financing institutions.

Establish demonstration programs

Nascent industries such as CSP and green hydrogen need to be built up through constant experimentation and steady improvement. For CSP, China, for example, built knowledge and experience within domestic firms through “megaprojects of science-research”, experimenting with different technical designs on the ground.[132] Similarly, in Chile, with the support of international investors, the National Development Agency established several green hydrogen pilot projects.

2. ASSESS AND SUSTAIN SECTORAL SYSTEMS

Governments need to assess the current conditions and then strengthen sectoral innovation systems. Much of this happens within ‘green industrial policy,’ which mainly involves mobilizing the necessary actors and resources and directing how knowledge capacities are upgraded – often amid considerable technological, economic, and political uncertainties.

Evaluate existing conditions

Successful exploitation of green windows naturally depends on pre-existing conditions in the sectoral system. Dynamic conditions will unfold and develop in an emergent trajectory. Both public and private preconditions are essential. Public preconditions involve both overall state capacity and governance capability in the relevant areas, such as the strength of relevant public agencies in the regulation field, the extension support system, and the provision of public-goods services. A lead agency within government should mobilize resources and convene stakeholders to assess overall state capacity as well as the strengths of public agencies, particularly for regulation, and extension support systems, and for providing public services. Without a lead agency it can be hard to ensure experience sharing and interactive learning between stakeholders. Kenya, for example, found it difficult to take advantage of wind power in the absence of a national agency to assemble expertise, enable systematic learning and allow for transfer of knowledge between projects.[133]

For each technology, tailored strategies should be developed and adjusted along with the necessary support systems, knowledge infrastructures and design and engineering capabilities – identifying activities that local firms can feasibly undertake.

In industries where the technology is mature, as with wind and solar, it may be difficult for latecomers to produce core components. But there can be opportunities further down the value chain related to deployment, such as project development, engineering, procurement, and construction.[134] These need to be carefully examined because some policy instruments rely on private sector capacity; there is little point for example in stipulating local content requirements if local companies lack the capacity to deliver.[135]

Governments need to assess at various stages where and how production and innovation must be strengthened and changed.[136, 137] To do so, they can take advantage of UNCTAD’s Science, Technology and Innovation Policy reviews which cover the activities of national and local governments, private companies, universities, research institutes, financial institutions, and civil society organizations.

Access external knowledge

Building domestic production typically means learning from other countries. In China, for solar PV for example, firms were encouraged to carry out research with international partners.[138]

Invest in domestic R&D

Nascent green technologies are usually biased towards capital and the use of high-skill labour, and require significant investments in R&D. Governments can offer subsidies to build up research, with the collaboration of universities and industry both domestic and foreign (Box III-7).

Public R&D investments are also needed in process improvements and complementary technologies.[139] And when technologies are rapidly evolving, as in the wind industry, this investment will need to be continuous. China, for example, did not provide sufficient support for its shift from onshore to offshore turbine technology.[140]

In the early stages, when the domestic market cannot support a competitive industry, governments can set up demonstration projects, as happened with CSP in China and green hydrogen in Chile.

Box III 7
Promoting R&D in green areas

Oman - Innovation Park Muscat is an initiative under the Ministry of Higher Education, Research & Innovation that encourages scientific research, innovation, and collaboration between various sectors. It provides access to various facilities and services to create an environment that motivates innovators, entrepreneurs, and companies to develop ideas in energy, food and biotechnology, health, water, and environment sectors.

Philippines – The Department of Science and Technology (DOST) supports R&D projects in line with green technology and innovation. Topics covered include Machinery for Decontaminating Rice Hull as Litter Floor for Broiler Breeder Production; Black Soldier Fly farming for agricultural productivity and waste management; Development of nano fertilizer from poultry waste biogas digestate; and Extraction of Phytohormones from Waste Coconut Water using Biochar Derived from Agricultural Residues. The DOST is pushing for the passage of the Science for Change Bill, which provides programmes for establishing R&D centres and collaborative R&D between academia and industry. This initiative bolsters the productivity and competitiveness of industry players and drives R&D on renewable forms of energy and green technologies. Also in the Philippines, the "Niche Centers in the Regions for R&D" will focus on sectors related to health and industry, energy, and emerging technology. This initiative will allow the country's academic and R&D institutions to upgrade their research facilities, develop policies, transfer technologies, and ramp up regional initiatives and efforts toward a competitive innovation ecosystem. Through these R&D centres, the DOST cultivates the innovation landscape in various sectors to ensure no one is left behind in R&D progress.

Switzerland – The Swiss Federal Office of Energy (SFOE) subsidizes research projects that correspond to the priorities of the current energy research concept of the SFOE 2021-2024. The focus is on application-oriented and development-related research projects. The SFOE's energy research programmes cover the entire spectrum of energy research and all major technology fields in renewable energies and energy efficiency. There is also a socio-economic research programme and a programme on the social aspects of dealing with radioactive waste.

Türkiye – The Scientific and Technological Research Council of Türkiye (TÜBİTAK) designs its R&D support for compliance with the European Green Deal and for mobilizing R&D and innovation accumulation within the scope of co-creation models. Programmes include the 1501 Industrial R&D Projects Grant Programme and the 1507 SME R&D Start-up Support Programme. Also, the TÜBİTAK 1512 Entrepreneurship Support Programme's 2021 call targeted R&D and innovation topics within the scope of the European Green Deal Agreement. The 1512 Entrepreneurship Support Programme's 2022 call also targets green growth. In TÜBİTAK's new call for proposals for the "High Technology Platforms Support" and "Industry Innovation Networks Mechanism (SAYEM)", areas focusing on sustainable solutions to mitigate and adapt to climate change attracted significant attention.

Source: UNCTAD based on contributions to the Commission on Science and Technology for Development from the Governments of Oman, the Philippines, Switzerland and Türkiye.

Build domestic capabilities along the value chain

To absorb, adapt, and eventually develop, renewable energy industries, countries need to accumulate local expertise – scientific, technological, managerial, and organizational. Governments can offer support through public procurement, by stipulating local content requirements and by offering tax incentives targeted at specific energy facilities, production projects, or types of companies such as joint ventures.[141] In South Africa, for example, efforts to promote local tower and blade manufacturers failed because global multinational companies preferred to operate through long-standing relations with international first-tier suppliers. The industry need not necessarily focus only on the manufacturing phase. In wind energy, for example, there are opportunities for efficient domestic service providers to collaborate with lead firms.[142]

It is also important to build the capacity of SMEs – and particularly to tap the potential of women entrepreneurs. UNIDO research in Cambodia, Peru, Senegal and South Africa found that women entrepreneurs were particularly interested in green industries where they believed they had more opportunities.[143] Policymakers can publicise the options for women, while increasing access to technical vocational education and training, and investing capacity-building. They can also present successful women entrepreneurs as role models.

Invest in human capital

Dedicated training programmes may be needed to build local specialized scientific, technological, managerial and organizational capabilities. In Thailand, for example, this happens through universities and research centres.[144] In China, in 2008, the Government launched the "Thousands of Talents Plan" which offered full-time positions in research institutes and universities with good salaries and benefits. This attracted many Chinese researchers from western universities who had contributed to fields such as PV cell technologies.[145]

Skills are also acquired through learning-by-doing and on-the-job training. In China, for the biomass industry, state-owned design institutes diffuse technical knowledge and must be involved when constructing biomass power plants. Often the institutes have learned from pioneer companies and then disseminated the knowledge to others.[146]

Collaborate internationally

Participation with international organizations, along with collaboration with other national governments, and non-governmental organizations will provide valuable information for developing more diverse and more affordable energy technologies. International collaboration is more common in new industries such as CSP and green hydrogen – as has happened, for example, between Germany and African countries.

Another example of multilevel collaboration is the Africa- EU Energy Partnership – a forum for political dialogue, knowledge sharing and peer connection between EU and African stakeholders in renewable energies.[147] At the global level, in 2021, UNIDO launched a global programme for the green hydrogen industry with the support of the International Hydrogen Energy Centre in Beijing.[148]

A key area for international cooperation is setting and harmonizing international standards and technical norms that are then incorporated into national regulations. For green hydrogen, for example, this would include guarantees of origin, hydrogen purity, equipment specifications, and blending into the gas grid.[149] Establishing standards requires extensive consultation with stakeholders, public and private, from advanced and developing countries.

Reform intellectual property regimes

It will also be important to reform global intellectual property (IP) regimes so as to allow developing countries ready access to frontier technologies. This involves striking a balance between the disadvantages and advantages of IP rights. Weaker IP protection may enable companies to take up new ideas, but it could also discourage innovation. One recent study of 59 countries concluded that on balance stronger IP protection helps propagate the deployment of renewable energy technologies.[150] However, this area needs more robust empirical research on issues such as novelty requirements, compulsory licensing, and the length of patent protection.

Diffuse knowledge in the domestic ecosystem

Knowledge gained by leading pioneer companies should be diffused to other enterprises to encourage broader development. For the Chinese biomass industry, for example, the State encouraged information spillover to other domestic firms. This was enabled by weak enforcement of intellectual property rights, which smoothed copying and imitation by domestic competitors. Knowledge flows were also mediated by State-owned design institutes.[151]

Another example is the wind industry in Ethiopia, where the Government has asked national universities to submit proposals to act as consultants for wind projects. The Ministry of Water, Irrigation, and Electricity has liaised with several domestic universities to engage them in projects and apply their experience.[152]

[1] Hausmann and Hidalgo, 2011

[2] Malerba, 2002

[3] Data are from IRENA. 1 GW is equal to 1000 MW.

[4] Shubbak, 2019

[5] Shubbak, 2019; Binz et al., 2020

[6] Binz et al., 2020

[7] Shubbak, 2019

[8] Shubbak, 2019

[9] Xinhua News Agency, 2020 http://www.xinhuanet.com/nzzt/135/

[10] CGTN, 2021

[11] For a detailed description about how a national auction works see Box 1 in Section 5.

[12] Matsuo and Schmidt, 2019

[13] Matsuo and Schmidt, 2019

[14] Baker and Sovacool, 2017

[15] Johnson, 2016; Sahoo and Shrimali, 2013

[16] BOS components refer to all components of a PV system other than the modules. These includes wirings, inverters, switches, and battery chargers and other elements involved in the 'deployment chain' (as opposed to the core technology manufacturing chain) of solar energy (Lema et al., 2018).

[17] Do et al., 2021

[18] Mekong River Commission, 2022

[19] Ngan, 2021

[20] Kitchlu,Rahul, 2021

[21] Vietnam News, 2022

[22] Brown, 2019

[23] Weatherby, 2021

[24] Asian Development Bank, 2018, 2020

[25] Weatherby, 2021

[26] Bloomberg, 2021a

[27] Bhamidipati et al., 2021

[28] Bhamidipati et al., 2021

[29] Gorjian et al., 2019placing it among the world's top ten greenhouse gas (GHG

[30] The export volume of biodiesel in India was around 50 million litres in 2021 (Statista, 2022a). In 2020, ethanol fuel exports from Brazil amounted to 2.68 million cubic meters, out of which 37 % went into the U.S., and 34 % to South Korea.

[31] See, for instance, Antwi-Bediako et al. (2019), Romijn and Caniëls (2011), and Nygaard and Bolwig (2018).

[32] Antwi-Bediako et al., 2019; Romijn and Caniëls, 2011; Nygaard and Bolwig, 2018

[33] Antwi-Bediako et al., 2019

[34] Figueiredo, 2017; Andersen, 2015; Dos Santos e Silva et al., 2019

[35] Scientific American, 2013

[36] Hira and de Oliveira, 2009

[37] Duque Marquez, 2007.

[38] Lema et al., 2015

[39] Furtado et al., 2011

[40] Perez-Aleman and Alves, 2016; Andersen, 2015; Furtado et al., 2011

[41] Pereira and De Paula, 2018

[42] Landini et al., 2020

[43] Nygaard and Bolwig, 2018

[44] Ahmed et al., 2017

[45] The CDM is a 'project-based' mechanism under the Kyoto Protocol devised to encourage production of emission reductions in developing countries. To stimulate sustainable development, CDM facilitates low-carbon technology transfer from advanced to developing economies in connection with implementation of emission reduction projects (Clean Development Mechanism, 2022).

[46] Nygaard and Bolwig, 2018

[47] Benti et al., 2021

[48] Yimam, 2022

[49] Arora et al., 2014

[50] In contract farming, an out-grower is a farmer who commits to supplying a buyer and to meet certain requirements. In return, the buyer agrees to make the purchase, sometimes at a pre-agreed price, and the buyer may provide other support.

[51] Arora et al., 2014

[52] Biodiesel in India: The Jatropha fiasco, 2018.

[53] Methane reacts with steam under pressure the presence of a catalyst to produce hydrogen, carbon monoxide, and a small amount of CO_2.

[54] Fernando and Jackson, 2020

[55] UNIDO Industrial Analytics Platform, 2022

[56] Cammeraat et al., 2022

[57] McKinsey & Company, 2020

[58] Biogradlija, 2022

[59] IRENA, 2019

[60] MME, 2021

[61] Governo do Estado do Ceará, 2022

62 Michal, 2021

63 *Bloomberg*, 2021

64 Hydrogen Council and McKinsey & Company, 2020

65 UNIDO, 2022

66 Hydrogen valleys are characterized by a) large scale projects, beyond mere demonstration activities; b) a clearly defined geographic scope; c) the presence of multiple phases in the hydrogen value chain production; d) the supply to various end sectors (Weichenhain et al., 2022).

67 Department of Science and Innovation, 2021b

68 Load shedding is a way to distribute demand for electricity to keep the proper operation of the primary energy source when demand is greater than the primary power source can supply.

69 City of Johannesburg, 2022

70 Trace, 2020

71 Department of Science and Innovation, 2021a

72 Engineerinng News, 2021

73 Development Bank of Southern Africa, 2020

74 Huegemann and Oldenbroek, 2019

75 Executive Summary – Harambee Prosperity Plan II, 2022

76 Hyphen Hydrogen Energy, 2022

77 The H2Atlas-Africa project is a joint initiative of the German Federal Ministry of Education and Research and African partners in the Sub-Saharan region to explore the potentials of hydrogen production from the renewable energy sources within the sub-regions (H2Atlas-Africa, 2022).

78 *BBC*, 2021

79 Friedrich-Ebert-Stiftung, 2020

80 *Frontier Economics, 2021*

81 *The Guardian*, 2021

82 African Hydrogen Trade Partnership, 2022

83 Huegemann and Oldenbroek, 2019

84 Hansen and Hansen, 2020

85 Zhang et al., 2015

86 Gosens et al., 2020

87 Furtado et al., 2011

88 Lema et al., 2015

89 Malerba et al., 2021; Landini et al., 2020

90 Chowdhury et al., 2020

91 Fritzsche et al., 2011

92 Vidican, 2015

93 Lema et al., 2013

94 Dai et al., 2020

95 Reinauer and Hansen, 2021

96 International Climate Initiative, 2022

97 Gregersen and Gregersen, 2021

98 Gregersen, 2020

99 Gregersen and Gregersen, 2021

100 Gregersen and Gregersen, 2021

101 E. J. Ordoñez-Frías et al., 2020

102 Yaqoob et al., 2021

103 Gosens et al., 2021

104 Geels, 2002

105 ∑ Total Patent Applications 2000-2021 - ∑ Total Forward Citations 2000-2021 / ∑ Total Patent Applications 2000-2021

106 UNCTAD, 2018a; Agrawal et al., 2018

107 *Forbes*, 2021b

108 Lee and Park, 2006

109 Landini et al., 2020

110 Mazzucato, 2018

111 Lema et al., 2020

112 Landini et al., 2020

113 Suwanasri et al., 2015

114 Bwalya et al., 2009; Te Velde and Whitfield, 2013

115 Criscuolo et al., 2022

116 Evans, 1995

117 Meckling and Nahm, 2018

118 Johnstone et al., 2010; Palage et al., 2019; Pitelis, 2018

119 Jaffe and Palmer, 1997; Nesta et al., 2014

120 Jamasb and Pollitt, 2008; Nesta et al., 2014

121 Nesta et al., 2014; Palage et al., 2019; Pitelis, 2018; Zhang et al., 2013

122 Zhang et al., 2013

123 Schmitz et al., 2015

124 da Silva, 2015

125 Dos Santos e Silva et al., 2019

126 Hochstetler, 2020

127 Matsuo and Schmidt, 2019

128 Baker and Sovacool, 2017

129 Matsuo and Schmidt, 2019

130 Shubbak, 2019

[131] Shubbak, 2019

[132] Lilliestam et al., 2021

[133] Gregersen, 2020; Schmitz et al., 2015; Lema et al., 2021

[134] Matsuo and Schmidt, 2019

[135] Baker and Sovacool, 2017

[136] Participatory methods of assessment involve: (a) Policymakers (especially those closely related to innovation in Ministries of Science, Technology and Innovation, Trade, Industry, and Education) have broad decision-making power and the ability to design and implement public policies to increase national STI capacity and effectively support systems of innovation; (2) Private sector actors have an understanding of the challenges faced in building firm-level technology and innovation capacity, the local knowledge of the business environment and of the effects of policies in place as well as clear ideas on actions needed for upgrading and innovating; (3) Academic and research institutions have knowledge of specific technologies and R&D capacity; (4) Civil society organization have knowledge of the concerns and priorities of marginalized groups, and ability to voice these concerns and increase awareness in public institutions.

[137] Ministerial Declaration of the Group of 77 and China to UNCTAD XV.

[138] Shubbak, 2019

[139] Shubbak, 2019

[140] Dai et al., 2020

[141] Matsuo and Schmidt, 2019

[142] Morris et al., 2022

[143] UNIDO, 2021

[144] Suwanasri et al., 2015

[145] Shubbak, 2019

[146] Hansen and Hansen, 2020

[147] More information is available at https://africa-eu-energy-partnership.org/.

[148] More information is available at https://www.unido.org/green-hydrogen.

[149] Cammeraat et al., 2022

[150] Tee et al., 2021

[151] Hansen and Hansen, 2020

[152] Lema et al., 2021

CHAPTER IV

TWIN TRANSITIONS FOR GLOBAL VALUE CHAINS – GREEN AND DIGITAL

The digital and the green transformations can be twins if there are strong enough policy responses

The digital and green transformations can support each other

Capturing data using online-connected sensors and GPS can reduce carbon emissions

Smart manufacturing consumes less energy

Voluntary sustainability standards help upgrading value chains

Developing economies have to close the gap to take advantage of the twin transition

The countries best placed to move to smart production are those with stronger manufacturing industries and higher levels of skill

More than 90 per cent of all patenting in industry 4.0 technologies are from high-income countries and China

The top ten front runners in emerging digital technologies are all high-income countries and China

The government, private sector, and the international community can act to open windows of opportunity

Aligning digital and environmental strategies

Developing the digital infrastructure and setting regulations

International cooperation supports this process by facilitating access to finance and external knowledge

This chapter examines the options for latecomer countries in greening and digitalizing, and the opportunities to benefit from these twin transitions in global value chains (GVCs). These two processes have largely developed in parallel but have become increasingly intertwined. Technologies such as AI, cloud computing, and IoT can also help the economies become greener – while also accelerating progress for all 17 SDGs.

Since the early 1990s, GVCs have become the cornerstone of the world economic system. Through GVCs, firms specialize in specific tasks and break up the production process across different countries. Today, about two-thirds of international trade of services and goods comprises transactions within supply chains. These are often sales of intermediate goods – of parts, components and accessories used to produce final products.[1] Exports of such goods declined in 2020 because of the COVID-19 pandemic but rose again in 2021, surpassing the pre-pandemic level.[2] COVID-19 broke many chains, encouraging companies to reconfigure and diversify to be more resilient in the face of pandemics and other disruptions, but GVCs will be important components of world trade for some time to come.[3]

Many emerging and developing countries have been able to use GVCs based on their specific advantages and specialization in tasks rather than on final goods. But this kind of production is unlikely to stimulate sustainable growth: if developing countries are to gather the full benefits of GVCs they will need to move up the value-added ladders to more sophisticated manufacturing and services.

As they upgrade, companies and countries should also embed social and environment values. Social upgrading refers to improving the rights and entitlements of workers and their employment. Environmental upgrading refers to a firm's ecological footprint, including its use of natural resources, its emission of greenhouse gases and any destruction of biodiversity.[4] These improvements are increasingly being demanded by consumers who are seeking more ethical products, and by lead firms and global buyers, and governments. Changes are also being required by social and environmental standards and associated patterns of upgrading and downgrading across global supply bases.

This chapter focuses on technological and environmental upgrading, and on how GVCs can become greener by switching to digital frontier technologies associated with smart manufacturing – often referred to as Industry 4.0. Across the global South, most countries have operating within Industry 3.0, but have yet to adopt smart manufacturing and services or the more advanced methods of data processing and analysis. Indeed, many firms in these countries have yet to upgrade to the previous generation of manufacturing or service technologies. At present only a few countries are using advanced digital technologies, and even fewer are designing and producing them.[5]

A. THE GREENING OF GVCS

GVCs can become greener through two main routes. The first is by manufacturing the goods used for green production, such as, solar PV panels and wind turbines.[6] The second is by greening traditional manufacturing industries, such as food, garments and textiles, leather and shoes, and furniture – all of which are important for low- and middle-income countries.

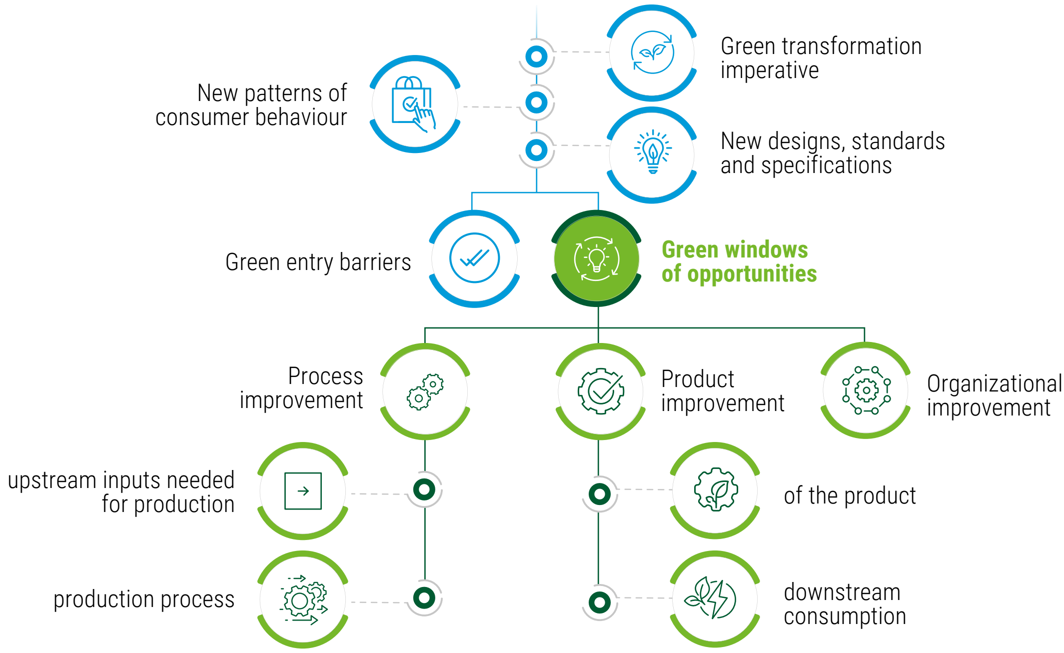
1. ENVIRONMENTAL UPGRADING

Environmental upgrading can be defined as any change that reduces a firm's ecological footprint through lower greenhouse gas emissions, low natural resource use or less impact on biodiversity.[7] As a result, the process can also use less energy or materials per unit of output. Or the upgrading can be through product improvements – removing harmful chemicals, for example, and making the products more recyclable and part of the circular economy. Or the upgrade could be organizational, such as the introduction of environmental management systems.[8]

Much of the impetus is coming from consumers. Informed by NGOs, and by the media, including social media. Consumers are increasingly seeking products and processes that have lower environmental footprints. They are also considering whole product lifecycles, starting from the sourcing of materials such as rare earth metals for electric vehicles and wind turbines,[9] through the management of chemicals in the production of solar PV panels, and then on to what happens after decommissioning, with the reuse of materials.[10] Customers, investors, and policymakers also want greater disclosure and transparency. At the same time, companies see opportunities not only to respond to consumer demand but also to make savings, through more efficient manufacturing and better use of materials.

The processes can be considered as a series of steps, starting from the initial demand, through new designs and product improvements (Figure IV-1).

Figure IV 1
Steps for greening GVCs



Source: UNCTAD.

These changes are transmitted along value chains through new designs, standards and specifications. Usually, the new designs start in countries that pioneer environmentally benign products, processes and services – 'green lead markets'.[11] These countries introduce new private standards, defined and enforced by lead firms. They also internalize several public environmental regulations and semi-private environmental certifications, such as the Technical Regulations (TRs) Certification (e.g., Round Table on Responsible Soy), which, beyond the core private sector firms and organizations, includes authorities and governmental agencies and public donors. The demands for sustainability have implications for the entire value chain, including its governance – how some firms in the chain set and enforce the parameters under which others in the chain operate.

The process is rarely smooth. Higher standards can also present barriers. Some suppliers may be unable to invest in new processes and thus get squeezed out of the value chain.[12] But for other enterprises the new standards signal green windows of opportunity, providing they can realign accordingly.[13] Well-functioning production and innovation systems depend on deeply embedded suppliers who are also flexible.[14]

This chapter focuses on four types of digitally driven upgrades:

- *In product design* – Upgrading the product, substituting environmentally harmful components and products, designing recycled products, designing for durability.
- *In production inputs* – Changing energy sources, substituting energy-intensive materials or scarce natural resources and removing toxic inputs.

- *In production process* – Reducing waste and energy consumption from the production processes and optimizing material flows.
- *In consumption* – Including use, recycling and re-use of waste.

2. THE TWIN TRANSITIONS

The environmental and digital transformations have largely developed in parallel, with their own trajectories and separate drivers and policy domains. However, this is now beginning to change as they merge into twin transitions with many functional synergies. This broader potential of digital technologies was also part of the Sustainable Development Goals which indicated that digitization could enable the changes needed for a just sustainable transition (Box IV-1).[15]

Box IV 1
The impact of Industry 4.0 technologies in global value chains

Digitalization is expected to have wide-ranging effects in manufacturing in GVCs.[16] It has been argued that digitalization will put developing countries at a disadvantage since it reduces the need for labour, and thus reduces the comparative advantage of many developing countries of offering low labour costs.

Companies may thus reshore some activities towards high-income economies.[17] However, reshoring remains a rare phenomenon.[18] In the European Union, for example, data from 2,500 firms in eight countries indicates that the phenomenon has been modest and varies from one industry to another, and that the main driver has been flexibility in logistics rather than the evening-out of labour costs.[19]

The impact of Industry 4.0 on GVCs could also depend on the technology. Robots and computerized manufacturing could reduce the advantage of producing in low-labour-cost countries. Similarly, 3D printing could shorten GVCs and enable firms to keep production closer to markets, as happened during the COVID-19 pandemic when 3D printing was used to remedy shortages in medical supplies. 3D printing can democratize manufacturing allowing companies in latecomer countries to engage in manufacturing without large investments, opening opportunities for distributed local production processes,[20] but it can also allow firms from high-income countries to produce closer to their customers.[21]

The new technologies can also present new barriers to entry in GVCs in terms of know-how, skilled human resources, and capital investments.[22] The IoT, for example, could make manufacturing less reliant on low-skilled labour and more dependent on the availability of engineers, programmers, and other specialized professions, which are in short supply in many latecomer countries.[23]

Nevertheless, GVCs do present channels through which developing countries can better engaged with digital technologies. A UNIDO study in five 'latecomer' countries found that, although less than 5 per cent of the surveyed firms were aware of Industry 4.0 technologies, firms could still integrate the technologies into their manufacturing processes and become more productive.[24]

Digital technologies such as IoT and AI could also encourage more SMEs from developing countries to participate in GVCs by tracking shipments and inventory bridging and thus reducing trade costs.[25] AI can help firms find the fastest, cheapest, and most sustainable routes for shipping goods around the world.

Industry 4.0 technologies could held decentralize advanced activities across regional production networks, allowing more peripheral locations to house activities such as engineering, design, and software development. This can help them better serve regional markets.[26] For example, Cloudfactory, a United States company offering data processing services for AI and automation, has opened subsidiaries in Nepal and Kenya. The company has sliced up its activities, retaining the more advanced parts of the value chain in the United States headquarters, while employing staff in Nepal and Kenya for data input, quality control and processing – offering new opportunities for, mainly young, well-trained workers.[27]

Source: UNCTAD.

Industry 4.0 technologies can enhance the productivity, improve safety, and decrease the environmental impacts (Box IV-2). They can reduce the carbon footprint of current production and consumption modes – facilitating the introduction of new green technologies and eco-products and enhancing the diffusion of business models based on circular economies. Nevertheless, digital technologies may also cause further environmental degradation due to the use of rare materials in their production, for example, and high energy consumption entailed in their use.

Box IV 2
Industry 4.0 technologies in mining

Mining might represent a challenge for frontier technologies. It is a relatively difficult sector to develop and apply technologies like IoT due to its environment, which involves dust, high humidity, and often isolated locations lacking connectivity.[28] This does not mean, however, that the sector must be stuck in the past with traditional methods. In fact, actors in the industry note that mining is going through the beginning of a profound digital transformation.[29]

One example is the Syama mine in Mali, which is a purpose-built and fully automated mine. It employs a fibre-optic network designed to control and monitor activities from above-ground centres, incorporating an automated haulage system, automated rehandle level, and digitalisation.[30] This is expected to generate a cut in costs by around 30 per cent and improve efficiency and productivity as the machines can operate 22 hours a day without losing time for shift changes.[31]

However, taking advantage of the opportunities available by Industry 4.0 technologies involves policy efforts. There must be investments in infrastructure to support the digitalisation of mines, as well as the provision of education and training to mitigate the impact on low-skilled labour. Policies and regulations are an important incentive for innovations in the sector through, for instance, pushing for stricter environmental regulations.[32]

Source: UNCTAD.

The more advanced technologies can be considered in two categories (Table IV-1):

1. *Smart manufacturing and service technologies* – leading to automation and decentralization of tasks and including advanced robotics, 3D-printing, wireless technologies, and sensors.
2. *Data processing technologies* – allowing interconnection and data exchange, including big data, blockchain, cloud computing, and AI.[33] What makes these technologies novel is the integration of hardware, software, and connectivity in complex production systems.[34]

Table IV 1
Selected industry 4.0 technologies in manufacturing

Technology		Description
Smart manufacturing and service technologies		
Industrial robots		Robots are programmable machines that carry out actions and interact with the environment via sensors and actuators, either autonomously or semi-autonomously. Industrial robots usually replace workers, automating almost entirely the processes on the factory floor. Examples are spot welding robots used in the auto industry.
Cobots		Cobots are robots that collaborate with humans. They are easily re-programable, for example, by a worker guiding the arm of the cobot through a new path. They can be used in machine tools in a manufacturing plant, packaging and palletizing.
3D printing		3D printing, also known as additive manufacturing, produces three-dimensional objects based on digital information. 3D printing can create complex objects, with little waste. 3D printers are used for prototyping and also for final production in manufacturing.
Internet of Things (IoT)		IoT refers to internet-enabled physical devices that collect, share and act based on data. The IoT is vast; typical fields include wearable devices, smart homes, smart healthcare, smart cities and industrial automation. In manufacturing, IoT connects traditional machinery and tools with actuators and sensors.
Actuators		An actuator is a component of a machine that is responsible for moving and controlling a mechanism or system. It could be pneumatic, hydraulic, electric, thermal or magnetic. Actuators could, for example, measure heat or motion to determine the resulting action in the machine.
Sensors		Sensors detect external and internal conditions of equipment and products and send that information through the digital network. They can measure temperature, humidity, pressure, proximity and level, and visual and infrared rays.
Data processing technologies		
Big data		Big data refers to datasets whose size or type is beyond the ability of traditional databases to capture, manage and process. Big data also refers to the used of traditionally inaccessible or unusable data for making decisions.
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 is already widely used for applications that focus on narrow tasks, such as recommending what to buy online, spotting spam or detecting credit card fraud.

Source: UNCTAD based on UNCTAD (2022d).

Smart manufacturing and service technologies

Digital technologies can upgrade GVCs in numerous ways:

Monitoring standards – Standard-setting organizations can use new technologies for monitoring food, forestry and fisheries.[35] Instead of making annual field audits, officials can install fixed or mobile sensors to collect real-time data. Embedded in harvesting and logging equipment, for example, the sensors can upload to satellites data on tree species and biodiversity – and help detect illegal logging and fishing. International organizations such as FAO and the World Bank are now adopting these methods for monitoring environmental standards.

Logistics – Data collected from online-connected sensors, and from GPS tracking systems, can optimize logistics and significantly reduce carbon emissions.[36]

Operating efficiency – Smart manufacturing consumes less energy.[37] One plastics multinational, for example, has used energy sensors and IoT to reduce the power consumption in one of its plants by around 40 per cent, saving over $200,000 a year in energy costs.[38] Similarly, a smartphone manufacturer in China has optimized the operation of robots to increase productivity by 50 per cent.[39]

Better design – 3D-printing has been shown to reduce the weight of aircraft parts by 50 per cent and that of the aircraft by 4 to 7 per cent, with an estimated six per cent drop in fuel consumption.[40] This technology could thus significantly reduce carbon emissions from air travel.[41]

Data processing technologies

The use of big data analytics, cloud computing, artificial intelligence and blockchain technology can aid the reduction of environmental impacts in the production, processes or practices involved in the inputs needed for production:

Artificial intelligence – AI is important for environmental domains such as energy, production and natural resource management.[42] For electricity, for example, firms are using ‘smart grids’, to optimize green energy use – as well as smart meters, and other equipment. In agriculture, AI can be used for intelligent food logistics, using sensors and other technologies to plan shipping and delivery of perishable goods and for monitoring the state of the cargo. Lead firms are increasingly adopting sustainability tools to cut operational costs, increase product value, and coordinate GVCs. Certifications, codes of conduct, supply chain reporting, lifecycle assessments, supplier audits, smart packaging, and eco-efficiency programs may all be aided by AI.

Blockchain – Blockchain is a distributed verification system, in which the authenticity of a transaction or item is not provided by one institution, such as a bank, but is securely distributed and encrypted across a network of computers. Blockchain can be used, for example, to provide authentic information on the origin and sustainability of products,[43] Similarly, blockchains can be used for supply chain management – systems such as Echochain, ElectricChain, and Suncontract[44] are tracking faulty products or components, helping reduce the number of recalls and their environmental impact. [45] Blockchain can enhance sustainability; the Supply Chain Environmental Analysis Tool for example, traces the carbon footprint of products, and the Endorsement of the Forestry Certification tool can indicate whether wood is sustainably sourced. In addition, blockchains have downstream implications, as with the RecycleToCoin system that enables people to return plastic containers for a financial reward. Nonetheless, such initiatives must also ensure that recyclers have the appropriate equipment and work conditions since they deal with potentially hazardous substances, making them vulnerable to a myriad of health risks.[46]

However, as in other areas, there is always the risk of greenwashing, since AI does not always enhance sustainability to the extent that companies claim.[47] Firm managers may overstate the impact of AI in order to boost brand and stock values.[48]

Greener relationships along the value chain

In assembly industries, there are many opportunities along the value chains to reduce materials, water and energy consumption, pollution emission, and waste reduction.[49] How this happens and who takes the initiative will depend on the nature of the relationships between each link in the chain – on the type of governance (Table IV-2). Governance can be classified as 'relational', if buyers and suppliers have reciprocal trust and long-term relationships and are interacting frequently to share information. Or governance can be 'captive' if there is a degree of monitoring and control by lead fires over small suppliers who are transactionally dependent, making it difficult to switch. In this case buyer firms may pay for upgrading service providers, both for reputational and cost-saving reasons.

Table IV 2
Five types of GVC governance

Type	Description
Market	This type has a low degree of explicit coordination and power asymmetry. Market linkages do not have to be completely transitory, as is typical of spot markets; they can persist over time, with repeat transactions. The essential point is that the costs of switching to new partners are low for both parties.
Modular	Typically, suppliers in modular value chains make products to a customer's specifications, which may be more or less detailed. Often, 'turn-key services' suppliers take full responsibility for competencies surrounding process technology, use generic machinery that limits transaction-specific investments, and make capital outlays for components and materials on behalf of customers.
Relational	In these GVCs, interactions between buyers and sellers are complex, which often creates mutual dependence and high levels of asset specificity. This may be managed through reputation or more trust-based ties. Spatial proximity may support relational value chain linkages, but trust and reputation might well function in spatially dispersed networks where relationships are built up over time. This type has an intermediate degree of explicit coordination and power asymmetry.
Captive	In these networks, small suppliers are transactionally dependent on much larger buyers. Suppliers face significant switching costs and are, therefore, 'captive'. Such networks typically have a high degree of monitoring and control by a lead firm.
Hierarchy	This governance form involves vertical integration. The dominant form of governance is managerial control, flowing from managers to subordinates, or from headquarters to subsidiaries and affiliates. This type has a high degree of explicit coordination and power asymmetry.

Source: UNCTAD adapted from Gereffi et (2005).

In Sri Lanka, for example, lead firms use environmental standards as an element of chain coordination.[50] In this case, supplier firms comply with environmental standards to increase their competitiveness.[51] But not all firms may agree. In the leather industry, for example, producers believe that processing with chrome has the lowest environmental impacts along the entire chain, while buyers for brands believe that processing without chrome is better for their image.[52]

Another example is the maritime industry where a simple option is to reduce vessel speed since emissions are lower for slow ocean-going vessels[53] or to create smart ports (Box IV-3).[54] Alliances with cargo-owners and regulators can also enable technology for onboard monitoring.[55] This is in line with the international maritime organisation's measures to cut emissions from ships and reach half of 2008 emissions' level by 2050.[56]

Box IV 3
The strategic importance of sustainable smart ports

Over 80 per cent of global merchandise trade by volume, and more than 70 per cent by value, is seaborne. International shipping and ports provide crucial linkages in global supply chains and are essential for the ability of all countries to access global markets. Ports are critical infrastructure assets that serve as catalysts of economic growth and development.

UNCTAD has a project to raise awareness among ports and national authorities about the strategic importance of "Sustainable Smart Ports" (SSP) and in the importance of everyone competing on a level playing field.[57] Sustainable Smart Ports take advantage of the new data environments and the energy transition of the maritime sector, artificial intelligence and green technology-based solutions to enhance port operational efficiency. They also promote energy efficiency and clean/renewable energy sustainability, as well as tap into the possibility of producing clean/renewable-energy production and distribution.

Funded by the United Nations Development Account, this $600,000, three-year project started in 2022 and will support port authorities in Morocco, Ghana and Mauritius to assess the SSP status of their ports and identify and implement key priority actions.

Source: UNCTAD.

Supplier squeeze

Lead firms may, however, push the costs of sustainability compliance onto their suppliers, as has happened in wine and coffee sectors – resulting in 'supplier squeeze'.[58] Higher demands may also raise the barriers for entry and thus keep out smaller producers and deepen imbalances of power between firms in the North and South. This is because sustainability measures along GVCs have allowed lead firms, which are usually from the Global North, to capture new rents, reinforcing imbalances of power between firms in the Global North and the Global South.

If buyers are to demand higher standards, they will need to support suppliers. European buyers of olive oil from Tunisia, for example, tried to impose standards but due to a lack of financial and technical assistance, the extent of environmental upgrading of suppliers remained limited.[59]

Similarly, in the apparel industry in Pakistan, suppliers see environmental upgrading mainly as a cost, and a necessary 'entry ticket' for GVCs, and will need to invest new technology, certifications, system modifications and skills development, for which they are not compensated.[60]

Voluntary sustainability standards

Upgrading value chains can be based on voluntary sustainability standards (VSS). The United Nations Forum on Sustainability Standards (UNFSS) defines VSS as "standards specifying requirements that producers, traders, manufacturers, retailers or service providers may be asked to meet, relating to a wide range of sustainability metrics, including respect for basic human rights, worker health and safety, the environmental impacts of production, community relations, land-use planning and others".[61] VSS aims to promote sustainability mainly through collaboration among NGOs, industry groups or multi-stakeholder groups. By 2020, there were 150 VSS in agriculture and around 30 for mining and industrial products

VSS are gaining ground among diversified, export-oriented economies. Viet Nam, Indonesia and India score fairly high on VSS adoption, as do Ethiopia and the United Republic of Tanzania whose coffee exports are certified to meet multiple standards.[62]

By 2020, the number of voluntary sustainability standards range from 150 in agriculture to around 30 in mining and industrial products (See Box IV-4 for examples from various sectors). In agriculture, 14 VSS organizations cover eight agricultural commodities globally – bananas, cocoa, coffee, cotton, oil palm, soybeans, sugarcane, tea and forestry products.[63] In 2019, those standards certified a minimum of 20 million hectares of the eight agricultural commodities, around 8 per cent of the global area.[64] For bananas, certifications are concentrated in Colombia, Costa Rica, the Dominican Republic, Ecuador and Honduras; for cocoa, Côte d'Ivoire; for coffee, Brazil, Central America and Colombia; for palm oil, Indonesia and Malaysia; for soybeans, Argentina and Brazil; and for sugarcane Brazil.[65]

For textiles and clothing there are two main standards.[66] The Global Organic Textile Standard is recognized as the world's leading processing standard for organic fibres, including ecological and social criteria, independent certification of the entire supply chain.[67] The Fairtrade Textile Standard has been produced by Fairtrade International which supports small producer organizations and agricultural workers in developing countries.[68]

Box IV 4

Examples of voluntary sustainability standards

Manufacturing: In textiles: Organic Content Standard (OCS), the Global Organic Textile Standard (GOTS) and the Fairtrade Textile Standard. GOTS certified final products may include fibre products, yarns, fabrics, clothes, home textiles, mattresses, personal hygiene products, and food contact textiles.

Other sustainability standards for manufactured products include: ABNT Ecolabel, ARSO - Agriculture, ASEAN Guidelines on Promoting Responsible Investment in Food, Agriculture and Forestry, BRCGS Food Safety, Carbon Trust Product Footprint Certification, East African organic products standard (EAOPS), EcoVadis, Ethical Trading Initiative (ETI), Fair Labor Association, GreenCo, Recognised - Environmental Credentials Scheme, Global Reporting Initiative (GRI), ZNU standard, and the Climate, Community & Biodiversity (CCB) Standards. CCBs are used to identify projects that simultaneously address climate change, support local communities and smallholders, and conserve biodiversity. As of May 2017, 102 projects in 32 countries have been validated by the CCB Standards. The preponderance of projects is in tropical developing countries, particularly in Africa.[69]

Forestry: Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) are the two leading VSS at the global level. In 2019, PEFC and FSC certified more than 433.5 million hectares of forest, representing 10.7 per cent of the global forest area.[70]

Fishing: The Marine Stewardship Council (MSC) is an international non-profit organisation, which aims to promote sustainable fish stocks, minimizing environmental impact and ensuring effective fisheries management through the MSC Fisheries Standard. Developing world fisheries account for around 8 per cent of the total of MSC certified fisheries and 11 per cent of fisheries. More than 40 developing world fisheries have had pre-assessment and are engaging in a Fishery Improvement Project with partners.[71]

Mining: The main sustainability standards include the Alliance for Responsible Mining (ARM), Fairtrade International (FLO), Fairmined Standard, Fair Stone, IGEP, Responsible Jewellery Council (RJC), Social Accountability International, the Aluminium Stewardship Initiative Performance Standard, SGE 21, XertifiX. Established in 2004, ARM is a leading global expert which aims to transform the mining sector into a socially and environmentally responsible activity, through developing standards and certification systems for responsible artisanal and small-scale mining and facilitate the access of certified metals to fair supply.[72] Likewise, the Fairtrade Standard for Gold and Associated Precious Metals for Artisanal and Small-Scale Mining makes changes to the conventional trading system. It aims to improve small producers' social and economic well-being and enhance environmental sustainability.[73]

Energy products: Sustainability standards include the Alliance for Water Stewardship, Carbon Trust Product Footprint Certification, EO100TM Standard for Responsible Energy Development, Green-e, ISCC Plus, Lasting Initiative for Earth Certification, TerraChoic, Verified Carbon Standard (VCS), WFTO Guarantee System, SOCIALCARBON® Standard. To illustrate, the VCS Program provides the standard and framework for independent validation of projects and programmes, and verification of GHG emission reductions and removals.[74] The Round Table on Responsible Soy (RTRS) is a civil organization that promotes socially equitable, economically feasible and environmentally sound soy production. The RTRS Standard operates in China, India Argentina, Brazil, Paraguay and Uruguay.[75]

Livestock and tourism: VSS include East African organic products standard, VietFarm, and the Wildlife Friendly Enterprise Network (WFEN). The WFEN is a global community which unites conservationists, businesses, artisans, producers and harvesters. Certified Wildlife Friendly enterprises protect threatened and endangered species in Asia, Africa, Europe and the Americas, conserve over 13 million hectares of diverse wetland, forest and grasslands, and benefit over 200,000 people who coexist with wildlife.[76]

Source: UNCTAD.

3. SLOW DIFFUSION OF DIGITAL TECHNOLOGIES IN LATECOMER COUNTRIES

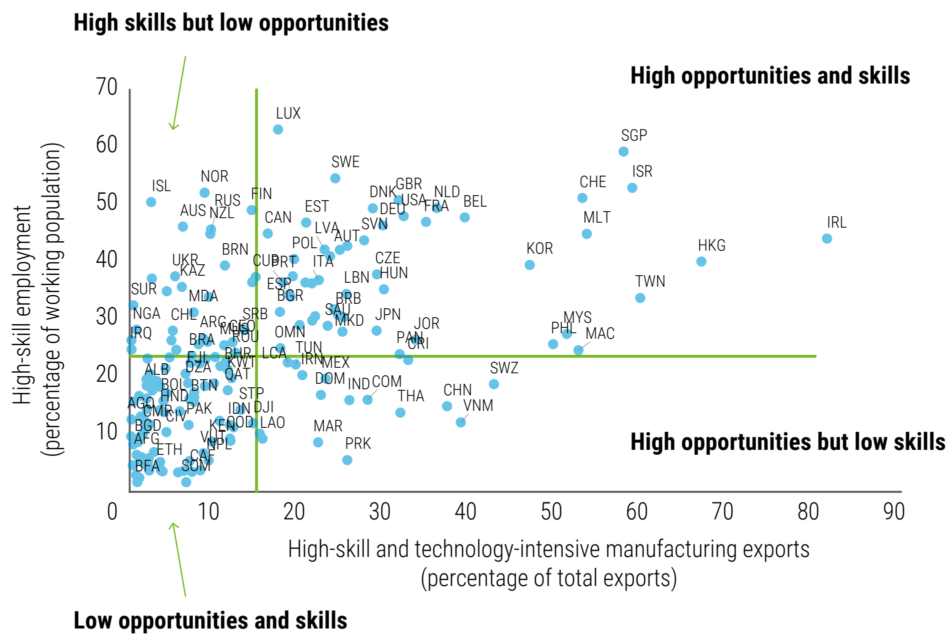
Thus far, Industry 4.0 technologies are mostly produced and adopted in a few leading economies.[77] More than 90 per cent of all patenting is in ten countries, all high-income except for China.[78] For exports the top ten countries, again including China, account for 70 per cent of the global market. Concentration is lower for imports: the top ten countries account for only 46 per cent of global imports of these technologies and include China, Mexico, India and Türkiye.[79]

For emerging digital technologies, UNIDO has identified the front-runner countries.[80] The top ten, are all high-income countries except for China. After these are 40 countries: 23 producer economies, among which there are Brazil and India; and 17 user economies comprising Algeria, Argentina, Bangladesh, Colombia, Indonesia, the Islamic Republic of Iran, Malaysia, Mexico, South Africa, Thailand, Türkiye and Viet Nam. The remaining countries show low to no activity, but all countries will be affected by the adoption of digital technologies in the more advanced countries.[81]

The adoption of digital technologies differs not just by country but also by sector and industry. As might be expected, the computer and machinery industry leads the way, making the greatest use of cloud computing and 3D printing technologies, while the transport equipment industry leads for the adoption of industrial robots.[82] In Morocco for example, the automotive industry is making more use of such technology than the garment industry.[83]

The countries best placed to move to smart production are those with stronger manufacturing industries and higher levels of skill. Figure IV-2 gives an indication of readiness, showing the high-skill and technology-intensive manufacturing exports as a percentage of total exports, and high-skill employment as a percentage of the working population. It is important to emphasise that the figure illustrates a simplified version of the analysis regarding the relationship between industry 4.0 benefits and manufacturing and labour skill levels.

Figure IV 2
Readiness to benefit from the diffusion of Industry 4.0



Source: UNCTAD (2022d: 18).
Note: The solid lines represent the unweighted global averages under these two indicators. Data labels use International Organization for Standardization economy codes.

The lines represent the unweighted global averages in these two indicators, segmenting the countries into four groups. According to these estimations, clustered in the top-right quadrant are the countries best placed, which are the United States and many countries in Europe, and in East and South-East Asia. To the bottom are countries which import high-tech goods, but lack the skills needed for a widespread diffusion of Industry 4.0. These include China, India, Mexico, Thailand, and Viet Nam. A third group has the necessary workforce but not the companies to take advantage of them, which may make it difficult to broaden beyond pockets of technology-intensive manufacturing. This includes many countries that rely heavily on commodity exports. such as Argentina, Brazil, Chile, Kazakhstan, and Nigeria. The fourth group, in the bottom-left quadrant, has neither the high-tech sectors nor the workforces, which applies to most developing countries.

For many countries, these technologies may seem distant prospects, but all will be affected by them sooner or later, so they need to anticipate the implications of the fourth industrial revolution on their economic and social systems.[84] Typically, most firms are at the stage of Industry 2.0.[85] This was corroborated by a firm-level survey in Argentina, Brazil, Ghana, Thailand, and Viet Nam.[86] For instance, in Ghana most firms were using analogue or rigid production, typically using computer-aided design only in product development. In Argentina, only 3 per cent of firms were using digital technologies and in Brazil only 4 per cent.[87] These countries have technological 'islands' that lack significant backward and forward linkages within their domestic economies.[88]

In Ghana, a recent UNCTAD survey encompassing 500 firms found very low adoption rates of frontier technologies – 3.6 per cent for industrial robots, 5.2 per cent for cobots, 5.6 per cent for 3D printing, 9.6 per cent for big data and 4.6 percent for virtual reality. The ICT sector had the highest levels, followed by tourism, agro-processing, pharmaceuticals and textiles (Box IV-5).[89] The three main barriers to adopting digital technology were identified as lack of finance, attachment to existing practices and traditional ways of doing things, and insufficient support from government.[90]

In a firm-level study in Bangladesh, local managerial staff were found to know very little about the potential for digital technologies, or the concepts of the circular economy.[91] Similarly, in Brazil companies in the plastics industry, particularly the smaller ones, had little understanding of the potential for digital technologies for more sustainable production.[92]

Box IV 5
A firm-level survey in developing countries

UNCTAD has partnered with researchers from the University of Johannesburg, the Science and Technology Policy Research Institute of the Council for Scientific and Industrial Research of Ghana, and the University of Nice Sophia-Antipolis on firm-level innovation surveys in Ghana, South Africa, and Tunisia concerning the deployment and use of new technologies. This project proposes a framework survey that could be applied in other developing countries

In Ghana, by mid-2022, the survey had been completed in 500 establishments. The survey found high levels of awareness of frontier technologies but very low levels of adoption. Only 4.1 per cent of the firms surveyed had adopted Industrial Robots and Virtual Reality, mainly in the agro-processing sector. Firms adopting cobots and 3D Printing constituted 5.2 per cent, and 5.6 per cent respectively, mainly in textiles and ICT sectors. Highest adoption levels were for social media at 84 per cent and mobile banking at 71 per cent. The main motivations for adopting these technologies were seen to be improvements in productivity working conditions and competitiveness.

Source: UNCTAD.

B. CREATING A TWIN TRANSITION

To seize windows of opportunity created by these technologies, latecomer countries will need to build digital competency along with the necessary infrastructure and institutions, while building innovation capacity and overcoming financial barriers.[93]

This is a task for governments, for the private sector and other stakeholders. The levels of industrialization, digital infrastructure, technological and productive capacities as well as involvement in GVCs are highly contextual. Therefore, the strategic responses will differ for emerging developing economies and less technologically advanced countries.

This section presents a list of critical policy areas that stakeholders in latecomer countries should consider, accounting for their technological level, existing preconditions, and different involvement in specific GVCs.

Aligning digital and green strategies

Several latecomer countries have national strategies for frontier technologies in the manufacturing sector. Examples are the 'Make in India' and 'Made in China 2025' programmes and the 'Industry 4.0 Agenda' in Brazil. In Africa, there are currently 83 strategic plans involving renewable energies, in Central and South America there are 65 plans, and in the Middle East 15.[94] Several developing countries have national strategies for enhancing digitalization, including Thailand, Viet Nam, South Africa, Chile, Argentina, Brazil and Mexico.[95]

Nevertheless, in the environmental and energy domain these strategies are often not coordinated with interventions or initiatives. In Bangladesh for example, footwear manufacturers have been found to have little motivation for adopting green technologies given the lack of environmental regulations and the general low level of environmental awareness.[96] Another study in Brazil finds that while the environmental laws are good, these are not linked with industrial policies.[97]

To take advantage of green windows of opportunity arising from the twin transitions in GVC manufacturing, policies need to be co-created across the energy-environmental, industrial and foreign investment spheres.

In the EU, Canada and the Nordic-Baltic countries, there is an increasing awareness of opportunities offered by digitalization for environmental protection and climate action, and of the need to reduce the environmental impacts of digitalization itself.[98]

Developing digital infrastructure

As these technologies progress, all countries will need stronger digital infrastructure, in particular high-speed and high-quality Internet connections.[99] There are, however, significant technological inequalities.

Concerning the fixed broadband connection, the observed average speed in developed economies (around 115 megabits per second) was almost eight times that of the least developed countries (LDCs) (around 15 megabits per second), reflecting infrastructure and technological.[100] But the technology divide is also visible within the same groups of countries and between rural and urban areas. An UNCTAD survey in 2021 found that 16 per cent of rural populations in LCDs had no access to any mobile network and 35 per cent could not connect using a mobile device.[101] In addition, the World Bank Enterprise Surveys[102] showed that more than 20 per cent of the interviewed companies in South Asia and around 14 per cent in Sub Saharan Africa identified electricity access as their biggest obstacle, which impacts their ability to use the Internet. Another constraint is the high cost of connectivity relative to income.[103] Moreover, the lack of reliable Internet access has been underlined in studies in Brazil[104] and India.[105]

Governments in developing countries should ensure high-quality Internet access. This will mean public and private investments in ICT infrastructure along with regulations to foster competition in the telecommunications sector. Governments should also address the connectivity gap between small and large firms and between urban and rural regions.

Some technologies may also need specific regulations. This would be the case for drones, which could help deliver lightweight, high-value goods, such as medical supplies, to remote areas. For instance, Rwanda is now allowing airspace to be accessed by pilotless aircraft.[106]

Building digital skills

UNCTAD has identified skills at four different levels – for adopting technologies, for basic use, for adapting technologies, and finally for creating new ones.[107] For developing countries it is particularly important to have the capacity to adapt and modify technologies since these are likely to be used in circumstances different from those in which they were originally developed.

Governments need to support businesses, including SMEs, to help them build digital skills in areas such as market research, product development, sourcing, production, sales, and after-sales services.[108] Special consideration should be given to women in informal and artisanal small and microenterprises, particularly for entrepreneurs.[109]

In Malaysia, for example, the Penang Skill Development Centre provides technical knowledge and organizes training programmes for advanced industrial operations.[110] Another relevant institution in Malaysia is CREST, an R&D consortium that researches Industry 4.0 topics and provides scholarships for advanced degrees. In Thailand, the Government, in collaboration with the Government of Japan, has established the Automotive Human Resource Development Program to upgrade the skills of local suppliers: domestic universities and research institutes are training engineers and technicians in AI, robotics, and mechatronics.

Countries also need to reduce brain drain, retain skilled professionals, and attract skilled expatriates. An interesting example is the NerUzh program in Armenia, which offers start-up funding designed to attract potential tech entrepreneurs from the diaspora.[111]

Building international partnerships

In the European Union, 26 member states, along with Norway and Iceland, have signed a declaration to accelerate the use of green digital technologies, deploy energy-efficient AI solutions and introduce digital passports to track products and improve circularity and sustainability.[112]

Developing countries in particular can benefit from participation in international projects and organizations.[113] An example is Prospecta Americas, a regional programme aimed at improving knowledge about technologies such as big data, AI, IoT, robotics, blockchain, and at evaluating their economic, social and environmental impact across OAS member states.[114] Another example is the UNIDO multi-stakeholder platform for sharing available tools and methods for digital transformation among SMEs.[115]

The UNDP is supporting projects aimed at building cross-sectoral ecosystems of partnerships across governments, companies, and NGOs. In Armenia, for example, the ImpactAim Venture Accelerator, in cooperation with the Enterprise Incubator Foundation, Innovative Solutions and Technologies Center Foundation, is supporting energy efficiency and exploring the application of AI and data sciences in the environmental field. The project is accelerating 33 start-ups in Armenia, two in Belarus and one in the Philippines[116]. Accelerators and incubators can facilitate learning and diffuse knowledge through best practices and demonstration projects.

Setting standards and regulations

Following international standards helps ensure interoperability and promotes productivity and innovation. Standardization offers obvious benefits in international trade networks and within global value chains – strengthening SDG pillars and their impact on the environment.[117] Regulations and standards are also important for securing data privacy.[118] In the case of 5G technology standard setting also involves political considerations.[119]

The International Communication Union (ITU) publishes international standards related to industry 4.0 and associated technologies such IoT. These standards are available free of charge for downloading and use in developing countries. ITU also organizes events that enable countries to obtain new knowledge and works with developing countries to bridge standardization gaps and assist them to become more involved in standardization activities.[120] The ITU has established focus groups that address the environmental efficiency industry of 4.0 technologies, as well as water and energy consumption, and provide guidance on how to operate these technologies in a more environmentally efficient manner.[121]

Providing financial support

Most developing countries have few resources for R&D programmes in digital and green technologies and the use of Industry 4.0. Smaller companies in particular find it difficult to make the necessary investments. In India for example, such companies have struggled to invest in the necessary technology in the automotive, metals and machinery, food, textile, and electrical equipment industries.[122] Similarly in Brazil many companies lack the necessary investment funds.[123, 124]

If companies are to combine both green and digital objectives, they will need convincing evidence about the return on investment. In Brazil for example most companies investing in digital technologies are doing so primarily to boost productivity.[125] For this purpose, the public sector, in partnership with international donors and development banks, needs to set up demonstration projects.[126]
A number of countries have established innovation and technology funds, sometimes in collaboration with international donors or multinational development banks

- *Malaysia* – The Bank Pembangunan has allocated RM3 billion in its Industry Digitalisation Transformation Fund (IDTF).[127]
- *Peru* – The ProInnovate Program funds and provides technical support for Industry 4.0 projects.
- *Türkiye* – Small and Medium Enterprises Development Organization of Turkey (KOSGEB) funds SME investment projects products medium-high and high-technology manufacturing.
- *Philippines* – The small enterprise technology program (SETUP) offer seed funds for acquiring technology along with training and other forms of support.[128]
- *South Africa* – The post-COVID recover plan[129] includes support for MSMEs for green innovation, and an artificial intelligence institute.[130]
- *Uganda* – Uganda Green Enterprise Finance Accelerator facilitates the flow of green finance by strengthening green SMEs and improving available financial mechanism.[131]

These activities are complemented with foreign direct investment (FDI). Governments can encourage FDI with public investments infrastructure and offering incentives for companies that adopt green and digital technologies.[132] An example is the Green Channel initiative in Latvia, which offers a fast track for FDI in fields such as ICT, bioeconomy, smart materials, smart energy, and mobility.[133]

1 OECD, 2020.

2 Data are available at https://www.wto.org/english/news_e/news22_e/stat_04feb22_e.htm.

3 "[T]he drive to increase supply-chain resilience will not lead to a "rush to reshore" but could become a "drag on development", with new investments in international networks no longer looking for locations offering low cost factors of production to the same degree" (UNCTAD, 2021) (177). Also see for example Gereffi et al., 2021; Miroudot, 2020.

4 De Marchi et al., 2019

5 The techno-economic paradigm driven by information and communication technologies (Perez, 2013).

6 Surana et al., 2020; Zhang and Gallagher, 2016; Amendolagine et al., 2021

7 De Marchi et al., 2019

8 De Marchi et al., 2019

9 Alves Dias et al., 2020

10 Gallagher et al., 2019

11 Beise and Rennings, 2005

12 Ponte, 2020

13 Lema et al., 2020

14 Pietrobelli and Rabellotti, 2011

15 UNDP - Chief Digital Office, 2022

16 Strange and Zucchella, 2017

17 Rodrik, 2018

18 ILO, 2020.

19 UNIDO, 2019

20 UNCTAD, 2018a

21 Akileswaran and Hutchinson, 2019

22 Banga, 2022

23 Akileswaran and Hutchinson, 2019

24 Delera et al., 2022

25 WTO, 2019

26 UNIDO, 2019

27 For more information about Cloudfactory and its presence in Nepal and Kenya see https://www.cloudfactory.com/hs-fs/hub/351374/file-1151354869-pdf/press-files/gscouncil-In_Their_Own_Words_An_Interview_with_CloudFactory.pdf.

28 Pincheira et al., 2022OEMs, owners, users, and inspectors

29 Sánchez and Hartlieb, 2020

30 Sánchez and Hartlieb, 2020; *Project Sindicate*, 2021

31 *Project Sindicate*, 2021

32 Sánchez and Hartlieb, 2020

33 De Marchi et al., 2019

34 Andreoni and Anzolin, 2019

35 Gale et al., 2017

36 Mangina et al. (2020) drawing on data from EU and EFTA.

37 UNCTAD, 2022e

38 Efficiency Vermont, 2020

39 Elmo Motion Control Ltd, 2020

40 Huang et al., 2016

41 UNCTAD, 2022e

42 Toniolo et al., 2020. AI is relevant to addressing several targets across the SDGs but it is also an obstacle in certain cases. In the energy field the data centres used to power AI have a very high energy demand (Vinuesa et al., 2020).

43 Nikolakis et al., 2018

44 Echochain (Echochain, 2022) measures the impact of product portfolios and measures and designs sustainable products. ElectricChain (Positive Blockchain, 2022) is a project that verifies and publishes data from solar energy generators. Suncontract (Sun contracting, 2022), as the name indicates, is a contracting model for commercial users that avoids the need of users buying the photovoltaic system.

45 Saberi et al., 2019

46 UNEP, 2019

47 Dauvergne, 2020

48 Ibid.

49 Golini et al., 2018; Jin et al., 2022; Wang et al., 2022

50 e.g., LEED; ISO 14001

51 Khattak et al., 2015

52 De Marchi and Di Maria, 2019

53 Poulsen et al., 2018

54 For a discussion on environmental sustainability and the maritime industry, see (UNCTAD, 2019a).

55 Virtual vessel arrival systems offer a low-cost strategy to reduce these emissions by informing vessel operators of expected delays and aligning arrival times with berth availability.

56 IMO, 2022

57 https://unctad.org/project/sustainable-smart-ports-african-countries-including-small-island-developing-states-recover

58 Ponte, 2020

59 Achabou et al., 2017.

60 Khan et al., 2020

61 UNFSS, 2013

62 UNFSS, 2020

63 Those VSS organisations include: 4C Services (4C), Better Cotton Initiative (BCI), Bonsucro, Cotton made in Africa (CmiA), Fairtrade International (Fairtrade), Forest Stewardship Council (FSC), GLOBALG.A.P., IFOAM, Programme for the Endorsement of Forest Certification (PEFC), ProTerra Foundation (ProTerra), Rainforest Alliance (Rainforest), Roundtable on Sustainable Palm Oil (RSPO), Round Table on Responsible Soy (RTRS) and UTZ (a programme and certification scheme for sustainable farming) (Elamin and Fernandez de Cordoba, 2020).

64 Global Survey on Voluntary Sustainability Standards, 2022

65 UNFSS, 2020

66 Opperskalski et al., 2020

67 https://standardsmap.org/en/factsheet/30/overview?origin=&products=&name=Global%20Organic%20Textile%20Standard%20-%20GOTS

68 https://www.fairtrade.net/

69 https://www.climate-standards.org/ccb-standards/

70 Global Survey on Voluntary Sustainability Standards, 2022

71 https://www.msc.org/

72 https://www.responsiblemines.org/en/

73 https://standardsmap.org/en/factsheet/468/overview?origin=&products=&name=Fairtrade%20International%20-%20Gold%20Standard

74 https://verra.org/project/vcs-program/

75 https://responsiblesoy.org/about-rtrs?lang=en

76 https://wildlifefriendly.org/tag/certified-wildlife-friendly/

77 UNCTAD, 2022

78 Source: UNIDO, 2019. The countries are USA, Japan, Germany, China, Taiwan, France, Switzerland, UK, Korea, and The Netherlands.

79 According to UNIDO (2019) the top 10 exporting countries are Germany, Japan, China, Italy, Taiwan, Austria, USA, Korea, Switzerland, and France. The top importing countries are China, USA, Germany, Mexico, Russia, Italy, India, UK, Türkiye, and France.

80 UNIDO, 2019

81 Followers in production are identified based on their patenting or export activities while followers in use based on import of digital related technologies. Three more groups of countries are identified: latecomers in production including 16 economies, latecomers in use with 13 countries and laggards (88 countries) showing no or very low engagement with I4R technologies. For details about the classifications see UNIDO, 2019.

82 UNIDO, 2019

83 Auktor, 2022

84 UNCTAD, 2022.

85 Cirera et al., 2022; Lee, 2019

86 UNIDO, 2019

87 Andreoni and Anzolin, 2019

88 Matthess and Kunkel, 2020

89 Essegbey et al., 2022

90 Essegbey et al., 2022; UNCTAD, 2022f

91 Dwivedi et al., 2022

92 Nara et al., 2021

93 UNCTAD, 2022e.

94 Information is available at https://www.iea.org/policies?type=Strategic%20plans&region=Africa%2CCentral%20%26%20South%20America&status=In%20force&source=IEA%2FIRENA%20Renewables%20Policies%20Database.

95 UNIDO, 2019 and UNCTAD, 2022.

96 Dwivedi et al., 2022

97 Cezarino et al., 2019

98 For more information see (https://www.consilium.europa.eu/en/press/press-releases/2020/12/17/digitalisation-for-the-benefit-of-the-environment-council-approves-conclusions/) and Nordic Council of Ministers (2021).

99 UNCTAD, 2021c

100 UNCTAD, 2021a

101 UNCTAD, 2021c

102 Data are available at enterprisesurveys.org.

103 UNCTAD, 2021c

104 Cezarino et al., 2019

105 Luthra and Mangla, 2018

106 World Economic Forum, 2019

107 UNCTAD, 2019b

108 UNCTAD, 2022

109 UNCTAD, 2014a, 2019b

110 Lee et al., 2020

111 More information about the NerUzh program is available at http://diaspora.gov.am/en/programs/31/neruzh

112 More information is available at http://diaspora.gov.am/en/programs/31/neruzh

113 UNCTAD, 2022

114 More information is available at http://diaspora.gov.am/en/programs/31/neruzh

115 UNCTAD, 2022

116 More information is available at impact.aim.com.

117 UNIDO, 2021

118 Luthra and Mangla, 2018

119 For details see the article *China, US and Europe vie to set 5G standards* on https://www.ft.com/content/0566d63d-5ec2-42b6-acf8-2c84606ef5cf (February 6th, 2022)

120 UNCTAD, 2022

121 More information is available at https://www.itu.int/en/ITU-T/focusgroups/ai4ee/Pages/default.aspx.

122 Luthra and Mangla, 2018

123 Cezarino et al., 2019the authors aim to explore the relationship between the concepts of Industry 4.0 and circular economy

124 Nara et al., 2021

125 Nara et al., 2021

126 UNCTAD, 2022

127 UNCTAD, 2022e

128 Contribution from UNIDO

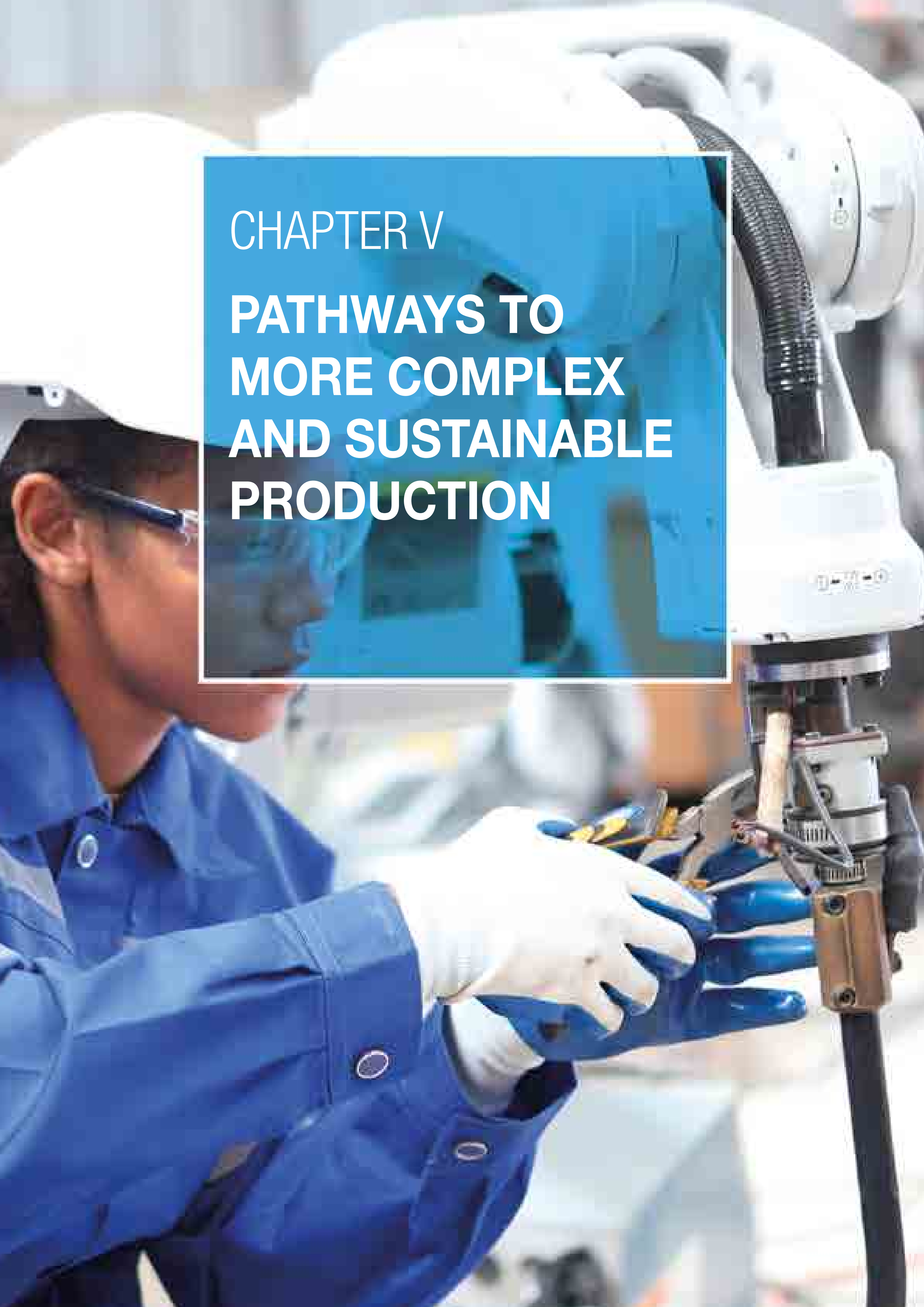
129 https://www.gov.za/sites/default/files/gcis_document/202010/south-african-economic-reconstruction-and-recovery-plan.pdf

130 Contribution from UNEP

131 https://ugefa.eu/

132 UNCTAD, 2022d

133 More information is available at investinlatvia.org.



CHAPTER V

PATHWAYS TO MORE COMPLEX AND SUSTAINABLE PRODUCTION

There is a path to diversify towards more complex and greener production, but taking it might be harder for developing countries

Strategic diversification is key because:

- Diversification is path dependent
- Different products within the same industry can have higher or lower levels of carbon footprint
- In general, more complex products have higher carbon footprints

Countries have not followed a path of increasing complexity and reducing emissions

For selecting more complex and greener directions, governments should:

- Strengthen national capacities for analysing these new sectors
- Consider how they can fit into global value chains

Developing countries need to diversify their economies towards sectors that have lower carbon emissions (see Box V-1).[1] In low-income developing countries, economic diversification involves emulating industries in more developed countries – a steady progression that builds on existing industries – it is thus 'path-dependent'.[2] If a country already has the capacity for machinery or electronics production, it can more easily move in a number of directions that build upon this competence. But if it is largely producing primary products, it has fewer starting points. And when basic technologies need to be learned or transferred from abroad, then innovation is likely to require greater government support.[3]

If developing countries follow the previous growth path of the developed countries, then global greenhouse gas emissions will continue to increase rapidly.[4] Analyses of the historical experience are mixed. Some studies indicate that moving to more complex products leads to an initial increase in greenhouse gas emissions per unit of output, followed by a decline.[5] Others have found that increasing economic complexity results in better overall ecological performance.[6]

In either case, countries will need to aim in greener directions, particularly through the use of renewable energy, and concentrating on more knowledge-intensive industries.[7] But whatever path they choose, governments in low- and lower-middle-income developing countries have to act strategically, quickly and decisively; otherwise, they will be left further behind.[8]

Box V 1
Transforming economies through diversification

Transforming economies through diversification is one of the four major transformation needs identified in UNCTAD XV's outcome document, the "Bridgetown Covenant: From inequality and vulnerability to prosperity for all," to move to a more resilient, digital and inclusive world of shared prosperity.[9] This reemphasizes UNCTAD's focus on helping countries understand the benefits and the policies required to foster diversification.

In addition to its technical cooperation programmes which have advised countries in harnessing trade, investment and technology for structural transformation, UNCTAD has produced several Reports on the topic. Some recent examples are:

- The *Least Developed Countries Report 2022 - The path towards the green structural transformation of the LDCs*, which provides elements to help LDCs better understand where they stand in terms of historical responsibilities for climate change, the impact of their participation in the global economy, including GVCs, on material use and carbon emissions, the impact of unilateral trade policies with environmental goals by their trading partners on the sustainable structural transformation of LDCs, and the policy options available for these countries and their development partners to help put their economies on a greener path.
- *The Economic Development in Africa Report 2022* - Rethinking the Foundations of Export Diversification in Africa: The catalytic role of business and financial services, which examined how countries can help foster the growth of a highly competitive, technology-intensive services sector in Africa to drive export diversification.[10] The Report showed how African countries could increase manufacturing productivity, driving the region's economic growth and structural transformation, by addressing barriers to trade in services, boosting relevant skills and improving access to innovative alternative financing.
- UNCTAD's *Catalogue of Diversification Opportunities 2022*,[11] which presents potential new products for export diversification for 233 economies based on analysing their economic complexity and position in the product space. Its objective is to inform governments, the private sector and other stakeholders of the national innovation systems on possible directions for technological transformation of these economies. The catalogue presents information on four main areas: 1) basic statistics regarding diversification, 2) potential new sectors for diversification, considering all products and the markets that offer growing export opportunities, 3) potential new sectors for diversification considering only agri-business products and the markets that offer growing export opportunities, and 4) examples of potential new products with higher export opportunities.

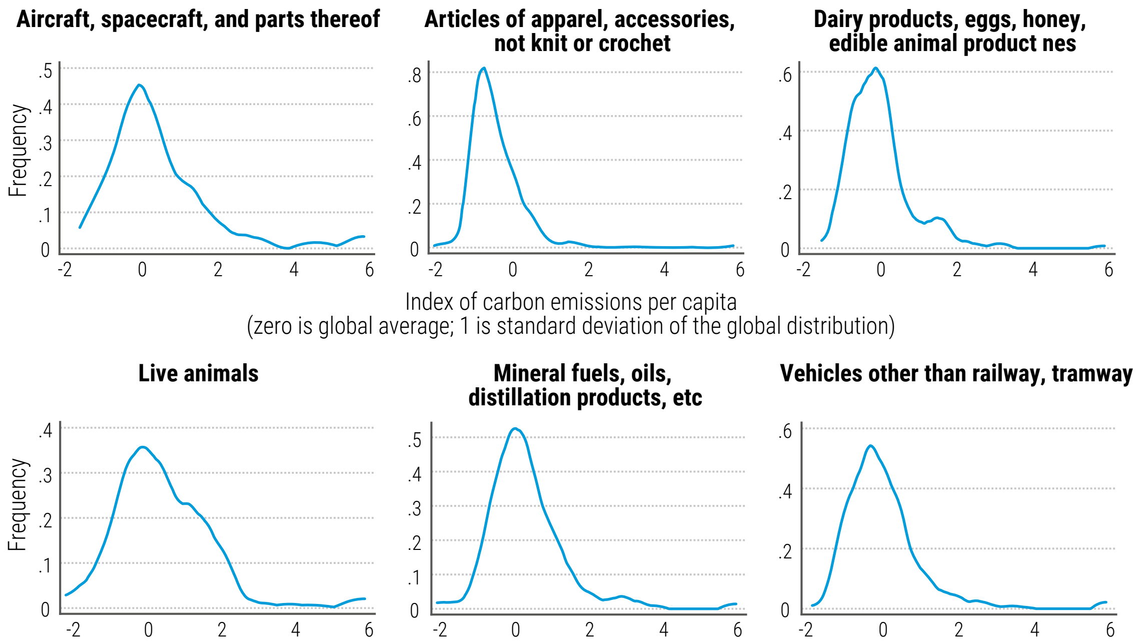
Source: UNCTAD.

A. IDENTIFYING GREENER PRODUCTION

To help countries choose greener pathways, UNCTAD has produced indices of economic complexity and carbon footprints for over 43,000 products exported in international markets.[12] This analysis shows that within each industry, there is a range of carbon emissions similar to a statistically normal distribution. This is illustrated in Figure V-1 which indicates that for apparel the average emissions are lower, with the distribution shifted to the left, while for live animals there is a greater weight on the right.

Figure V 1

Distribution of carbon emissions by products within sectors, 2018

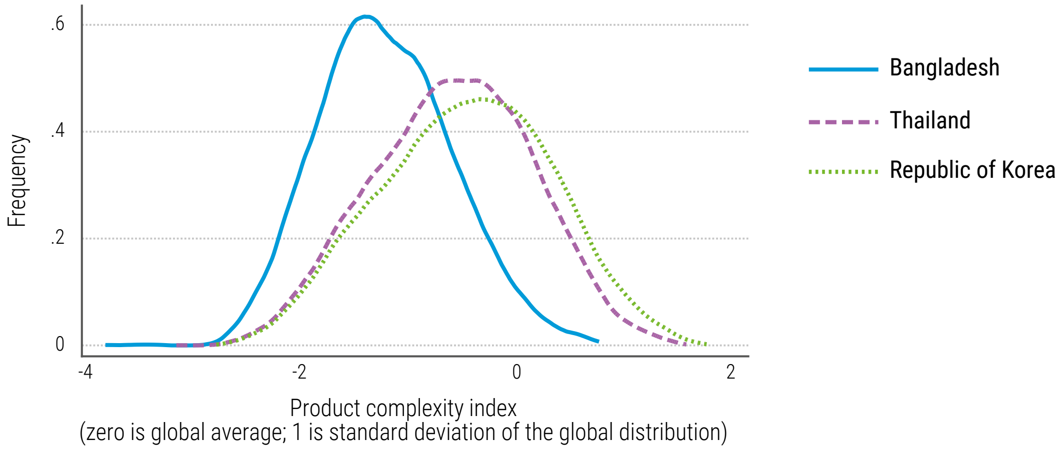


Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

Note: On the horizontal axis, zero represents the global average, and 1 is the standard deviation of the distribution. The vertical axis shows the frequency in which a level of carbon emissions is associated with products within a sector.

The result is similar when considering the output of countries – which generally have products from low to high carbon footprints. This is illustrated in Figure V-2 for Bangladesh, Thailand and the Republic of Korea in 2010. For Thailand and the Republic of Korea the distribution is close to the global average while Bangladesh's product mix is shifted to the left with a lower carbon footprint.

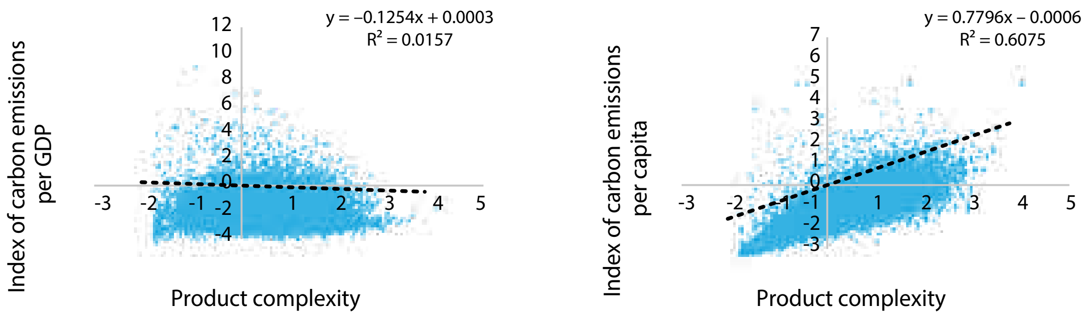
Figure V 2
Distribution of index of carbon footprint, selected countries 2010



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

When this output and consumption is taking place in a country that is growing from a low base, there is likely to be an increase in carbon emissions per capita. Over the past two decades, however, that link seems to have been weakening, so that increasing complexity is less likely to result in increasing emissions. As the product mix becomes more complex and more sophisticated, carbon emissions fall per unit of GDP (Figure V-3).

Figure V 3
Association between carbon footprint and product complexity, 2018

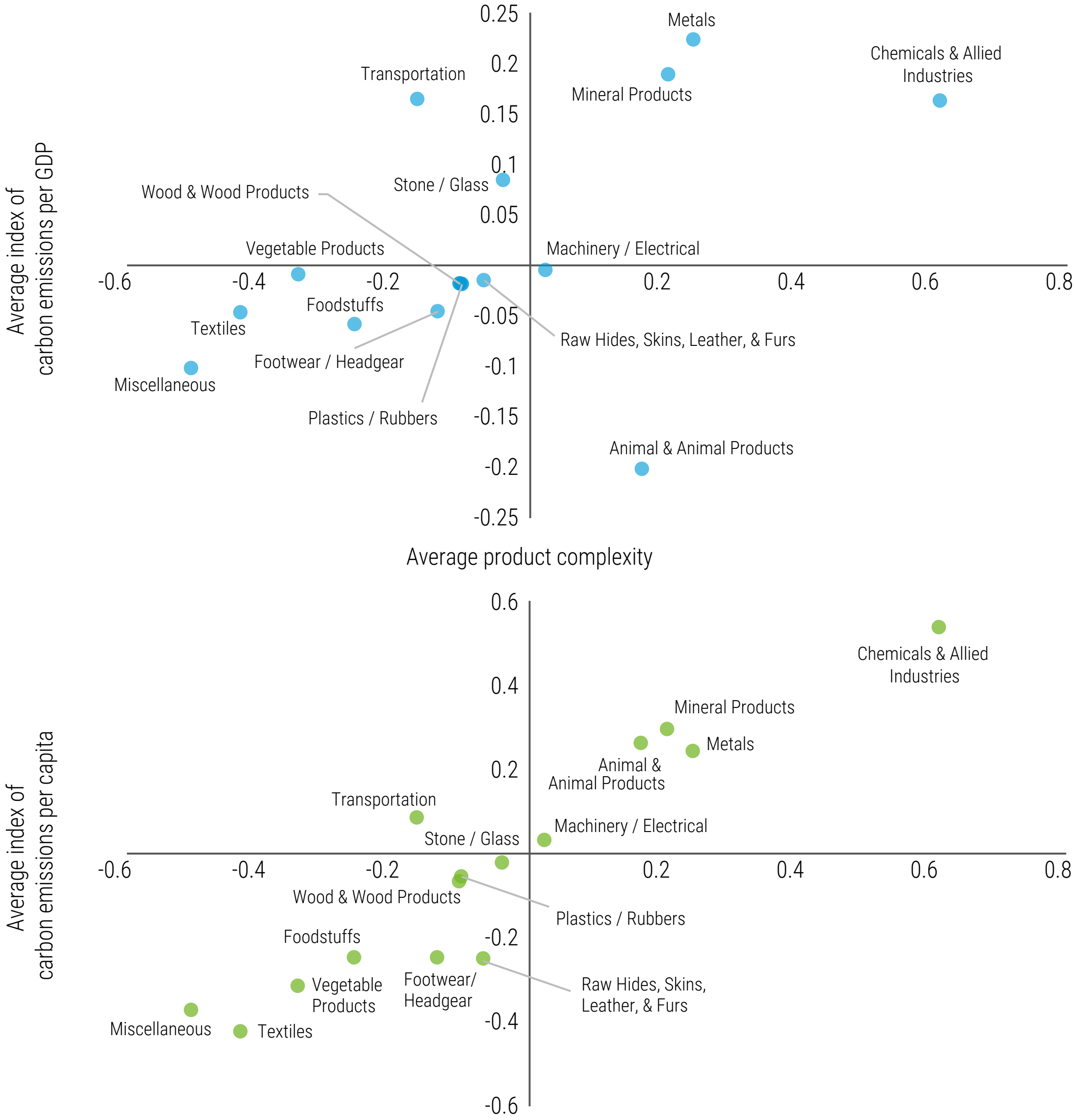


B. PATHS TO GREENER PRODUCTION

Generally, as countries move from agriculture to industry and to medium and high-tech manufacturing there is an increase in 'complexity' which refers to higher levels of technology to be produced.[13] Increasing complexity does not necessarily lead to greener production. Much will depend on the product mix. Figure V-4 compares indices of product complexity and carbon emissions by sectors. The less complex sectors that also have lower carbon footprints are textiles, vegetable products, foodstuffs and footwear. The sectors that are more complex and have higher carbon footprints are chemicals and allied industries, metals and mineral products.

Figure V 4

Green outcomes and complexity by sector, 2018

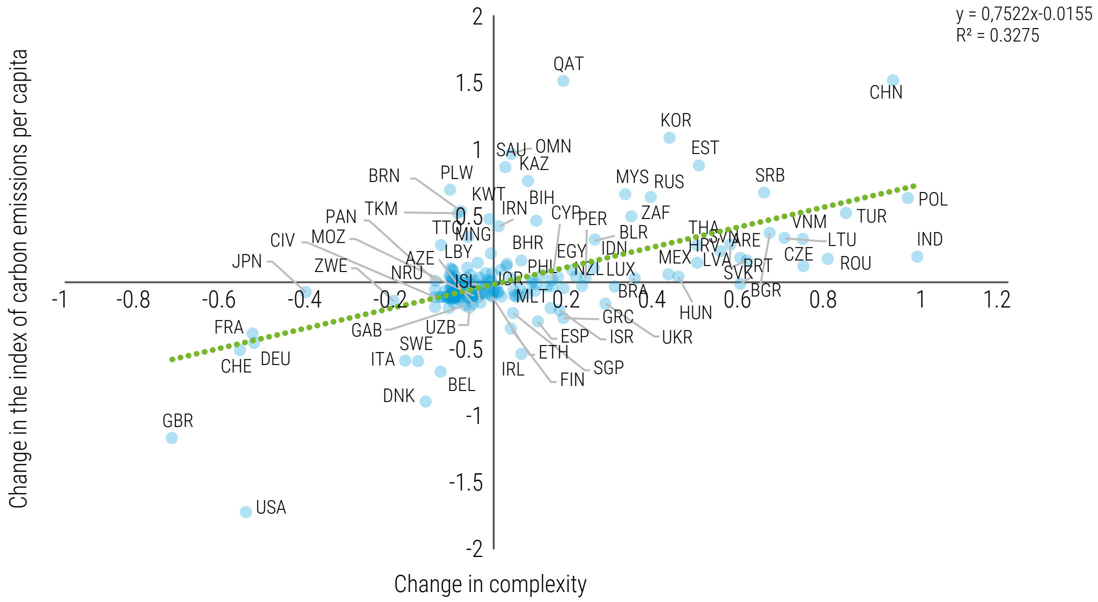


Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).
Note: On both axes, zero represents the global average, and 1 is the standard deviation of the distribution.

Figure V-5 shows how for each country these two indices have changed over the past decades. Some of the countries that have increased their complexity the most are India, Poland, China, Türkiye, Romania, Czech Republic, Viet Nam, Latvia, Lithuania, Bulgaria, and Serbia. These countries have generally also increased their index of emissions per capita. On the other hand, countries have reduced complexity and their indices of carbon emissions include the United States and the United Kingdom.

Figure V 5

Change in complexity and carbon footprint, 2000-2018

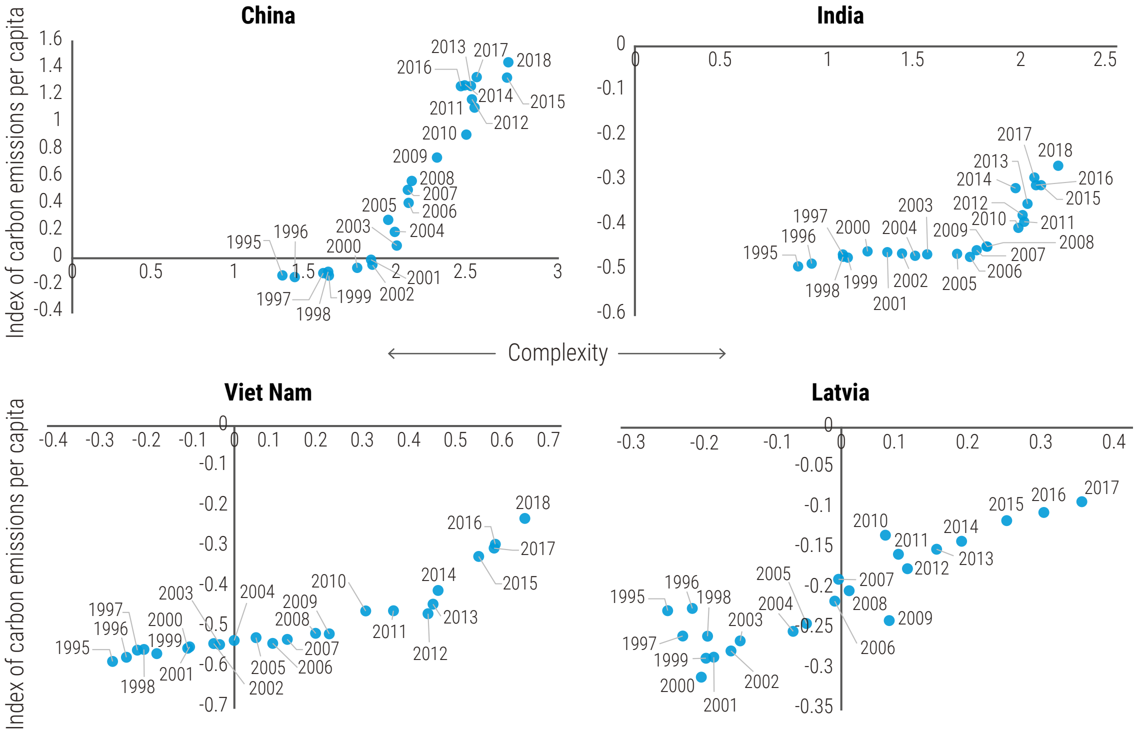


Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).
Note: On both axes, zero represents the global average, and 1 is the standard deviation of the distribution.

China – In the period before entering WTO in 2001, China diversified towards products with about the same level of carbon emissions per capita, using roughly the same technologies. Subsequently, the country diversified towards output that involved higher carbon emissions per capita (Figure V-6).

Figure V 6

Examples of changes in complexity and carbon footprint, selected countries



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).
Note: On both axes, zero represents the global average, and 1 is the standard deviation of the distribution.

India – Here the rapid increase in the index of carbon emissions per capita was in 2010, though less pronounced than in China. The index of emissions per capita for India is, nevertheless, still much lower than the global average.

Viet Nam – From 1995 to 2018, the country moved from below to above average economic complexity. The increase was faster following the global financial crisis, but the increase in carbon emissions per capita was far below the global average (Box V-2).

Latvia – Since the 2000s, complexity and the index of carbon emissions per capita have increased at a fairly constant rate. The increase in complexity has been accompanied by increasing carbon efficiency, particularly between 1995 and 2007. The index of carbon emissions is below the global average (Box V-3).

Box V 2
Viet Nam thrives with foreign direct investment

Over the past 30 years, the economy has witness unparalleled changes. From one of the poorest nations, Viet Nam has grown into a lower middle-income emerging economy. Between the 1990s and 2019 the poverty rate declined from above 70 per cent to below 6 per cent with average per capita income of $2,700.[14] Average economic growth was almost 7 per cent. This has involved structural transformations away from agriculture to include machinery, footwear, and electronics.

Rapid economic growth has been fuelled by foreign direct investment which between 1990 and 2018 rose from $180 million to $15.5 billion.[15] Beyond footwear and textiles and garments, FDI intensified in industries such as electronics and electrical equipment.

The increase in FDI was a response to national-level strategies. In 1987, the Law on Foreign Investment allowed for FDI via joint state-private ventures and wholly foreign-owned corporations. This was followed in the 1990s by laws on land ownership, and on private enterprise. The 1992 Constitution further encouraged FDI by providing for state guarantee of ownership.

Viet Nam explored new comparative advantages in electronic and telecommunication equipment products through foreign direct investment and active participation in the Asian electronic regional network.[16]

The enhanced economic diversification can be linked to Viet Nam's active participation in international agreements, whether bilateral, plurilateral or through membership of ASEAN. Viet Nam signed the Textile and garment trade agreement with European Community in 1992, acceded to the Association of Southeast Asian Nations (ASEAN) in 1995, and normalized political relations with the United States in the same year. In 1998, Viet Nam joined APEC, and signed the US-Viet Nam Bilateral Trade Agreement in 2000. Assertive international integration culminated in accession to the WTO in 2007 which has enhanced diversification and participation in GVCs. In 2015, Viet Nam engaged with Trans-Pacific Partnership negotiations.

Due to Viet Nam's continuing efforts to integrate into the global trade and investment system, exports of goods and services grow constantly even when neighbouring countries have stagnated or deteriorated.[17]

The Government has established special economic zones (SEZS) which between 2000 and 2014 have attracted $257 billion in FDI. SEZs contribute to 40 per cent of national industrial output and over 50 per cent of export value.[18] Viet Nam has also invested in science and innovation, creating 17 key national laboratories in the mid-1990s. The Law on Science and Technology and S&T Development Strategy (2003) further paved the way for transformation towards a fully-fledged and functional innovation system. [19]

Despite economic growth, Viet Nam's current development path has not led to a lower carbon footprint of production. In 2021, Viet Nam adopted the National Green Growth Strategy for the 2021-2030 period, Vision to 2050.[20] The overall goal of the strategy is to accelerate the process of restructuring the economy in association with growth model transformation to achieve economic prosperity, environmentally sustainability, and social equality. It also aims to facilitate the transition to a green and carbon neutral economy and contribute to reducing global warming.

Source: UNCTAD.

Box V 3
Latvia increases complexity through regional clusters

The expansion and diversification of Latvia's trade from 1995 can be divided into two main periods. The first from 1995 to 2007 involved an intensification of commodity trade and transport when exports were divided equally between services, transport, agricultural goods, and minerals fuels. The second after the financial crisis from 2008-09 saw a shift towards higher value-added production in electronics and chemicals. From 2009 to 2020, the contribution of services was about 25 per cent, of agricultural products around 19 per cent, of electronics 8 per cent, and of chemicals 8 per cent.

Latvia joined the World Trade Organization in 1999 and the European Union in 2004, and in 2014 the euro became the country's currency. The process of joining the European Union has created favourable supply and demand factors that contributed to the expansion and diversification of Latvia's exports. With support from the European Regional Development Fund, Latvia shifted towards electronics and other priority sectors.

From 2009 to 2012, the Government focused on improving the general business environment with direct subsidies and grants to priority sectors aiming to remove constraints.[21] One key policy instrument was the development of regional clusters. The Government led by the Ministry of Economics also supports networking and promotes cooperation among business, research, educational, and other institutions During the period 2009-2015, in total, 13 clusters were supported, of which 11 are in the Riga region: chemistry and pharmacy, furniture, food, IT, mechanical engineering and metalworking, electrical engineering and electronics, light industry, timber construction, sustainable tourism, Industrial energy efficiency, and clean technology cluster.[22]

Source: UNCTAD.

Greener products

Identifying suitable production paths thus is neither easy nor intuitive. Table V-1 lists the world's top 20 products in terms of product complexity and greener production. These are relatively expensive – and involve a larger number of professions, from design to high-precision manufacturing to branding. They are very diverse – ranging from primary commodities such as cocoa paste to precision manufacturing products such as clocks. This list even includes coke, semi-coke of coal, lignite, and gas-fuelled pocket lighters. But their diversity is encouraging since it indicates countries do not need to produce the same things but rather can choose their own unique paths.

Table V 1

Degree of complexity of products that are greener than global average, 2018

Description	complexity	CO_2 / per unit of gdp	CO_2 /per capita
(520291) Garnetted stock of cotton, $145-211	2.41	-1.50	-0.04
(540331) Yarn of viscose rayon, single untwisted nes not retai, $321-1234	2.41	-1.50	-0.04
(842330) Constant weight scales, including hopper scales, $417709+	2.41	-1.50	-0.04
(810810) Titanium, unwrought, waste or scrap, powders, $4678+	2.41	-1.50	-0.04
(720943) Cold rolled iron or non-alloy steel, flat, width >600mm, t 0.5-1mm, nes, $13-14	2.41	-1.50	-0.04
(845819) Horizontal lathes nes for metal, $317867+	2.41	-1.50	-0.04
(180320) Cocoa paste wholly or partly defatted, $105-331	2.41	-1.50	-0.04
(520535) Cotton yarn >85% multiple uncombed <125 dtex, not ret, $45-61	2.41	-1.50	-0.04
(845310) Machinery to prepare, tan, work hides, skins, leather, $114096-158773	2.41	-1.50	-0.04
(270400) Coke, semi-coke of coal, lignite, peat & retort carbo, $15-31	2.41	-1.50	-0.04
(160416) Anchovies, prepared or preserved, not minced, $206+	2.41	-1.50	-0.04
(580429) Mechanical lace, other material (piece, strip, motif), $891-948	2.41	-1.50	-0.04
(700232) Tubes of low expansion glass (Pyrex etc), $862-906	2.25	-2.01	-0.14
(961320) Pocket lighters, gas-fuelled, refillable, $414-463	2.25	-2.01	-0.14
(631010) Used or new rags textile material, sorted, $260+	2.14	-1.46	-0.00
(580639) Woven fabric materials nes, < 30 cm wide, $446-555	2.13	-1.53	-0.03
(852210) Pick-up cartridges, $5100-8966	2.09	-1.85	-0.06
(551221) Woven fabric >85% acrylic staple fibres, unbl/bleache, $390-472	2.09	-1.85	-0.06
(950611) Snow-skis and parts, $1505-1920	2.09	-1.84	-0.18
(911280) Clock, etc cases, except metal, $3244-3894	2.09	-1.84	-0.18

Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

Note: In the measures of complexity, index of CO_2 per capita and index of CO_2 per GDP, zero represents the global average, and 1 is the standard deviation of the distribution.

C. COMPLEXITY AND GREENNESS

For this report, UNCTAD investigated the connection between carbon footprints and complexity for over 100 economies over the period 1996 to 2015.[23] The analysis considers the influences on carbon emissions of economic complexity, FDI, trade openness, innovation measures, and environmental policy stringency. It assesses the impact of previous CO_2 emissions, GDP per capita, population, energy intensity, and electricity production from oil, gas and coal. The results are summarized in Table V-2.

Table V 2

Factors affecting complexity and carbon footprint

Variable	Impact on index of carbon footprint	Impact on complexity
Economic complexity	Temporary increase but long-term reduction. The increasing impact is less for developing countries, along with some evidence that the long-term reduction effect is stronger in developing countries.	.
FDI	Increase	Non-significant
Trade openness	Reduction, but less with developing countries	Increase
Number of researchers in R&D	Reduction	Increase
Research and development expenditure	Increase, but less with more open trade	Increase
Environmental policy stringency	An inverted U-shaped relationship	Increase
Energy intensity of primary energy	Increase	Reduction
Electricity production from oil, gas and coal	Increase	Reduction

Source: UNCTAD.

Economic complexity – Initially, economic expansion and a greater use of resources increases the carbon footprint. Later however, more complex and sophisticated products can embed environmentally friendly technologies.[24] Notably, the initial temporary increase is less for developing countries. There is also some evidence that long-term reduction effect is greater in developing countries[25] – opening up windows for addressing employment, economic growth and environmental sustainability, and for their firms to adopt sustainable practices in their supply chains.[26]

Energy use – This depends on intensity and type of energy use. Emissions will increase if primary energy and electricity production is from oil, gas or coal.

Foreign direct investment – FDI can help developing countries move to more complex production but generally at the expense of higher levels of emissions.[27]

Trade openness – Trade with other countries generally enhances complexity, while also diffusing green technologies, spreading better environmental practices, and fostering investment in renewable energy.[28] Meanwhile, increase in trade can also lead to an increase in energy consumption, which in turn causes increased environmental degradation. Therefore, this reduction effect is less in developing countries with more relaxed or non-enforced regulations. This underlines the importance of strengthening environmental regulations and giving preference to trade opportunities that can facilitate clean technology transfer and build green innovation capacities.

Research and development – Historically having more people working in R&D has increased carbon emissions since many researchers have been working on fossil energy.[29] On the other hand increasing R&D expenditures on renewable energy seems to have no significant impact on CO_2 emissions probably because of the persistently low use of renewable energy.[30] It is also worth noting that R&D expenditure increases emissions intensity less as countries become more open to trade.

Energy intensity – Having primary energy and electricity production from oil and gas is associated with higher complexity but also higher emissions.[31] Policymakers should break away from the energy path dependency and ensure that renewable energy is more competitive.[32]

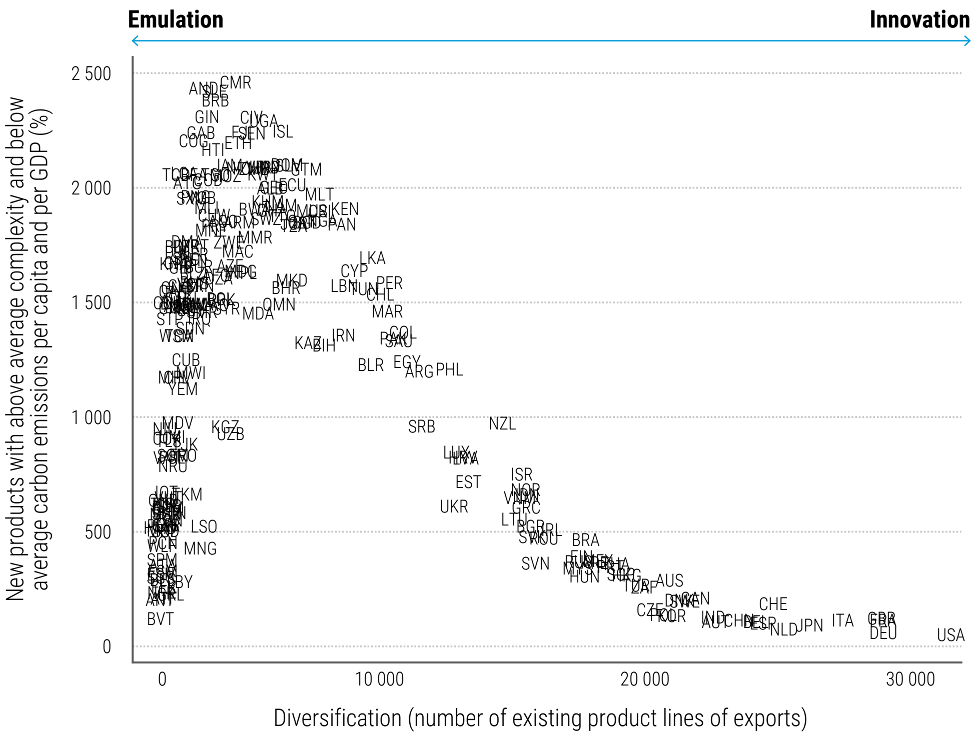
Environmental policy – Empirical literature suggests an inverted U-shaped relationship. Initially stringent policies only lead to improvements in the environment beyond a certain threshold.[33]

Opportunities for diversification

When the existing product mix is limited, countries have more options to diversify in greener directions (Box V-4). For the UNCTAD analysis this remains true for up to around 3,000 products. Beyond that point, the number of potential new products that are both more complex and greener tends to fall off (Figure V-7).

Initially, developing countries can diversify largely by emulating the paths of other countries. But those opportunities diminish as diversity increases, so countries need to set their own paths. For China, Brazil, India and South Africa, for example, the more important strategy is now innovation. They thus have to increase support to R&D and the creation of original knowledge and new and greener products. This will increase the opportunities for entrepreneurs to discover and invest in business with better social outcomes.

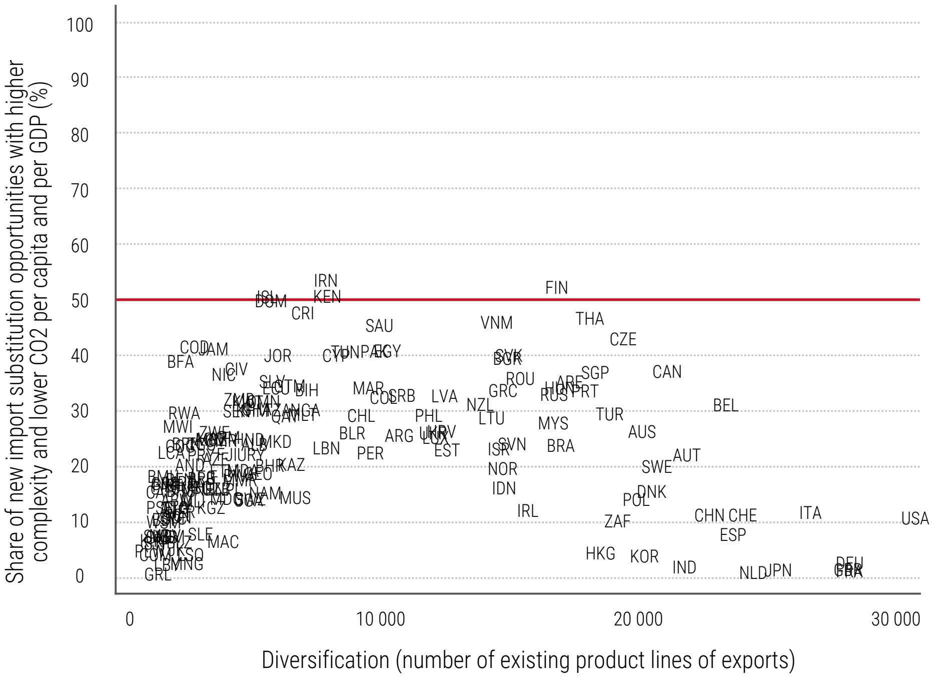
Figure V 7
Emulation vs innovation



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

While most countries can diversify to more complex products, some are in a better position to achieve greener outcomes. These include Andorra, Barbados, Cameroon, Chad, Côte d'Ivoire, Dominican Republic, El Salvador, Ethiopia, Guatemala, Honduras, Kenya, Panama, Saint Lucia, Senegal, Sri Lanka, and Uganda. This may start with import substitution. In Figure V-8 this shows opportunities for developing countries such as Iran and Kenya as well as developed countries such as Finland.

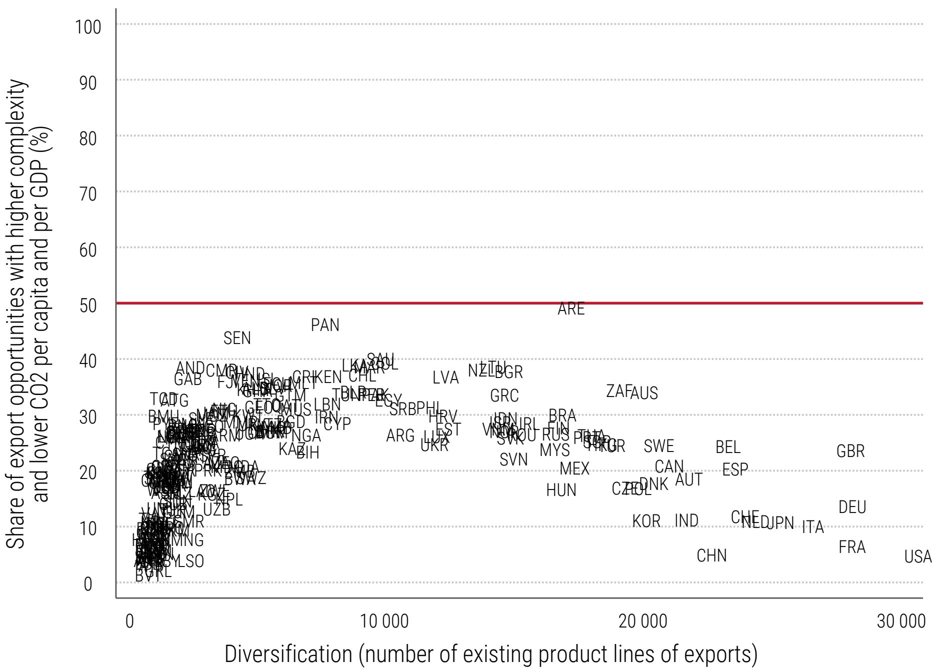
Figure V 8
Import substitution opportunities for diversification



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

In other cases, the products likely to attract entrepreneurs are those that are in high demand for exports – as for Senegal, Panama and the United Arab Emirates (Figure V-9).

Figure V 9
Export opportunities for diversification



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

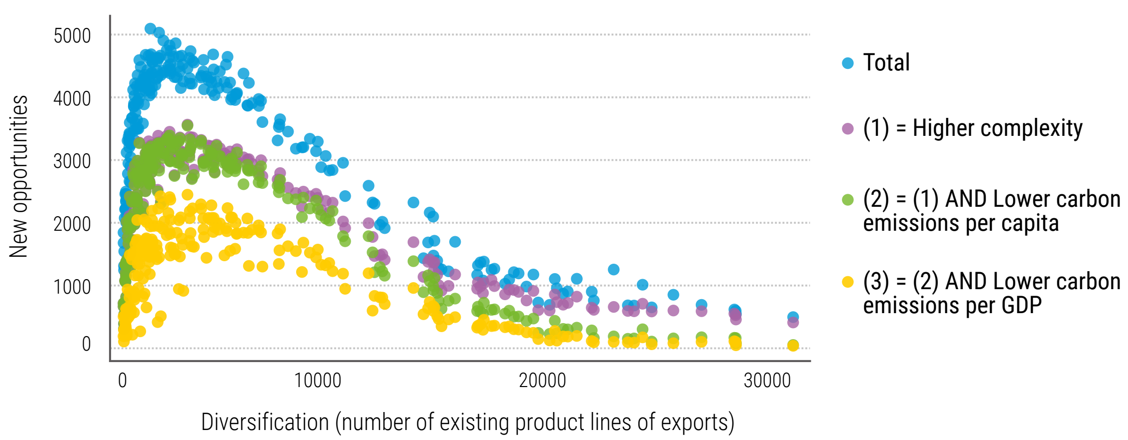
Box V 4
Opportunities for green diversification

The figure below shows the number of opportunities relative to the number of existing products in a country's product mix. Each dot represents one of the 234 economies analysed. The position of the blue dots represents the number of existing products and the number of potential new products for diversification given its proximity in the product space. The red dots add another requirement. They represent the number of existing products and potential new products that are close in the product space and that have complexity higher than the average complexity for that country. At lower levels of diversification there is a sizeable difference between the blue and red dots, but when countries move past 10,000 products, the difference becomes smaller.

The green dots add the further requirement of carbon emissions lower than the global average. For countries with low levels of diversification, the green requirement does not reduce the number of opportunities. On the other hand, as countries diversify it becomes harder to find new products that are both more complex and greener.

Orange dots in the figure represent new opportunities for diversification that are more complex and are associated with lower carbon emissions per capita and per GDP. In this case, the extra requirement makes it harder for less diversified countries to find these opportunities. Therefore, as countries diversify, the likelihood of further diversifying towards more complex and greener products change in a non-linear away, which is summarized in the figure below.

Association between number of existing and potential new products



Source: UNCTAD based on data from the United Nations Commodity Trade Statistics Database (COMTRADE).

Number of potential new product as countries diversify

	Economy	
	Less diversified	**More diversified**
Average complexity and carbon emissions.	High compared with the level of diversification of the economy. It is relatively easy to find potential new products for diversification.	Low compared with the level of diversification of the economy. As countries diversify, there are fewer opportunities for diversification based on products that already exist elsewhere in the world.
With complexity above country's average	Much lower than the total number of potential new products. It is more challenging to find new products that also contribute to increasing the level of technological capacity of the economy.	Not much less than the total number of potential new products. The opportunities for diversification are likely to also be associated with higher complexity.
With complexity above country's average and carbon emissions per capita below global average	About the same number of potential new products that are more complex. Thus, it is likely that by finding new and more complex products, these would also be associated with lower carbon emissions per capita.	Lower than the potential new products that are more complex. As countries diversify, their firms have to make an extra effort to diversify towards products that are also associated with lower carbon emissions per capita.
With complexity above the country's average and carbon emissions per capita and per GDP below global average	The extra requirement of lower carbon emissions per GDP significantly reduces the number of potential new products for diversification.	About the same number of potential new products that have lower carbon emissions per capita.

Source: UNCTAD.

D. OPPORTUNITIES FOR GREENER PRODUCTION

Identifying and prioritizing new sectors

For selecting more complex and greener directions, policymakers are faced with incomplete information as well as continuing changes in technology and demand. Governments must therefore strengthen their capacities for assessing and analysing potential new sectors. This will mean taking into account the country's existing technological and productive capacities and the availability of natural resources such as wind or agricultural waste. They also need to consider how their companies can fit into global value chains. And, as green windows open, policymakers must be prepared to adjust their institutional frameworks.

These assessments should be participatory and involve a wide range of stakeholders. Within government, for example, this would include ministries of science, technology and innovation, trade, industry, and education – all of which can increase national STI capacity and improve systems of innovation. In this, they can be supported by specialized academic and research institutions. Policymakers also need to draw in expertise from the private sector, people who know what it takes to build capacity within firms and who understand the business environment. Just as important, they need to engage with civil society organizations who know the concerns and priorities of those in vulnerable situations. And throughout all this they should balance the contributions of women and men to ensure clear gender perspectives.

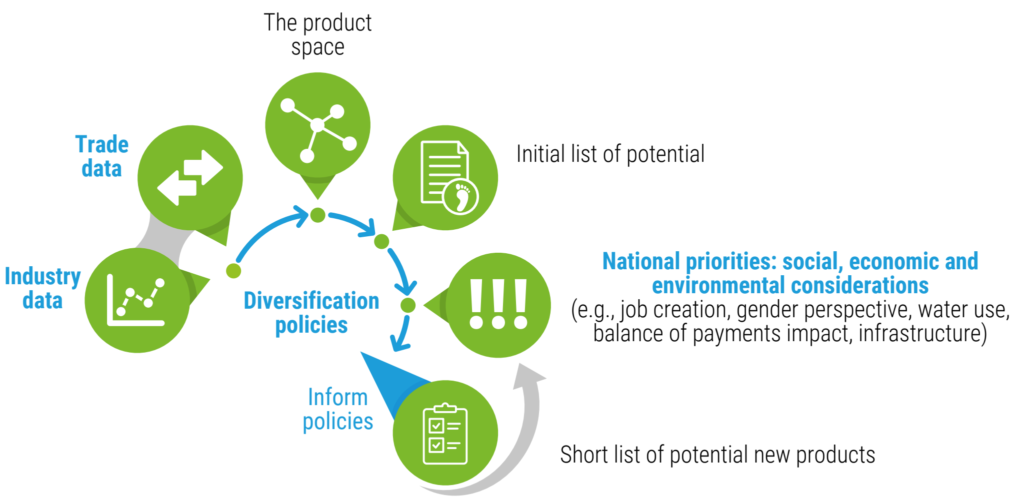
This will require all the essential trade and industry data, with the latest information on what the country is producing and exporting (Figure V-10). Policymakers can then apply concepts such as 'growth diagnostics economic complexity' and 'product space'. The evaluation can also take advantage of international resources, such as UNCTAD's Catalogue of Diversification Opportunities 2022,[34] the ITC

Export Potential Map[35] and the Atlas of Economic Complexity provided by the Harvard Center for International Development.[36]

Governments, the private sector and development partners can then consider each product, taking into account social, economic and environmental considerations. They can look at them from the perspective of job creation for example, and in particular for boosting women's employment. They can consider what infrastructure is required and how it uses resources, including water, FDI-based light manufacturing, or any other strategy for industrialization.

This interactive process should produce a shortlist of potential products and will need to be repeated every few years to take into account changes in the countries' production structures and in opportunities in international markets.

Figure V 10
Identification and selection of realistic opportunities for diversification



Source: UNCTAD.

Fostering new sectors

Countries that want to compete in new sectors, will need 'infant industry' policies to enable entrant firms to reach the levels of productivity required to compete with more technologically advanced countries. Subsequently this support can be phased out so that further increases in productivity are guided by competition and market incentives.[37]

To foster green technology, governments can also take specific measures such as establishing clusters of industries developing green technology, starting pilot and demonstration projects, and setting out technology road maps (Box V-5).[38]

In China, for example, the government has established "megaprojects of science-research" to build knowledge and experience within domestic firms, who can learn through experimentation with different technical designs.[39] Similarly, in Chile with the involvement of international investors the National Development Agency (CORFO) is setting up several pilot projects to support the development of a green hydrogen industry.

All these activities will need finance, which can be through dedicated funds. In Austria, for example, the Ministry of Climate Protection and Environment planned to implement a €300-million investment subsidy budget for green energy in 2022.[40] In Belgium, the Walloon Government plans to invest more than €160 million to lay the foundations for the hydrogen and synthetic fuels economy.[41]

Box V 5

Instruments for fostering green technologies

Clusters

Austria – To strengthen hydrogen research and contribute to the national hydrogen strategy, Graz University of Technology and Montanuniversität Leoben are intensifying their activities through a hydrogen cluster that comprises 19 universities and research institutes and several companies in Austria's Green Tech Valley.[42]

Belgium – Created in 2011, GreenWin is a regional competitiveness cluster in Wallonia dedicated to the industrial and environmental transition of chemicals, innovative construction and renovation processes and materials, and environmental technologies (Green Techs). GreenWin organizes unlikely encounters between companies of all sizes, the academic and scientific communities and key partners to consider new products. The goal is to stimulate the creation of complete value chains in Wallonia, generate new sustainable, eco-responsible and non-relocatable industrial sectors, and contribute to creating and maintaining sustainable Walloon jobs. To this end, each project supported by GreenWin is subject to a life cycle analysis.[43]

Belarus – Electrotransport is an innovation and industrial cluster that has been created to develop and manufacture new means of electric transport and its components and to coordinate the research and technology, education and industry sectors. Several electric vehicles have been developed within the cluster, for example, electric buses, and autonomous trolleybuses.

Demonstration areas and projects

Philippines – The Department of Science and Technology (DOST) Region IVB Office, through its Provincial S&T Office in Marinduque led the 6M-project on the deployment of solar energy systems to 29 rural health units regionwide. The DOST Marinduque office also serves as a demonstration area for "green building" using solar energy systems. As a result, different government agencies in the province signified interest in adopting solar energy systems.

India – The Department of Science & Technology (DST) works at the initial stages of the technology and innovation chain for cleaner, more productive, and competitive production. DST supports R&D, technology concepts, experimental proof, and technology demonstration projects on Clean Energy.

Russian Federation – In February 2021, a pilot programme was launched to deploy plots of land as 'carbon polygons'. Within a carbon polygon, highly qualified personnel can develop and test technologies for controlling the balance of climatically active gases in natural ecosystems. In addition, the polygon provides training in state-of-the-art methods of environmental control, advanced technologies for low-carbon industry, agriculture and municipal economy. The initiative is expected to play a key role in developing a reliable nationwide system for monitoring greenhouse gas emissions in ecosystems.

Switzerland – The Swiss Federal Office of Energy Pilot and Demonstration Program supports the development and testing of new technologies, solutions and approaches in the area of economical and efficient use of energy, energy transmission and storage as well as the use of renewable energies. The programme is positioned at the interface between research and the market and aims to bring new technologies to market maturity. [44]

Technology roadmaps

Türkiye – The Ministry of Industry and Technology and TÜBİTAK are carrying out "Green Growth Technology Roadmap" studies for the iron-steel, aluminium, cement, chemicals, plastics and fertilizer sectors – which are critical for the Turkish economy and have high carbon emissions. Priority R&D and innovation themes will be detailed, in cooperation with the Ministry of Industry and Technology, leading to STI and investment support programmes to enable private sector organizations to adapt to green transitions.[45]

Chile – The economic development agency, CORFO, has developed the "Transforma" Strategic Programmes, including the Roadmap for the Sustainable Management of Construction and Demolition Waste, and the Ministry of Agriculture has drawn up the roadmap, Circular Economy of Agroindustry.[46]

Peru – The Roadmap towards a Circular Economy in the Industry Sector was approved to establish State actions to support manufacturing and processing in their transitions from linear to circular economic models.

Source: UNCTAD based on contributions to the Commission on Science and Technology for Development from UNEP and the Governments of Austria, Belarus, Belgium, Chile, India, Peru, the Philippines, the Russian Federation, and Switzerland.

Participating in global value chains

By participating in global value chains countries can diversify – producing and exporting new products or upgrading existing output to have greater value added.[47] Some policies for promoting integration into GVCs are improving transportation infrastructure, as well as supporting for trade and for trade facilitation, lowering tariff and non-tariff barriers particularly for intermediate goods, and lowering barriers to trade in services. Other less targeted policies are investing in basic and dedicated education, fostering university-industry linkages, and reforming intellectual property laws and patent processes.[48]

Within value chains governments can consider more targeted policies, such as support for small and medium-size enterprises with finance for new machinery and other requirements for upgrading. They can also create training or demonstration centres as well as industrial institutes.

1 This analysis responds to UNCTAD's mandates and complements its ongoing analytical work focusing on fostering economic diversification for structural transformation. In particular, it complements the analysis presented in The Least Developed Countries Report 2022, which examined ways to create a path towards the green structural transformation of the LDCs.

2 Reinert, 2008; Hausmann and Hidalgo, 2011; Petralia et al., 2017

3 Lall, 1992,Freire, 2019

4 IPCC, 2007

5 Such as in an analysis of the relationship in a selected group of 18 top economic complexity countries (Abbasi et al., 2021), selected European Union countries with low and high economic complexity (Neagu and Teodoru, 2019), a group of countries when considering the impact on environmental performance index (EPI), the per capita ecological footprint of consumption, and the per capita ecological footprint of production (Kosifakis et al., 2020), a group of 86 countries with different development levels (Laverde-Rojas and Correa, 2021), and a study on Colombia (Laverde-Rojas et al., 2021), and another on Brazil (Swart and Brinkmann, 2020).

6 Kosifakis et al., 2020, Boleti et al., 2021

7 Chu, 2021

8 Mealy and Teytelboym, 2020

9 UNCTAD, 2021d

10 UNCTAD, 2022f

11 UNCTAD, 2022d

12 The term economic complexity refers to the level of non-tradable capabilities in the economy as defined in the strand of literature on economic complexity (see, for example, the seminal paper Hidalgo and Hausmann, 2009, and a review of this literature in (Freire, 2021b)). More complex products are considered to require higher levels of technology to be produced. The index of carbon footprint of a product assesses the level of carbon emissions per capita associated with the countries that export that product. The methodology for the calculation of these indices is presented in the background paper prepared for this chapter: Freire (2023). Opportunities in greener diversification trajectories. Available at https://unctad.org/webflyer/technology-and-innovation-report-2023.

13 UNCTAD research also identifies a positive significant impact of CO_2 emission on the economic complexity index, which may result from a reverse causality. Moreover, the quadratic term of GDP exerts a negative and significant impact on the complexity index, which suggests a concave relationship between GDP and the economic complexity index.

14 WTO Trade Policy Review: Viet Nam, 2021

15 UNCTADstat, 2022

16 Hong, 2021

17 OECD, 2018a

18 OECD, 2018a

19 OECD and World Bank, 2014

20 Ministry of Industry and Trade (MOIT) of the Socialist Republic of Vietnam, 2021

21 Soms, 2016

22 Garanti and Zvirbule-Berzina, 2013

23 UNCTAD analysis is based on longitudinal data and a dynamic linear model. For more details see the background paper prepared for this chapter: Ni Zhen and Freire C (2023). The interlinks between the economic complexity and carbon footprint: differentiated analysis for developed and developing countries. Available at https://unctad.org/webflyer/technology-and-innovation-report-2023.

24 Neagu, 2019; Can and Gozgor, 2017

25 Seuring and Müller, 2008

26 Furthermore, UNCTAD research conducted the subgroup analysis for developed and developing countries on the link between economic complexity and carbon emissions, which corroborates the robustness of our previous findings. For more details see the background paper prepared for this chapter: Ni Zhen and Freire C (2023). The interlinks between the economic complexity and carbon footprint: differentiated analysis for developed and developing countries. Available at https://unctad.org/webflyer/technology-and-innovation-report-2023.

27 FDI has the potential to contribute to increasing complexity of production in developing countries, but historically it is associated with higher levels of emission in the receiving countries (e.g., Omri et al., 2014; Shahbaz et al., 2015). FDI inflows may provide direct capital financing, generate positive externality to stimulate further economic growth, which eventually leads to environmental degradation (Lee, 2013).

28 Shahbaz et al., 2017; Yu and Qayyum, 2021

29 Koçak and Ulucak, 2019

30 Koçak and Ulucak, 2019; Amri, 2018; Cheng et al., 2017; Garrone and Grilli, 2010

31 Neagu, 2019

32 Bilgili et al., 2017

33 Wolde-Rufael and Mulat-Weldemeskel, 2021, 2021 UNCTAD research has not discovered significant impact of environmental policy stringency in reducing CO_2 emission, due to a limited number of observations. The estimation sample reduces to around 400 observations when controlling for environmental policy stringency, which greatly hampers the validity of dynamic model.

34 UNCTAD, 2022d

35 ITC Export Potential Map: Spot export opportunities for trade development, 2022

36 The Atlas of Economic Complexity by Harvard Growth LAB, 2022

37 Reinert, 2009

38 For in depth analysis of smart specialization strategies and their implementation, see (Foray, 2014, 2016).

39 Lilliestam et al., 2019

40 Renewables Now, 2022

41 UNCTAD, 2022d

42 Greentech, 2022

43 Greenwin, 2022

44 Bundesamt für Energie, 2022

45 UNCTAD, 2022b

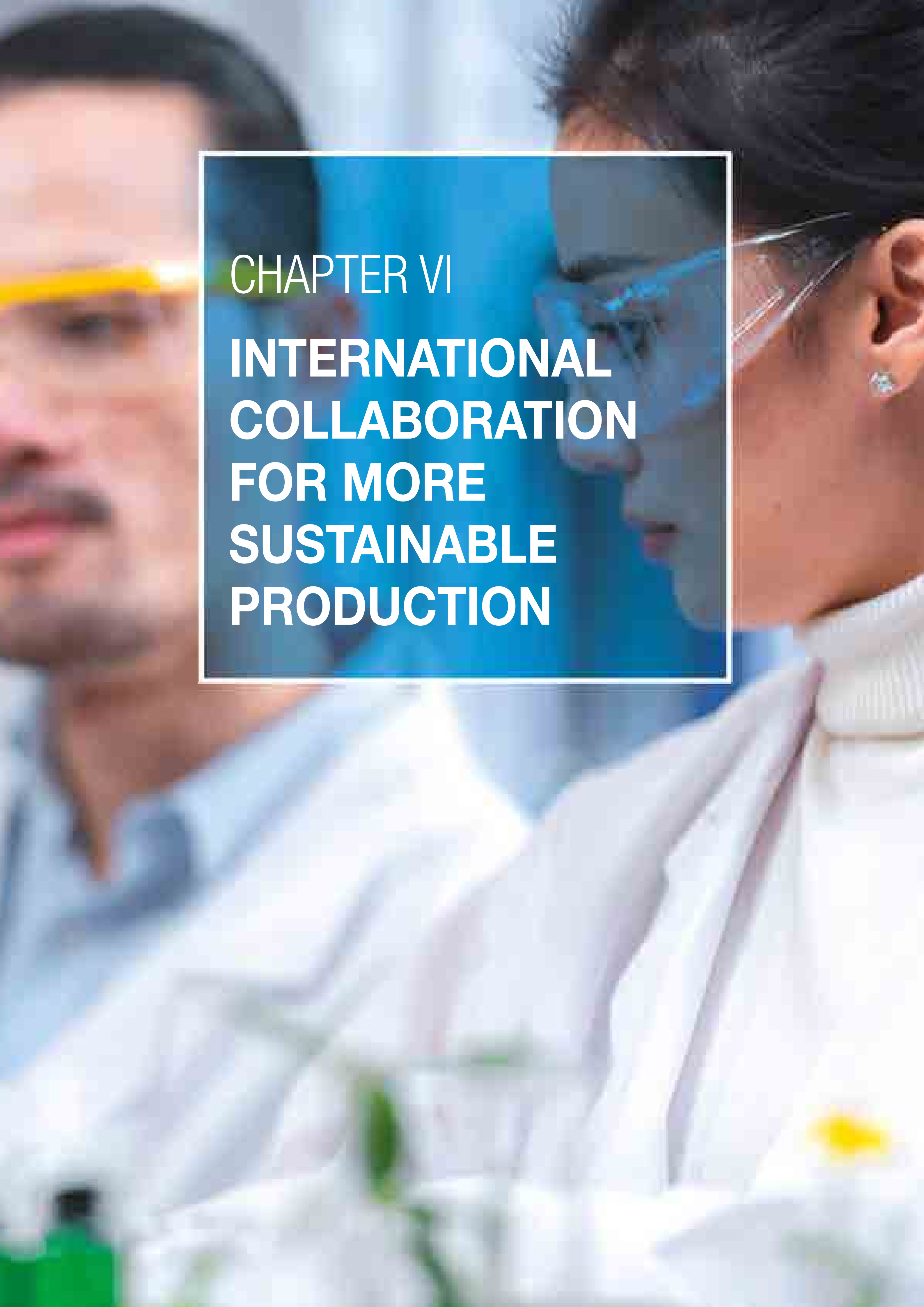
46 CORFO, 2022

47 UNCTAD, 2018b

48 UNCTAD, 2018b

CHAPTER VI

INTERNATIONAL COLLABORATION FOR MORE SUSTAINABLE PRODUCTION



Developing countries may not, on their own, take advantage of green windows of opportunities. International cooperation and improving the consistency of the trading system with the Paris Agreement are critical

Priorities for opening green windows:

1 Set the direction:

- Aligning environmental, STI and industrial policies
- Investing in more complex and greener sectors
- Shifting consumer demand to encourage recycling and the circular economy

2 Build green productive and innovative capacities:

- Investing in nascent green technologies
- Raising awareness of green technologies
- Building required digital infrastructure and skills

Action lines to foster international cooperation for green innovation:

1. Align trade with the Paris Agreement
2. Reform international protection of IPRs for less technologically advanced countries
3. A more partnership-oriented approach to green technology development
4. Shifting research for green innovations from the national to the multilateral level, including open innovation approaches
5. Multilateral approaches to technology assessment
6. Support South-South STI cooperation for green innovation
7. A multilateral challenge fund "Innovations for Our Common Future"

The least technologically able countries lack many preconditions for seizing green opportunities, such as effective sectoral innovation systems, the required digital infrastructure, or adequate finance. These countries may thus depend on the support of the international community – through an enhanced architecture that facilitates sustainable global growth.[1] At present, however, there is little international cooperation for green innovation.

Innovation will require novel business models, new approaches to financing, and policy innovations within national and global institutions.[2] As developing countries' technological needs and capabilities change and international political and economic landscapes shift, support for innovation also has to evolve.[3]

This support should be based on equitable partnerships to build local innovation capabilities and marshal the necessary technologies. Collaboration can promote access to green technologies for climate change mitigation and adaptation, human resource development, and building local capacity.[4] Such technology transfer can facilitate the enhancement of national capabilities, adding to the accumulation of knowledge necessary for countries to promote the structural change of the economy. [5]

Effective innovation transfer not only offers capital goods and equipment, but it also enables people to develop the skills needed to operate and maintain the equipment (know-how) and understand why it is running (know-why).[6] These capabilities are essential for green technologies, which typically need adaptation to specific conditions on the ground. Enabling and empowering developing countries to take advantage of green windows of opportunities and build national innovation systems thus requires broad and comprehensive international cooperation strategies.

A. COOPERATING FOR GREEN INNOVATION

1. A WIDENING NORTH-SOUTH DIVIDE

The gap between developed and developing countries is evident in the expenditure on research and development (R&D). Many countries in the European Union reach R&D expenditure of 3 per cent of GDP, while the top global performers, such as Israel and the Republic of Korea, invest around 5 per cent (Table VI-1). For developing countries, the proportions are far lower. Only a few are around 1 per cent, such as Brazil, Egypt, Thailand and Türkiye, while others, such as South Africa and Viet Nam, range between 0.5 and 1 per cent. Mexico and Colombia invest around 0.3 per cent. The average for the lower middle-income countries is 0.53 per cent.

Table VI 1

R&D expenditure, selected countries and regions (percentage of GDP)

	2013	Latest
World	1.99	2.63 (2020)
Lower Middle-Income Countries	0.44	0.53 (2017)
High-Income Countries	2.40	2.97 (2020)
Colombia	0.26	0.29 (2020)
China	2.00	2.40 (2020)
Brazil	1.20	1.20 (2019)
Egypt	0.64	0.96 (2020)
European Union	2.10	2.32 (2020)
Israel	4.07	5.43 (2020)

Japan	3.28	3.26 (2020)
Mexico	0.42	0.30 (2020)
Republic of Korea	3.95	4.81 (2020)
South Africa	0.66	0.62 (2019)
Thailand	0.44	1.14 (2018)
Türkiye	0.81	1.09 (2020)
United States	2.71	3.45 (2020)
Viet Nam	0.37	0.53 (2019)

Source: UNCTAD based on World Development Indicators (accessed in June 2022).

Another concern is that even the relatively advanced developing countries have not increased that expenditure. In Brazil, between 2013 and 2019, R&D expenditure as a percentage of GDP was largely unchanged at 1.2 per cent, while in South Africa, it decreased from 0.66 to 0.62 per cent. Exceptions were Thailand, where between 2013 and 2018, the figure grew from 0.44 to 1.14 per cent, and Egypt, which grew from 0.64 to 0.96 per cent.

Other important indicators of the strengths of national innovation systems are the percentage of researchers per million inhabitants (Table VI-2) and the number of scientific and technical papers published in journals (Table VI-3). This latter table separates China from the statistical group of middle-income countries, as 48 per cent of the total number of publications from that group are from China.

Table VI 2

Researchers in R&D per million inhabitants

	2010	Latest
World	1,279	1,592 (2018)
Middle-Income Countries	650	812 (2018)
High-Income Countries	3,776	4,671 (2019)
Colombia	57 (2013)	88 (2017)
China	885	1,585 (2020)
Brazil	686	888 (2014)
Egypt	492	838 (2020)
European Union	3,092	4,258 (2020)
Japan	5,104	5,455 (2020)
Mexico	337	349 (2020)
Republic of Korea	5,331	8,714 (2020)
South Africa	366	484 (2019)
Thailand	539 (2011)	1,790 (2019)
Türkiye	890	1,775 (2020)
United States	3,883	4,821 (2019)
Viet Nam	679 (2013)	757 (2019)

Source: UNCTAD based on World Development Indicators (accessed in January 2023).

Table VI 3
Scientific and technical journal articles, 2018

Country Group	Absolute number of articles	Articles per million people
Low-Income Countries	5,429	8
Middle-Income Countries (MIC)	1,105,887	192
MIC without China	577,624	133
China	528,263	377
High-Income Countries	1,450,500	1,177

Source: UNCTAD based on World Development Indicators (accessed in December 2022).

Note: The table separates China from the statistical group of middle-income countries, as 48 per cent of the total number of publications from the group are from China.

Even in fields critical for the global South, most of the science is carried out in the North. One analysis found that between 2000 and 2014, for the 93,584 publications on climate change, more than 85 per cent of author affiliations were from OECD countries, less than 10 per cent were from any country in the South, and only 1.1 per cent were from low-income economies.[7] This has the effect of narrowing research paradigms to the cultural settings and perspectives of the global North and of countries mainly in the West, while depriving the scientific community of considerable intellectual capital. Similarly, only 10 per cent of funding for health research is spent in the South, which has 90 per cent of the world's disease burden.[8]

Another important perspective is shown by the number of patents granted for green technologies. [9] These have been increasing, but primarily in the traditional industrial economies and newly industrialized economies (Table VI-4).

Table VI 4
Top green patenting economies - cumulative number of patents, 1975-2017

All patent offices			USPTO		
Country	**Patents**	**Percentage of total patents**	**Country**	**Patents**	**Percentage of total patents**
Japan	155,501	18.6	United States	133,219	42.7
China	148,032	17.7	Japan	72,837	23.3
United States	143,145	17.1	Germany	21,464	6.9
Republic of Korea	112,699	13.5	Republic of Korea	19,490	6.3
Germany	94,927	11.4	China, Taiwan Province of	9,441	3.1
France	27,764	3.3	France	7,222	2.3
China, Taiwan Province of	22,389	2.7	China	6,238	2.0
Russian Federation	21,915	2.6	Canada	6,191	2.0
United Kingdom	12,813	1.5	United Kingdom	5,249	1.7
Canada	9,477	1.1	Sweden	3,135	1.0

Source: Corrocher and Morrison, 2020

China has had a very fast take-off in green patenting, mostly since 2000. From 1975 to 2017, more than 6,200 patents granted in the United States Patent Office (USPTO) were to inventors from China – two per cent of all patents.[10] This is a remarkable result, given that relatively few patents had been granted in the previous 25 years. None of the other emerging economies has registered many patents and the gap with the industrialized world does not seem to be narrowing. Between 1980 and 2009, only 1 per cent of all international patents in clean energy were filed in Africa, and 85 per cent of these came from South Africa.[11] In the majority of Lower Middle-Income Countries and Low-Income Countries, patenting activities are hardly measurable.

Table VI 5

Green patents from emerging countries (number of patents and per cent of total)

All patent offices			USPTO		
Country	**Number**	**Percentage**	**Country**	**Number**	**Percentage**
China	148,032	17.70	**China**	6,238	2.00
Russian Federation	21,915	2.62	**India**	1,003	0.32
Brazil	4,676	0.56	**Brazil**	277	0.09
India	1,663	0.20	**Russian Federation**	273	0.09
Mexico	1,130	0.14	**Mexico**	209	0.07
Türkiye	875	0.10	**South Africa**	202	0.06
South Africa	437	0.05	**Türkiye**	79	0.03
Argentina	363	0.04	**Argentina**	75	0.02
Chile	267	0.03	**Chile**	66	0.02
Egypt	97	0.01	**Egypt**	21	0.01
Indonesia	35	0.00	**Indonesia**	9	0.00

Source: Corrocher and Morrison, 2020.

2. ODA FOR GREEN INNOVATION

Following the Paris Agreement of 2015, most countries have increased their climate-change-related, green official development assistance (ODA). [12] In 2016/2017, many large international donors committed at least 40 per cent of their development assistance as green ODA (Table VI-6). Nevertheless, ODA directed to green innovation urgently needs to increase.

Table VI 6

Green ODA as a percentage of all ODA in leading donor countries (2016/2017)

Country	**Percentage**
Canada	41
EU institutions	34
France	67
Germany	42
Japan	48
Sweden	47
United Kingdom	42
Republic of Korea	9
United States	7

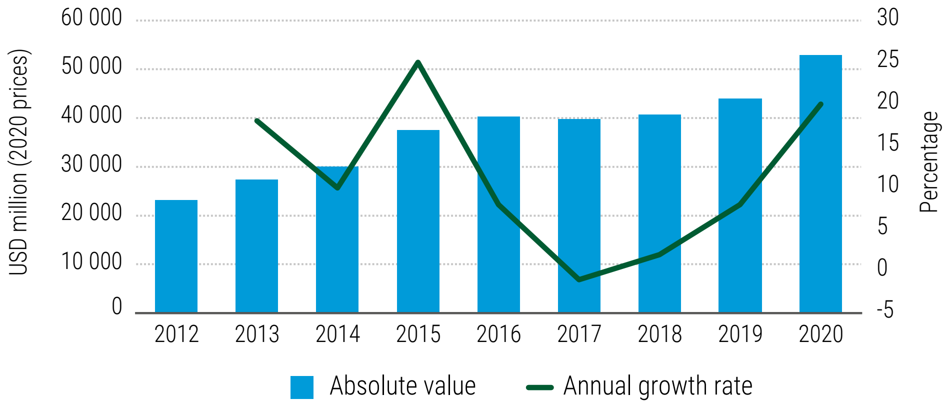
Source: UNCTAD based on Rijsberman (2021).

In general, climate finance is still falling far short. Reaching net zero by 2050 will require around $4 trillion in annual investment in clean energy by 2030.[13] At present, only around $520 billion is available for climate finance per year, and only about $130 billion of this is being spent in developing countries.[14]

The primary instrument of public climate finance for developing countries is ODA.[15] Between 2012 and 2020, as reported by bilateral donors, the absolute value of climate-related ODA increased from $23.2 billion to $52.9 billion (Figure VI-1).[16] However, this falls short of the Paris Agreement pledge of $100 billion per year by 2020. It should also be noted that this reflects commitments, not disbursements which are typically considerably less.

Figure VI 1

Changes in climate-related ODA 2012-2020

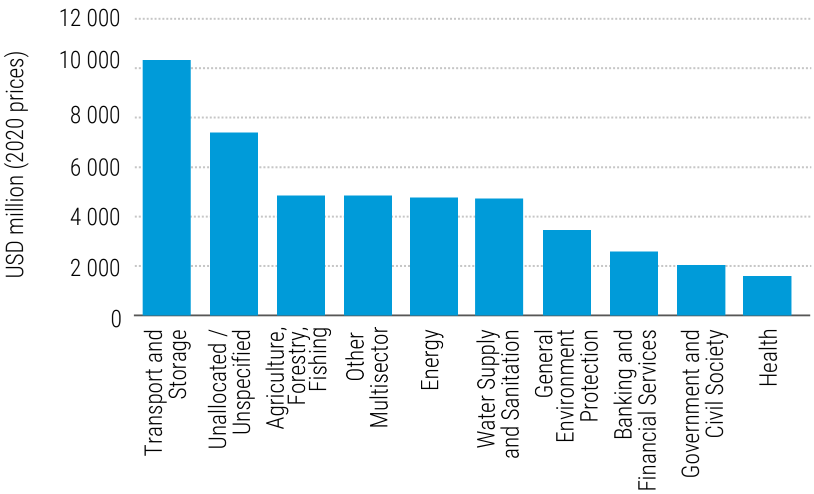


Source: UNCTAD based on data from OECD.[17]
Note: The values include both bilateral and imputed multilateral development finance.

Figure VI-2 shows that the sectors that attracted green ODA the most in 2020 were transport and storage, and agriculture, forestry, and fisheries. Of this, 51 per cent was in the form of grants, and 45 per cent in debt instruments.

Figure VI 2

Top ten sectors in 2020 (bilateral provider perspective)

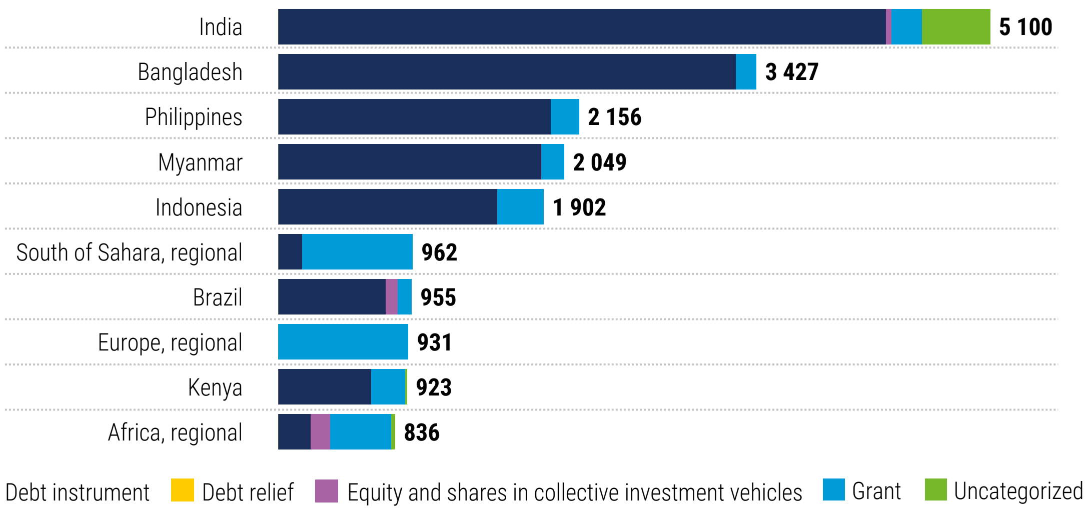


Notes: Values refer to commitments and are expressed in $ million, 2020 constant prices. Unallocated/unspecified are largely imputed values. Imputed multilateral contributions are calculated by estimating, per international organisation, the climate-related share within its portfolio and attributing it back to bilateral providers, based on their core contributions (disbursements) to the organisation in a given year, it is an approximation.[18]
Source: UNCTAD based on data from OECD.[19]

Of total green ODA, 41 per cent went to Asia, and 25 per cent to Africa (Figure VI-3). One concern is the use of debt instruments which appears to be highest, surprisingly, in the lower middle-income countries, at 75 per cent, followed by upper-middle-income countries – at 67 per cent. Other low-income countries received ODA solely through grants, though in far lower amounts (Figure VI-4).

Figure VI 3

Financial instrument by the top ten recipients in 2020 ($ millions, 2020 prices)

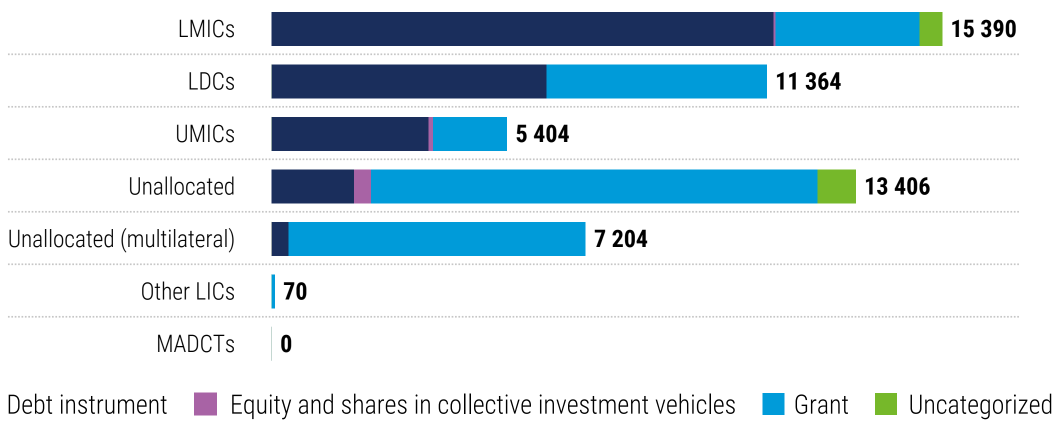


Notes: As reported by bilateral donors. Imputed multilateral contributions and financial flows from non-DAC members not included.

Source: UNCTAD based on data from OECD.[20]

Figure VI 4

Financial instrument by income group of recipients in 2020, $ millions, 2020 prices

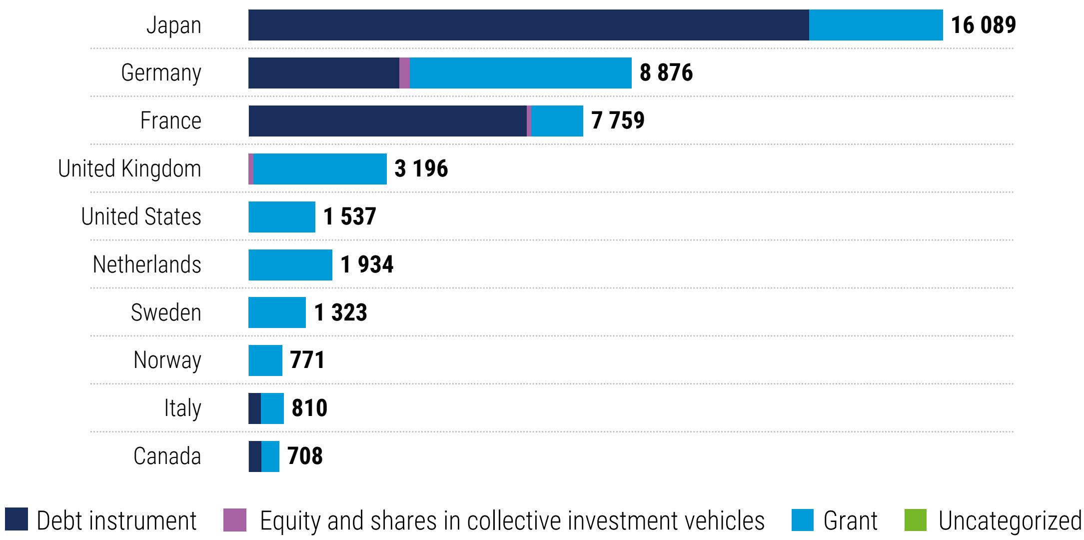


Note: Notes: As reported by bilateral donors. Imputed multilateral contributions and financial flows from non-DAC members not included.

Source: UNCTAD based on data from OECD.21

The three largest donors of green ODA in 2020 were Japan, Germany, and France (Figure VI-5). Between 2019 and 2020, the commitment from Japan doubled while that of France increased by 40 per cent.[22] There are, however, differences between these countries. From Germany, 58 per cent of green ODA took the form of grants, while the other two countries primarily gave support as debt instruments, which represented 81 per cent and 83 per cent of Japanese and French ODA, respectively.[23]

Figure VI 5
Top ten providers of green ODA and used financial instruments in 2020, $ millions, 2020 prices

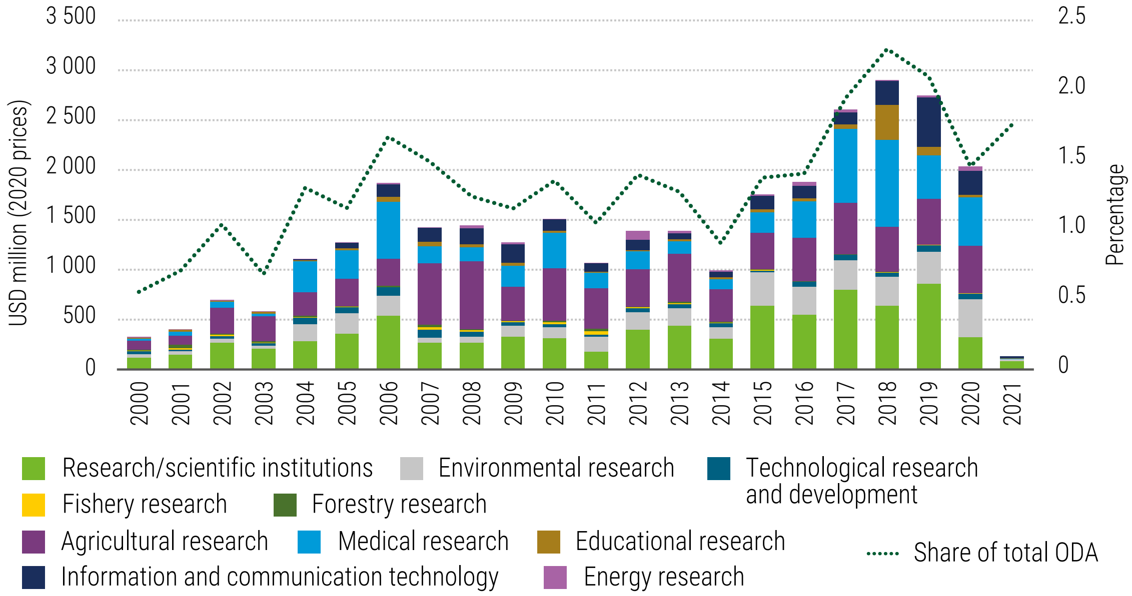


Notes: As reported by bilateral donors.
Source: UNCTAD based on data from OECD.[24]

In the European Union, the backbone of recovery and of the green growth strategy is the EU Green Deal. As a proportion of total ODA, some European countries are arguing that green ODA, for both environment and climate finance combined, should rise from 30 to 50 per cent.[25] In October 2021, the OECD Development Assistance Committee (DAC) adopted a new approach to align development cooperation with the Paris Agreement on Climate Change.

Only around 2 per cent of total ODA is for STI capacities, and even that proportion has been fluctuating (Figure VI-6). The greatest growth, though from quite low values, has been for environmental and medical research and ICT. In 2020, of total ODA targeting STI capacities, 24 per cent was for medical research and 16 per cent went to research/scientific institutions, at $327 million, though this represents a significant decline. Additionally, the share of ODA targeting specifically technological research and development of total ODA for STI fell from 11 to 3 per cent in from 2000 to 2020, though increasing in absolute value (see Figure VI-6 and Figure VI-7).

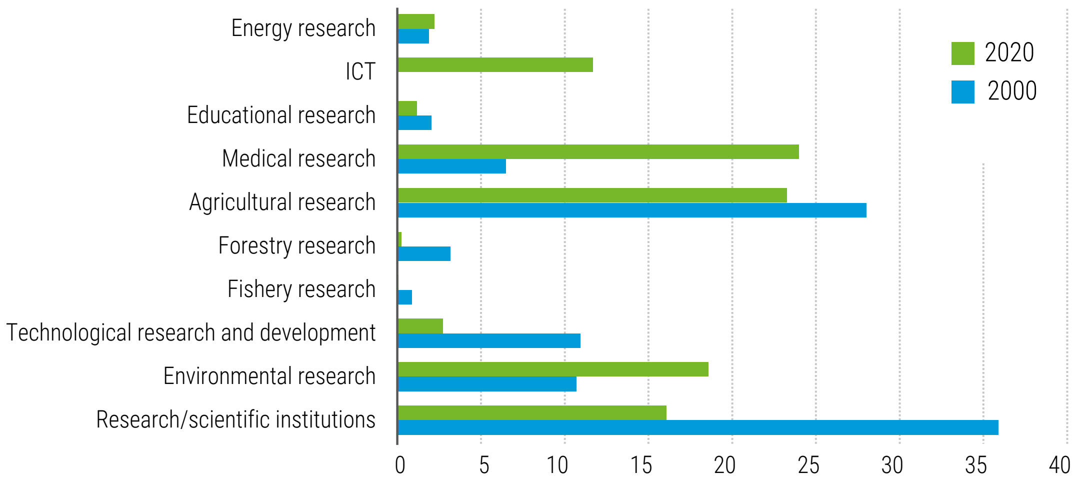
Figure VI 6
ODA for STI by sector, 2000–2021



Notes: 2021 values are projections. Technological research and development, fishery research, forestry research, and ICT do not yet have values for 2021. The series for ICT starts in 2003.

Source: UNCTAD based on data from OECD.[26]

Figure VI 7
ODA by STI category as percentage of total ODA for STI, 2000 and 2020



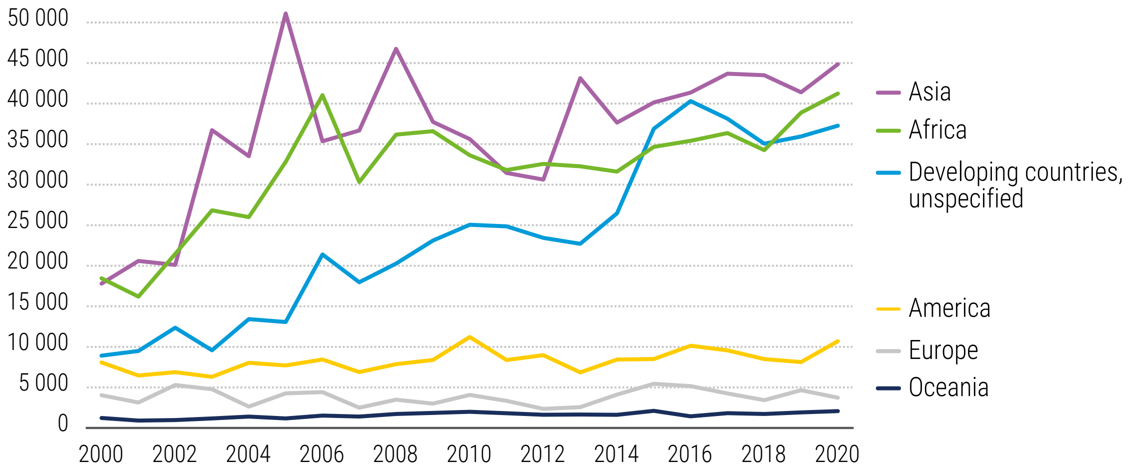
Notes: The series for information and communication technology starts in 2003.

Source: UNCTAD based on data from OECD. [27]

The growth in ODA for STI capacities has been greatest in Asia and Africa, in both percentage and absolute terms (Figure VI-8).[28] Countries in the Americas and Oceania had modest growth.

Figure VI 8

Total ODA for STI per region ($ million, 2020 prices)

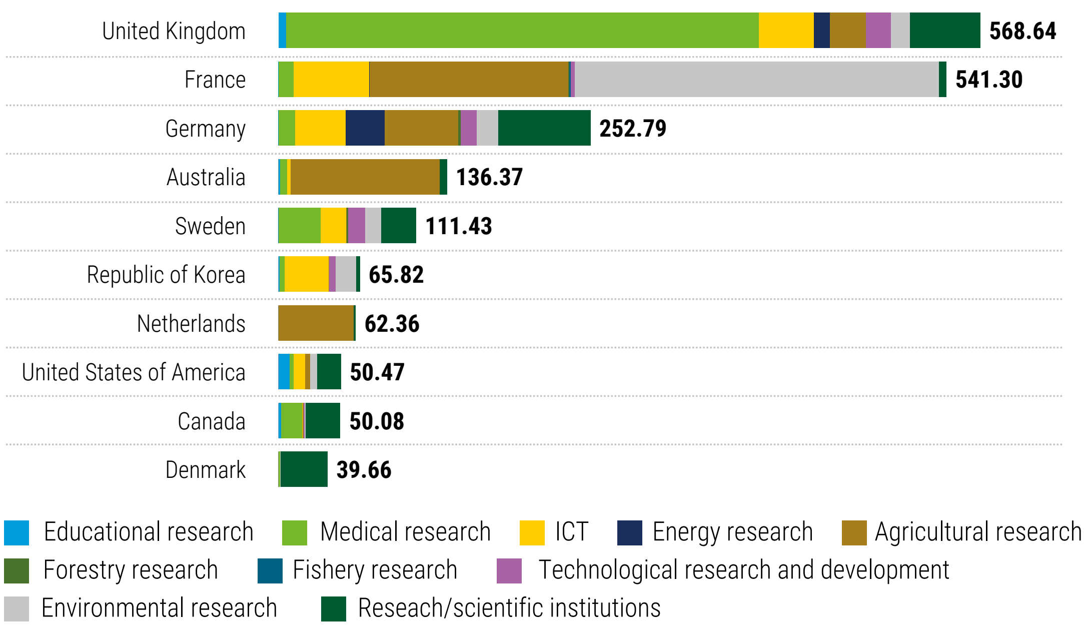


Source: UNCTAD based on data from OECD.[29]

Most ODA for STI capacities comes from bilateral DAC members – United Kingdom, France, Germany, Australia, Sweden, the Republic of Korea, the Netherlands, the United States, Canada, and Denmark (Figure VI-9).[30] Each, however, has different priorities. In 2020 most of the assistance from the United Kingdom was medical research, while France concentrated more on environmental research, Germany on research/scientific institutions, and Australia on agricultural research.

Figure VI 9

Top 10 donor countries of ODA targeting STI capacities in 2020, $millions, 2020 prices)



Source: UNCTAD based on data from OECD.[31]

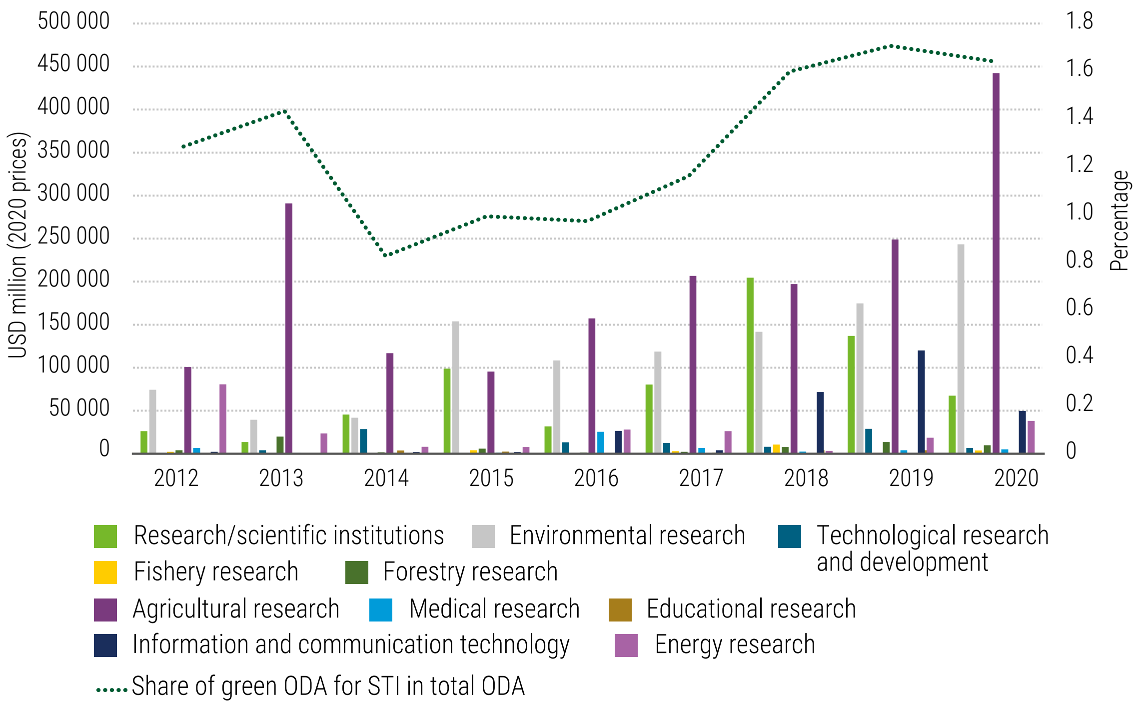
The priorities set for their STI support vary significantly between donors:

- *The United States* – Support from the largest donor is mostly aimed at research, capacity building and innovative approaches to fight the spread of infectious and tropical diseases and prevent maternal and child deaths.
- *The United Kingdom* – In 2013, the United Kingdom pledged to provide 0.7 per cent of its gross national income (GNI) as ODA, and subsequently established new research funds for challenges faced by developing countries – the Newton Fund, the Ross Fund, and the Global Challenges Research Fund which also aim to allow developing countries to take advantage of the high-quality research conducted in the United Kingdom.
- *Sweden* – The research co-operation programme strengthens developing countries' research capacity and finances research projects. The Government's Strategy for research cooperation and research in development cooperation 2015-2021 aims to carry out research on poverty reduction and sustainable development, primarily in low-income countries and regions.
- *Canada* – International STI cooperation is primarily through the Ottawa-based International Research Centre (IDRC), which invests in high-quality research in developing countries, shares knowledge with researchers and policymakers for greater uptake and use, and mobilizes global alliances.
- *Germany* – The country has a long tradition of supporting the technical and vocational education and training systems that can pave the way for green technologies in businesses and societies. In addition, organizations such as the German Academic Exchange Service and Alexander von Humboldt Stiftung provide scholarships for students from developing countries at the postgraduate and post-doctorate levels.

Both the absolute value and the share of green ODA targeting STI capacities as a percentage of total green ODA have been increasing but the absolute values remain low (Figure VI-10).

Figure VI 10

Green ODA targeting STI capacities, 2012-2020 ($ million, 2020 prices)



Source: UNCTAD based on data from OECD.[32]

If developing countries are to achieve the transition to renewable energy sources and low-emission development, they will need more ODA – an issue they are increasing raising in international negotiations. Mongolia for example has committed to increasing its emissions reduction goal by 2030 from 22.7 to 27.2 per cent – if it receives assistance with carbon capture and storage and waste-to-energy technologies.[33] Similarly, Thailand has promised to raise its emissions reduction target from 20 to 25 per cent – if it gets greater access to technology and more financial and capacity-building support.[34]

3. UNITED NATIONS SUPPORT FOR TECHNOLOGY TRANSFER

The largest public-sector funding source for transferring environmentally sound technologies (ESTs) is the Global Environment Facility (GEF). Since 1991, financial contributions by donor countries to the several GEF-related trust funds administered by the World Bank have amounted to over $30 billion.[35] The primary source of GEF grants is the GEF Trust Fund.[36]

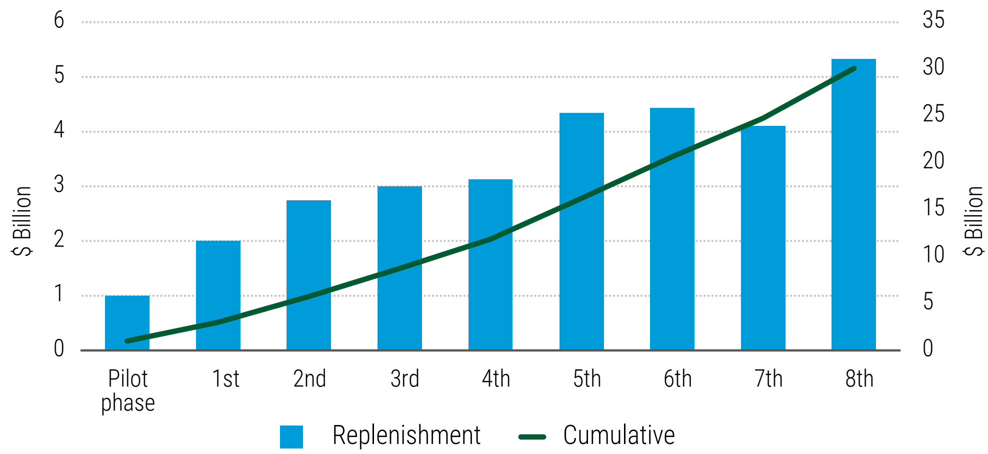
The GEF supports innovation and technology transfer at critical early and middle stages, focusing on the demonstration and early deployment of innovative options. Its addresses elevated risks associated with innovation, mitigating the barriers of technology transfer and piloting promising approaches.

Since its inception, the GEF has allocated more than $22 billion in grants and blended finance, and mobilized $120 billion in co-financing, for more than 5,000 projects in 170 countries, supplemented by 27,000 community-led initiatives through a Small Grants Programme.[37]

GEF is funded by donor countries and finalized its eighth replenishment in 2022, with 29 donor governments pledging $5.33 billion for the period 2022-2026 – a fivefold increase since the first replenishment round (Figure VI-11). The GEF 7 supported 131 projects in developing countries, with $590 million for the Climate Change Mitigation focal area that is expected to contribute to aggregate emission reductions of more than 1,543 megatons of CO_2 equivalent.[38]

Figure VI 11

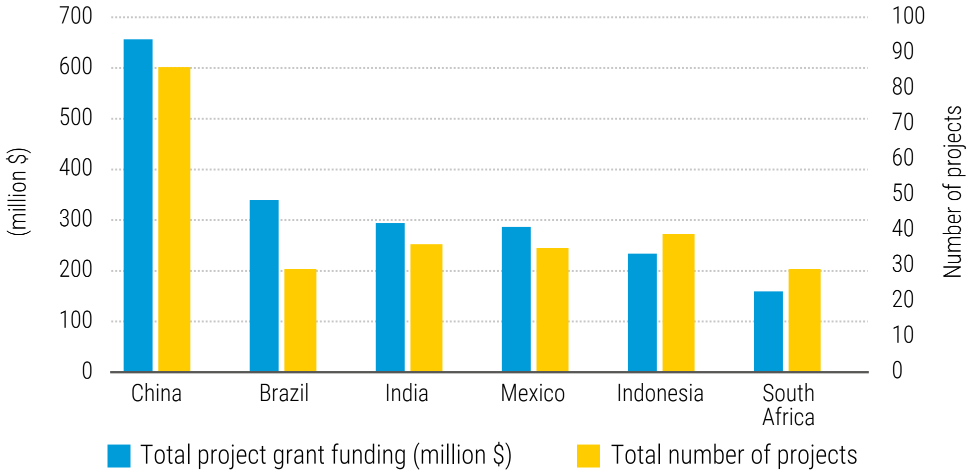
Pledge of countries to the GEF of the successive replenishment rounds



Source: UNCTAD based on (Global Environment Facility, 2022).

Since GEF-5, the largest recipient countries of the GEF Trust Fund grants have been China (86 projects, $656 million), Brazil (29 projects, $340 million), India (36 projects, $294 million), Mexico (35 projects, $ 287 million), Indonesia (39 projects, $234 million), and South Africa (29 projects, $160 million) (Figure VI-12). From the pilot phase to GEF7, biodiversity and climate change account for around 25 per cent of the total GEF Trust Fund, while the corresponding share amounts to 10 per cent for international waters, 9 per cent for chemicals and waste and 3 per cent for land degradation.[39]

Figure VI 12
Largest recipients of GEF Trust Fund by number of grants since GEF-5 (2010)



Source: UNCTAD based on (GEFIEO, 2022).

In addition to GEF, within the United Nations System, the UNFCCC has a technology transfer framework covering technology needs and needs assessments, technology information, enabling environments for technology transfer, capacity-building for technology transfer, and mechanisms for technology transfer. Part of this framework is the United Nations Climate Technology Centre and Network (CTCN), which provides technical assistance in response to requests submitted by developing countries via their nationally-selected focal points (Box VI-1). Upon receipt of such requests, the Centre quickly mobilizes its global Network of climate technology experts to design and deliver a customized solution tailored to local needs.

Another United Nations framework for technology transfers is the Addis Ababa Action Agenda (AAAA) which outlines action areas to guide global Financing for Development efforts. The AAAA established the Technology Facilitation Mechanism (TFM) to support the SDGs by encouraging the development, adaptation, dissemination, diffusion and transfer of environmentally sound technologies to developing countries.

In addition, the United Nations system has several programmes to build new capabilities and skills for all national innovation system actors to develop and deploy technologies for greener and more productive production. International cooperation supports tailored programmes supporting countries in their environmental management efforts, including implementing multilateral environmental agreements and providing sustainable energy.

Box VI 1
United Nations Climate Technology Centre and Network (CTCN)

The CTCN delivers five main types of technical support on climate technologies: (1) Technical assessments, including technical expertise and recommendations related to specific technology needs, identification of technologies, technology barriers, technology efficiency, as well as piloting and deployment of technologies; (2) technical support for policy and planning documents, including strategies and policies, roadmaps and action plans, regulations and legal measures; (3) training; (4) tools and methodologies; and (5) implementation plans.

The CTCN does not provide funding directly to countries but instead supports the provision of technical assistance provided by experts on specific climate technology sectors. Technical assistance on climate technologies is provided to developing countries at request, free of charge (with a value up to $250,000), at local, national or regional levels, to academic, public, NGO, or private sector entities, and for a broad range of adaptation and mitigation technologies. Technical assistance is provided at all stages of the technology cycle: from identification of climate technology needs, policy assessment, selection and piloting of technological solutions to assistance for technology customization and widespread deployment.

Source: UNCTAD based on https://www.ctc-n.org/technical-assistance.

B. FOSTERING INTERNATIONAL COOPERATION FOR GREEN INNOVATION

International action for green innovation comes from many sources. It may be the result of businesses seeking greater efficiency and profits, or government action or philanthropy contributing to global public goods. Such fragmentation might be thought to hinder progress but can also be considered an advantage in that it matches the complexity and the scale of what is needed.[40]

Currently, most international support for green innovation relates to specific green products such as energy-efficient transport or fuel-saving improved cooking stoves. Much less is intended to strengthen innovative capacities and national innovation so that developing countries can adapt and adopt green technologies and arrive at their own solutions.

1. ALIGN TRADE WITH THE PARIS AGREEMENT

International trade should be consistent with the Paris Agreement on climate change. Trade rules should, in particular, permit developing countries to protect infant industries so new green sectors can emerge to build cleaner and more productive production. Historically, successful infant industry policies promote new exports so that they cannot just meet local demand but also can reach the necessary economies of scale and provide the proper incentives and discipline to the firms in the infant sector. Governments in developing countries should be able to protect infant industries through selective export subsidies for specific new sectors, local content requirements and tariffs for related imports. There should also be direct and indirect subsidies, investment measures and government procurement that promote domestic products over imported ones. The ability to sequence and manage these interventions is critical to avoid the pitfalls that faced earlier industrial policies in developing countries.[41]

Recent initiatives in developed countries show that these policies are needed even in more technologically advanced countries to build their technological and productive capacities in new sectors that contribute to tackling climate change. For example, in 2022, the United States passed the Inflation Reduction Act, which provides significant funds for climate change mitigation and adaptation, including a $7,500 tax credit for electric vehicles assembled in the United States. [42] Moreover, by 2023, the eligibility criteria of half of these tax credits will require 40 per cent of the minerals of the electric vehicle batteries come from the United States or FTA partners.

While developed economies have the capabilities and economic strength to promote targeted industrial policies for climate action, most developing countries will require the support of the international community. The existential threat of climate change justifies all support for less technologically capable developing countries to build these technological, innovation and productive capacities, including through targeted industrial policies. The Paris Agreement, signed 193 member states and the EU, in articles 9, 10 and 11 enshrines this support for technology development and transfer, capacity building and required finance.[43]

Essential for implementing these Articles is a well-functioning trade system with effective global governance that enables countries to address this pressing global challenge. Current trade rules, however, are not always compatible with the infant industry policies – notably those related to export subsidies and import restrictions. Under WTO rules, governments should design and implement policies that are non-discriminatory among the sources of imported goods and services (most-favoured-nation principle) and between imported and domestic goods and services (and services providers) (national treatment principle). Subsidies should be given only for domestic production, not exports.[44] In the case of agricultural products, subsidies for domestic production are not allowed when they have a distortive effect on trade, unless under prescribed monetary limits as provided for in national schedule (AMS) and under certain allowance. Moreover, developing countries may face additional constraints in WTO+ rules under Regional Trade Agreements like on IPRs.[45]

Previous WTO rules on subsidies used to provide some flexibility. They allowed R&D subsidies and subsidies for regional development and environmental protection, but rules on these subsidies expired in 2000.[46] Article 27 of the Subsidies and Countervailing Measures (SCM) permitted low-income developing countries to implement export subsidies for a period (eight years from the date of entry into force of the WTO Agreement, in the case of the least developed countries).[47] Although developing countries can still ask for extensions that the WTO Ministerial Conference can approve, the expiry of the initial time limit sets the tone for a less flexible system.

Developed countries have more frequently used the dispute settlement mechanism to raise cases against middle-income developing countries. For example, out of 301 countervailing actions initiated by the United States between 1995 and 2021, 104 were related to measures enacted by China. Other developing countries that cases from the United States refer to are India (39 cases), Türkiye (16), Indonesia (12), Brazil (9) and Viet Nam (8).[48] At the same time, whenever a developing country wins a case against a developed country, its ability to use remedies or retaliate is limited because the developed country often represents a significant export market.[49] Also, the lack of financial resources prevents small developing countries from using dispute settlement mechanisms (DSM).[50]

This pattern is revealed by an analysis of WTO disputes and Subsidies and Countervailing Measures cases (Table VI-7). Developed countries have been the primary users of these mechanisms, raising almost 5 out of every 6 cases. Most cases were against other developed countries or middle-income countries. However, no case was presented against low-income countries.[51] Thus, the current trade regime may constitute a more significant challenge for implementing infant industry policies in middle-income developing countries, not low-income countries.

Table VI 7

Top reporters and exporters in countervailing actions, 1995-2021

Reporting member	Number of cases	Exporters	Number of cases
United States	301	**China**	196
European Union	92	**India**	96
Canada	77	**Republic of Korea**	33
Australia	39	**Indonesia**	30
India	29	**Türkiye**	26
China	17	**United States**	24
Brazil	14	**Viet Nam**	23
South Africa	13	**Thailand**	22
Egypt	12	**Malaysia**	19
Peru	10	**Italy**	16

Note: The total was 651 cases

Source: UNCTAD based on data from https://www.wto.org/english/tratop_e/scm_e/scm_e.htm.

Nevertheless, the WTO has been responding to demands for more sustainable trade. In 2020, 50 WTO members expressed their intention to collaborate, prioritize and advance trade and environmental sustainability discussions through Trade and Environmental Sustainability Structured Discussions (TESSD) between interested WTO Members and dialogues with external stakeholders. In December 2021, WTO members adopted a Ministerial Statement setting out the future work of TESSD agreeing, among other things, to "[i]ntensify [their] work on areas of common interest and to identify concrete actions that participating Members could take individually or collectively to expand opportunities for environmentally sustainable trade in an inclusive and transparent way, consistent with their obligations."[52]

In June 2022, WTO members launched a broader reform process. The intention is to enhance negotiating functions and restore the dispute settlement mechanism, but they could also change the rules in favour of a green transition. In this context, member countries should consider extending the UNFCCC principle of "common but differentiated responsibility and respective capabilities," to trade, investment, and intellectual property rights. This principle could be considered under the mechanism established by the Bali Ministerial Conference to review and analyse the implementation of special and differential treatment provisions through Dedicated Sessions of the Committee on Trade and Development.[53]

Efforts to align trade rules with the Paris Agreement should continue and be strengthened. Some authors have proposed other ways to change the rules to facilitate technological upgrading in developing countries.[54] For example, a rule could be created to require developed countries to meet their commitment of directing 0.7 per cent of their GDP to ODA before they are able to complain against developing countries that use subsidies to promote specific new export sectors. Also, by bringing back the non-actionable subsidies for R&D, regional development and environmental compliance under the now expired SCM.[55]

Meanwhile, countries should continue to seek to develop their infant industries in cleaner sectors under the existing WTO rules. For example, countries with larger domestic markets can implement specific subsidies for production for domestic consumption (since subsidies and local content requirements for exports are prohibited). Thus, these countries could subsidize nascent cleaner sectors focusing on import replacement; for example, for the production of components and parts of domestic solar and wind energy projects. As this production takes root, the capacities for export could be developed with the support of trade facilitation measures. Countries could also provide subsidies through regional development, technological and environmental policies. For example, a policy to promote the establishment of a new regional cluster on green technologies for cleaner production could be framed as WTO-compatible under these rules.[56] Another possible strategy to be followed by developing countries is to subsidize the production of new cleaner sectors and use a stable and competitive exchange rate as an alternative to tariffs. That combination would have the same effect as export subsidies for the priority targeted sectors.[57]

Alternatively, whenever less technologically advanced developing countries identify those rules that prevent their greening efforts, a waiver or some allowance should be explicitly (and more easily) provided by the WTO membership.

The international community should also be innovative and propose new and bold trade mechanisms to support the development of innovation and technological capacity in developing countries for cleaner and more productive production. Any such mechanism should address the supply and demand elements. On the supply side, developed countries can use development assistance to help countries to emulate the production of more advanced countries – to diversify their economies and produce cleaner, more productive and competitive products. On the demand side, developed countries should open their markets to production from latecomer economies.

A challenge that would need to be addressed in such an approach is the identification of products and countries that would benefit from such measures. Some observers point to this identification problem as one of the reasons for the past failure of the WTO efforts on environmental goods and services.[58] Moreover, as seen in Chapter 5, it is possible to find products associated with lower carbon footprints in all sectors and at very disaggregated levels, from primary products to manufacturing. Thus, designing rules that identify these products is challenging, particularly if they rely on government self-assessment. Similarly, the level of technological capacity of a country requires a sophisticated methodology to be assessed. This suggests that a new institutional arrangement would be required at the international level to generate the information to be used in the stipulation of trade rules.

A possible arrangement to pilot this approach would be to create an international programme of guaranteed purchase of tradable green products that can be used for energy transition (e.g., products, parts and components used in renewable energy projects). The programme could be set up so that to participate in it, firms from developed and developing countries should partner in an innovation collaboration arrangement to develop the technological and productive capacities of developing country firms. The programme could match the complexity of products to be purchased to the technological capacity of the developing country, providing a reasonable "challenge" for countries to build their technological and productive capacities. For example, only countries with low technological capacities could participate in the programme producing the less complex products. More technologically advanced developing countries would have to participate in producing more complex products.

2. REFORM INTERNATIONAL PROTECTION OF IPRS FOR LESS TECHNOLOGICALLY ADVANCED COUNTRIES

More stringent international protection of Intellectual property rights (IPRs) reduces the opportunity for firms to reverse engineer and copy the production they try to emulate. Historically, many countries have caught up primarily by copying existing technologies – as happened in the century after the industrial revolution when other countries sought to emulate Britain. It was also evident from the 1960s when Asian countries such as Japan and the Republic of Korea copied from industries in Europe and the United States.[59] Only some way into the catching-up process did they increase their levels of intellectual protection.

Emulation became more difficult as international protection of IPRs was tightened up – especially from 1994, with the WTO Agreement on Trade-Related Aspects of Intellectual Property (TRIPS) (Box VI-2).[60] This set a much higher bar and has no provisions for differential IP regimes for countries at different levels of technological capabilities – the special and differential treatment provisions only relate to time lags in the implementation of the agreement, which are not linked to any objective measures of technological or productive capacities.[61] A less-stringent IPR regime at the global level (which is unlikely) would increase the opportunities for emulation for less technologically advanced countries.[62]

Box VI 2
Selected elements of the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS)

Flexibility and compulsory licenses

TRIPS Article 31: Where the law of a Member allows for other use of the subject matter of a patent without the authorization of the right holder, such use may only be permitted if, before such use, the proposed user has made efforts to obtain authorization from the right holder on reasonable commercial terms and conditions and that such efforts have not been successful within a reasonable time. A Member may waive this requirement in case of a national emergency or other circumstances of extreme urgency or in cases of public non-commercial use. The scope and duration of such use shall be limited to the purpose for which it was authorized. In the case of semi-conductor technology, it shall only be for public non-commercial use or to remedy a practice determined to be anti-competitive after judicial or administrative process. Any such use shall be authorized predominantly for the supply of the domestic market of the Member authorizing such use.

Transitional periods

TRIPS Article 65.2 to 5: A developing country Member was entitled to delay for a further period of four years the date of application of the provisions of the Agreement.

TRIPS Article 66.1: Given the special needs and requirements of least-developed country Members, their economic, financial and administrative constraints, and their need for flexibility to create a viable technological base, such Members shall not be required to apply the provisions of this Agreement for ten years from the date of application. The Council for TRIPS shall, upon duly motivated request by a least developed country Member, accord extensions of this period. In June 2021, the TRIPs Council agreed to extend the LDC transition period to 1 July 2034.[63]

Technology transfer

TRIPS Article 66.2: Developed country Members shall provide incentives to enterprises and institutions in their territories to promote and encourage technology transfer to least-developed country members to enable them to create a sound and viable technological base.

Technical and financial cooperation

TRIPS Article 67: To facilitate the implementation of this Agreement, developed country Members shall provide, on request and on mutually agreed terms and conditions, technical and financial cooperation in favour of developing and least-developed country Members. Such cooperation shall include assistance in the preparation of laws and regulations on the protection and enforcement of intellectual property rights as well as on the prevention of their abuse, and shall include support regarding the establishment or reinforcement of domestic offices and agencies relevant to these matters, including the training of personnel.

Source: UNCTAD based on (WTO, 1994; Cimoli et al., 2009b)

TRIPS Article 66.2 does oblige developed countries to "provide incentives to enterprises and institutions in their territories for the purpose of promoting and encouraging technology transfer to least developed country members in order to enable them to create a sound and viable technological base." However, although developed countries have reported incentives to their firms and institutions to engage in technology transfer not only to the LDCs but also, in some cases, to developing countries in general, compliance with the Article has been low and difficult to enforce.[64]

Considering the imperative to tackle the existential threat of climate change, the international community should align the international protection of IPRs with the principle of "common but differentiated responsibility and respective capabilities" set out in the UNFCCC. Manufacturers in technologically weak and less-diversified countries should be allowed to imitate the production of more technologically advanced economies. [65] The international IPR system should also allow for tailored IP regimes in which governments manage their IP systems to support climate action and their industrial and technological development strategies, balancing IP regimes to address the needs of different sectors and different stages of development.[66]

The principle that the international trade framework should place sustainable development considerations above commercial objectives has already been demonstrated during the COVID-19 crisis. In 2022, the 12th Ministerial Conference of WTO adopted a Ministerial Decision allowing eligible Members until 2027 to produce and supply vaccines without the consent of the patent holder to the extent necessary to address the COVID-19 pandemic. [67] Similarly, the 2022 WTO Ministerial Declaration on Response to the COVID-19 Pandemic and Preparedness for Future Pandemics,[68] recognized "the role of the multilateral trading system in supporting the expansion and diversification of production of essential goods and related services needed in the fight against COVID-19 and future pandemics, including through identifying opportunities and addressing barriers."

Similarly, countries have used existing WTO mechanisms to try to promote consistency of the trade regime with the climate change agreements. In 2013, Ecuador, for example, proposed a series of actions to use flexibilities in the TRIPS Agreement for environmentally-sound technologies for vulnerable developing countries and least developed countries whose effective adoption and dissemination constitute a matter of "public interest" due to the existential threat of climate change (Box VI-3). The proposal received a mixed reaction; it was welcomed by some countries, while others welcomed the debate but not necessarily the proposals.[69]

Box VI 3
2013 proposals by Ecuador to adapt the Trade-Related Aspects of Intellectual Property Rights

The 2013 proposals by Ecuador in a Communication to WTO's Council for Trade-Related Aspects of Intellectual Property Rights were:

- Reaffirmation of the existing flexibilities in the TRIPS Agreement so that Members use them in connection with ESTs, for example through a declaration addressing flexibilities in the TRIPS Agreement, climate change and access to ESTs;
- Initiation of a review of Article 31 of the TRIPS Agreement to determine which of its provisions may excessively restrict access to and dissemination of ESTs, and particularly its paragraph (f) and the need to include provisions on, as the case may be, the transfer of expertise or know-how to implement compulsory licences;
- Evaluation of the regulation of voluntary licensing and the conditions thereof from the standpoint of the most pressing needs of the most vulnerable developing countries in relation to adaptation to and mitigation of climate change;
- Recognition that adaptation to and/or mitigation of the harmful effects of climate change should be assimilated to the concept of "public interest", with the adoption of a provision authorizing exemption from patentability, on a case-by-case basis, for inventions whose exploitation is vital for the diffusion of ESTs needed for adaptation and/or mitigation of climate change;
- Evaluation of Article 33 of the TRIPS Agreement to establish a special reduction in the term of protection for a patent of [X] years in order to facilitate free access to specific patented ESTs for adaptation and/or mitigation of the effects of climate change because of urgent need in the public interest; and
- Inclusion of a mechanism in the TRIPS Agreement to promote open and adaptable technology licensing for results obtained from research into climate change and ESTs financed through public funds.

In the light of the above points, the application of new flexibilities included in the TRIPS Agreement would be understood to be only in favour of the vulnerable developing countries and least developed countries.

Source: WTO documents online (IP/C/W/585).[70]

3. PARTNERS FOR GREEN TECHNOLOGY

Policymakers are keen to guarantee the benefits of green transformations for national companies and workers, and private actors who strive to protect their intellectual capital through patents and royalties. All of which will inhibit the rapid and widespread diffusion of innovation.

International and national governance of green innovation must deal with these tensions and develop partnerships for common public goods.[71] One ground-breaking model for this philosophy is the Intergovernmental Panel on Climate Change (IPCC). Others are the Paris Agreement of 2015 and the agreements for the Sustainable Development Goals, especially SDG 17 "Partnership for the Goals". As nearly all governments have approved the Paris Agreement and SDGs,[72] this should also be a guiding principle for public promotion of green innovations.

There are also successful examples of collective research whose results belong to all participating countries, particularly in natural sciences, including the European Organization for Nuclear Research (CERN), the International Thermonuclear Experimental Reactor (ITER) and the Square Kilometre Array (SKAO) project (Box VI-4). Similar collaborations can also shape international cooperation for green innovations that equitably incorporate the views and priorities of developing countries.[73]

These collaborations can still however, allow for conflicting views and diverging interests. This can be shown by the current discussion about a global transition towards a "green hydrogen economy". The recent debate about the EU energy "taxonomy" made it clear that countries have different views on what clean energy should be the basis for green hydrogen production. For Germany, the term clean energy should be exclusively reserved for renewables such as wind and solar, while France includes nuclear energy among clean energy sources.

Box VI 4
Examples of partnership-oriented approach to research

International Mega-Science collaborations are driven by a common goal. The founding fathers of CERN, for example, stated that "The spirit from the beginning, was that we are not at CERN to profit; we are there to help to achieve the common objective."[74] ITER similarly unites three continents and 35 nations under one ambition to employ fusion power as a large-scale, carbon-free energy source to build a new Sun on earth. That spirit resonates in SKAO international collaboration to demonstrate the scientific and technological feasibility for peaceful purposes. The knowledge obtained is expected to benefit all humankind eventually.

The common goal and scientific spirit are embodied in mandates or mutual agreements. CERN was example, established in 1954 as result of a Convention signed by 12 founding states in 1953.[75] Today it has 23 Member States, bringing together more than 17,500 people working to discover what the universe is made of and how it works. The ITER Agreement was signed in Paris in 2006 and entered fully into force in 2007 after the members' ratification.[76] Similarly, seven countries signed the SKA Observatory Convention in 2019 in Rome.

To avoid undue influence from any particular member, these collaborations, have been established as intergovernmental organizations (IGOs). For example, the ITER Organization enjoys privileges and immunities on the territories of the seven Members. [77] Likewise, founding members of SKAO came together in Rome in 2019 for the signature of the international treaty establishing the IGO that will oversee the delivery of the world's largest radio telescope.[78]

Funding agencies from Member and Non-Member States of CERN are responsible for the financing, construction and operation of experiments. [79] Members of ITER contribute to the project in-kind resources – components, equipment, materials, buildings, and other goods and services and may recommend staff). But they also provide financial contributions to the organization's budget. [80]

Today, global issues such as the energy crisis, scientific quests, climate change, and sustainable development are too complex to be answered by one nation's experts or facilities alone. International large-scale collaborations engender knowledge sharing, innovation, and economic development. Successful collaborations – such as CERN, ITER, and SKAO – leverage international talent to go beyond what can be done and discovered at smaller scales.

Source: UNCTAD.

4. MULTILATERAL AND OPEN INNOVATION

Most global STI efforts are governed by developed countries and generally reflect their priorities – domestic stakeholders define agendas and priorities of research, financing comes from public and private sources in the country, and usually national companies and societal groups are prioritized.[81]

Countries with different levels of socio-economic development and ecological conditions will set diverse priorities in their R&D agendas. For food security, for example, since food availability is no longer an issue in developed countries, R&D in the agricultural sector has declined, middle-income countries have rising populations and increasing incomes and need R&D on agriculture to further boost productivity.[82] Similarly, in energy research, the industrialized countries are primarily interested in decarbonizing grid-connected energy systems while low-income countries in Africa and Southern Asia need easy-to-roll-out renewable-energy-fed mini-grids. And when it comes to green hydrogen, the main focus of the current debate is on hydrogen to decarbonize the steel industry, while the developing countries might prefer to use green hydrogen to produce ammonia as the basis for nitrogen fertilizer.

The international community can address these priority differences by shifting research for green innovation from the national to the multinational level.[83] A useful model is the Consultative Group on International Agricultural Research (CGIAR), which is internationally financed and located mainly in developing countries (Box VI-5). CGIAR is intensively embedded in multi-stakeholder networks and aims to produce common goods and has contributed innovative solutions for a climate-smart, innovative and socially inclusive agriculture. International organizations and donors could adapt the CGIAR model to other sectors.

Multilateral research can cover the whole value chain, or just a part of it. Research institutions could, for example, bring products or processes close to technology maturity and invite private companies to take care of rapid deployment. Or they might only take concepts to the laboratory stage or early demonstration projects. The aim should be to combine the strengths of multilateral and publicly funded research with the creativity and endeavours of the private sector.

Multilateral research should be based on open innovation – with all the results available to international experts and knowledge communities, all of whom can contribute to the best possible solutions. Many innovators are already producing open-source designs and technologies, but there is no central repository – which hinders access for producers in developing countries.

In this regard, the Economic and Social Council of the United Nations recently adopted resolution 2021/30 which calls for a centralized repository of open-source technical information as a global stock of knowledge.[84] Such a database would require solid support from UN Member States and agencies. UNCTAD has been disseminating the proposals and seeking ways of implementing the resolution.[85]

Box VI 5
Examples of multilateral modes of research and research cooperation

Consultative Group on International Agricultural Research (CGIAR): CGIAR was formally launched in May 1971 by the World Bank and 16 donors, including governments of industrialized countries and other organizations CGIAR has, since then, become a major player for world agricultural research and a reference in terms of how scientific research can help develop agricultural solutions for the poor.[86] CGIAR is the largest global partnership focusing on "agricultural research for development" particularly in developing countries with a vision to create a "world free of poverty, hunger and environmental degradation". It operates globally through its 15 research centres in close association with "hundreds of partners, including national and regional research institutes (NARIs), civil society organizations, academia, development organizations and the private sector".[87] CGIAR's mandate is to contribute to regional or global public goods and, thus, technologies and knowledge generated are in principle freely transferred of shared. [88]

Global Carbon Capture and Storage (CCS) *Institute:* When the Global CCS Institute was launched in 2009 it had 15 governments and more than 40 companies and industry groups as foundation members. By 2010 membership had increased to 263 members, including 26 national governments. The mission of the Global CCS Institute is to accelerate the roll-out of commercial CCS for a low-carbon future. To achieve this objective, a set of CCS demonstration projects shall be rolled out and capacity building and knowledge sharing are crucial. The role of IPR has been intensely discussed since the institute's formation. While on the one hand, IP rights of partners are respected, the goals are 1) to gather and package non-proprietary information on CCS and make it accessible to all stakeholders, 2) to make IP generated through program activities as widely accessible to members as practical and to make IP jointly generated by the Institute and its partners through Institute activities available in reasonable terms to other Institute activities.[89]

International Energy Agency (IEA) Implementing Agreements: The IEA, an intergovernmental organization, acts as an energy policy advisor to its member countries. Through its work, IEA supports their efforts to ensure reliable, affordable and clean energy for their citizens. The triple goals are energy security, economic development and environmental protection.[90] IEA also provides opportunities for exploring alternative energy and conservation sources through long-term cooperation. One important mode of multilateral cooperation is the IEA Implementation Agreements (IA). By IEA rules and regulations, participation in an IA is to be based on equitable sharing of obligations, contributions, rights and benefits. Patents resulting from work within an IA may be filed in countries as appropriate by the inventing participant. Participants may be required not to disclose information related to these patents for a fixed period.

Source: UNCTAD based on Stamm and Figueroa (2012).

5. ASSESSING TECHNOLOGIES

Most technologies have both positive and negative consequences depending on the local context and on how they are used. Artificial intelligence in agriculture, for example, can enable farmers in developing countries to use much less fertilizer and pesticides. But if it is embedded in IT-powered robots for harvesting fruits and vegetables AI can eliminate the jobs of agricultural workers who are often women.[91] Also, how technologies are assessed regarding their opportunities and risks is often related to the specific value systems of a society and the challenges it faces. For example, the CRISPR-CAS genome editing technology can be used to boost agricultural yields but also raises a number of ethical issues.

A 2018 ruling by the EU court of justice made progress in genome editing technologies depending on bureaucratic procedures and, thus, slowed down the innovation process. Therefore, a decision based on normative considerations from one world region potentially has a significant global impact.[92]

Every country needs to be able to assess the benefits and dangers of each technology according to its own needs, priorities and concerns, but to date, technologies have largely been assessed either from the perspective of the developed countries or of emerging economies such as Brazil the Philippines or Türkiye (Box VI-6).

What is needed however is a more general multilateral system for assessing new technologies such as AI and gene-editing – based on the opportunities and risks they offer to different types of country.[93] UNEP, for example, through the Climate Technology Centre & Network (CTCN) conducted a Technology Needs Assessment in Brazil on the use of Industry 4.0 technologies, particularly on how they can help create a circular economy.[94] UNCTAD is currently carrying out pilot projects involving three African countries to build capacity for technology assessment. It could also consider how developing countries can be systematically supported to use such technologies.

Box VI 6
Technology assessment elements in emerging economies

Brazil – The Government is assessing the country's technological capacity through the project "Evaluation of the Technological Needs to the Implementation of the Climate Action Plans in Brazil" (TNA Brazil). It contributes to the national goals of mitigation of greenhouse gases, taking into consideration Brazil's Nationally Determined Contribution and Brazil's strategy for the Green Climate Fund.[95]

Philippines – DOST-National Research Council of the Philippines (NRCP) is investigating alternative energy sources in the Philippines through the The Clean Energy – ALERT (Alternative Energy Research Trends) programme. This programme is expected to lay out how renewable energy can reduce government's costs, bring jobs to the country, create wealth, expand access to energy for the most vulnerable in poor communities, and foster national energy independence.[96]

Türkiye – The Science and Technology Commission was established to anticipate the future technologies and contribute to the country's 2053 net zero emission target. The objective is to foresee future technologies for adaptation and mitigation, and to enable the country to develop its R&D and innovation capacity. With a multidisciplinary holistic approach, the Commission has held more than 40 online meetings with 97 experts from universities, the private sector, NGOs and public institutions. The outcomes are translated into prioritized RDI topics in TÜBİTAK's R&D, and innovation support programmes.

Source: UNCTAD based on contributions from the Governments of Brazil, the Philippines and Türkiye.

6. REGIONAL AND SOUTH-SOUTH STI

Climate change is a global issue; thus, technological innovations to address this threat might increasingly be generated on the transnational or even global level. However, this is not the case. One indicator is the volume of financial resources spent on R&D. The European Union arguably has most ambitious regional integration programme Horizon Europe on which predicted expenditure over the period 2014-2020 will be about 13 billion but this pales in comparison to EU countries' national spending. In 2020, Germany alone invested more than €15 billion in public R&D.[97]

In developing countries, there is even less regional cooperation on STI for sustainable development. Researchers and investors in the poorer countries have little incentive to work with their regional peers and are more likely to enter research projects with developed countries and emerging economies, which can offer access to world-class research and laboratories as well as computing power. In addition, individual researchers, would prefer to publish in internationally refereed journals and cooperate with researchers from well-known universities in the North.[98]

This is also reflected in the level of South-South cooperation in science and technology, which remains limited. On 15 April 2019, the UN General Assembly adopted a resolution recognising the importance of South-South cooperation to achieve the SDGs, calling for greater support to step it up.[99] The document also serves as an international framework of agreed principles covering the topic. It calls for regional mechanisms to share and strengthen successful science, technology and innovation policies and strategies, explore new opportunities, and promote cross-border and interregional coordination and collaboration between initiatives and research in scientific areas.[100] Moreover, there have been several initiatives in South-South cooperation. In 2020, for example, African governments launched the 10-year Science, Technology and Innovation Strategy for Africa (STISA-2024). But overall cooperation has been limited, even in issues such as climate change in which countries in the same region often face similar problems, as in the Caribbean with the rise in sea level or in sub-Saharan Africa (SSA) with changing patterns of precipitation.

The problem is partly that small and poor countries do not have sufficiently interesting home markets to attract local or international investment in the manufacture of goods related to green innovation. To address this issue, donor countries can support regional centres of excellence for green technologies and innovation – such as the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) and the West African Science Service Centre on Climate Change and Adapted Land Use.

For many countries the lack of South-South cooperation is being offset by the arrival of China. Between 1990 and 2018, China's share of total imports in sub-Saharan Africa rose from 1.1 to 16.5 per cent. And markets in China and Africa are being brought close together through the infrastructure of the Belt and Road Initiative. Accompanied by a change in China-SSA trade patterns, shifting from imports of products such as footwear and light manufactured to more sophisticated and capital-intensive goods, China is now the most significant source for machines and electronics for the region.[101]

And compared with investment from developed countries China seems to be more effective in promoting technological progress in Africa. [102] This could be because there are smaller technological gaps between enterprises in China and those in Africa which eases the transfer of technology. Moreover, many Chinese investors are very active in transferring technology-related knowledge to their staff in Africa, generally through on-the-job training rather than classroom-type training.[103] This often refers to small Chinese companies operating in Africa's domestic markets.

Nevertheless, the evidence for such technology transfer is limited and mixed.[104] Some studies indicates that Chinese companies are involved in more traditional styles of technology transfer, for smooth implementation of investment projects, when it is cheaper to employ a local contractor than to fly in staff from the home country.[105]

More technologically advanced developing countries should step up and strengthen efforts to promote regional and South-South cooperation for green innovation.

7. A MULTILATERAL CHALLENGE FUND "INNOVATIONS FOR OUR COMMON FUTURE"

Successful innovation systems create multiple incentives for companies and entrepreneurs to develop their own ideas and transfer them to practice. Many industrialised countries use business plan competitions or competition-based incentives for innovation. These inject dynamism to the business sectors and help reconfigure innovation systems. However, most developing countries lack the financial or management capacities to develop similar incentives. In addition, in the spirit of this chapter, innovation challenges should best be implemented, not on the national level, but internationally.

This Report proposes therefore a multilateral challenge fund "Innovations for our common future." The name echoes the 1987 report of the World Commission on Environment and Development (WCED), "Our Common Future", which embraced environment and development as one single issue. Funded by international organizations donors and international philanthropy, the fund would mobilize creative thinking and stimulate innovations that could respond to many global challenges. The governance mechanism could be similar to the Intergovernmental Panel on Climate Change (IPCC) with its own executive committee, technical support units and with a secretariat.

The next step would be to design a global green innovation competition. It could draw, for instance, on the international donors experienced in this area. The criteria for assessing projects would be the extent to which they incorporate North-South and South-South and Triangular STI cooperation for green innovation.

1 Hultman et al., 2012

2 Hultman et al., 2012, IMF, 2022; WEF, 2022

3 Pandey, Coninck, et al., 2022

4 Khor, 2012

5 UNCTAD, 2014b

6 Kirchherr and Urban, 2018

7 Blicharska et al., 2017

8 Blicharska et al., 2017: 22

9 For a significant period (1975-2017) patents were extracted from a database of the Cooperative Patent Classification (CPC). Green technologies were conceptualized as comprising technologies 1) in climate change mitigation and adaptation and 2) in systems that integrate technologies related to power network operation and ICTs in this area.

10 This office is considered to have very rigorous procedures and, thus, patents granted there can be seen as a “proxy” for quality.

11 EPO, 2013

12 The rather sophisticated methodology of OECD-DAC to collect and disseminate aid data permits to estimate the percentage of ODA addressing international environment goals, written down in Conventions on Climate Change, Biodiversity, Desertification, etc. OECD, 2019.

13 IEA, 2022a

14 *Foreign Affairs*, 2022

15 Michaelowa and Namhata, 2022

16 The OECD’s Development Assistance Committee (DAC) monitors ODA flows to developing economies that target the objectives of the Rio Convention on (i) biodiversity, (ii) climate change, and (iii) desertification, besides climate change adaptation, added in 2010. However, reporting Rio markers became mandatory only in 2006, with provider coverage varying across the years.

17 OECD, 2022

18 OECD, 2018b: 4

19 OECD, 2022

20 OECD, 2022

21 OECD, 2022

22 OECD, 2022

23 OECD, 2022

24 OECD, 2022

25 Rijsberman, 2021

26 OECD, 2022

27 OECD, 2022

28 The share of ODA targeting STI capacities as a percentage of total ODA per year has also increased for unspecified developing countries (15.24 per cent in 2000 and 26.65 per cent in 2020, after reaching a peak of 30.12 per cent in 2016).

29 OECD, 2022

30 There are, however, some exceptions. For example, for most years between 2001 and 2020, multilateral ODA constituted the main source of ODA targeting ICT.

31 OECD, 2022

32 OECD, 2022

33 Kosolapova, 2020

34 Ibid.

35 Global Environment Facility, 2022

36 The GEF also administers the Least Developed Countries Fund (LDCF), the Special Climate Change Fund (SCCF), the Nagoya Protocol Implementation Fund (NPIF), the Capacity-Building Initiative for Transparency (CBIT) Trust Fund and Adaptation Fund.

37 Global Environment Facility, 2022

38 Global Environment Facility, 2022

39 GEFIEO, 2022

40 Pandey, Coninck, et al., 2022

41 See for example Lall, 2004; Wade, 2015; UNCTAD, 2016.

42 U. S. Congress, 2022

43 United Nations, 2015

44 According to the Agreement on Subsidies and Countervailing Measures articles 2 and 3: Specific subsidies to certain enterprises or sectors, contingent on export performance or use of domestic over imported goods, are not allowed. Subsidies that have objective criteria or conditions governing the subsidy eligibility are considered not specific and, therefore, allowed. The criteria or conditions must be clearly spelt out in law, regulation, or another official document to be capable of verification. However, if the subsidy is used by a limited number of certain enterprises, or predominantly used by certain enterprises, it could be considered specific.

45 Cimoli et al., 2009a; UNCTAD, 2018c

46 Lee, 2019

47 WTO, 2022

48 UNCTAD calculations based on WTO, 2022

49 Lee, 2019

50 The DSM is blocked in practice given the ongoing vacancies of Appellate Body. See WTO, 2022

51 WTO, 2022

52 WTO, 2022

53 WTO, 2022

54 See for example Akyuz, 2009; Cimoli et al., 2009; Lee, 2019

55 Lee, 2019

56 Lee, 2019

57 Rodrik, 2007; Bresser Pereira, 2010; Lee, 2019

58 See, for example, WTO, 2012

59 Chang, 2002; Reinert, 2008; Lee, 2019

60 Cimoli, Coriat, et al., 2009

61 UNCTAD, 2007

62 Freire, 2021a

63 WTO, 2021

64 Moon, 2008

65 As proposed by Chang 2020

66 E.g. as suggested in Cimoli et al. 2009

67 WTO, 2022

68 WTO, 2022

69 For example, in the meeting of the Council on 10-11 October 2013, Ecuador's proposal was welcomed by Bolivia, China, Cuba, India, Indonesia, , but not by Canada, the European Union, Japan, New Zealand, Switzerland and the United States.

70 WTO, 2013

71 Pandey, Coninck, et al., 2022

72 UNFCCC, 2023; United Nations, 2015

73 Blicharska et al., 2017; Stamm, 2022

74 Engelen and Hart, 2021

75 CERN, 2008

76 ITER, 2022

77 Official Journal of the European Union, 2006

78 SKAO, 2022

79 CERN, 2022

80 ITER, 2022

81 Stamm et al., 2012.

82 Pardey et al., 2016.

83 These cases have been analyzed in more detail in an international research project under the umbrella of the OECD (2012).

84 ECOSOC, 2021

85 UNCTAD, 2021a

86 Fabre and Wang, 2012: 45

87 Pandey, Coninck, et al., 2022

88 Fabre and Wang, 2012

89 OECD, 2012

90 Stamm and Figueroa, 2012: 132-133

91 Stamm, 2022

92 Ibid.

93 Ibid.

94 ASDF, 2020

95 Ministério da Ciência, Tecnologia e Inovações, 2022

96 National Economic and Development Authority, 2019

97 Destatis, 2023

98 See, for instance, Blicharska et al., 2017

99 UN, 2019

100 UNOSSC, 2022

101 Darko et al., 2021

102 Hu et al., 2021; A study of firm-level data (Hu et al. 2021) and a meta-study of more than one hundred sources (Calabrese and Tang, 2022).

103 Calabrese and Tang, 2022.

104 Oya and Schaefer, 2019, 2019, Weng et al., 2019, Calabrese and Tang, 2022: 12.

105 For example, Kirchherr and Matthews, 2018, and Oya and Schaefer, 2019

ANNEX A
FRONTIER TECHNOLOGY TRENDS

ANNEX B
FRONTIER TECHNOLOGIES READINESS INDEX

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

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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