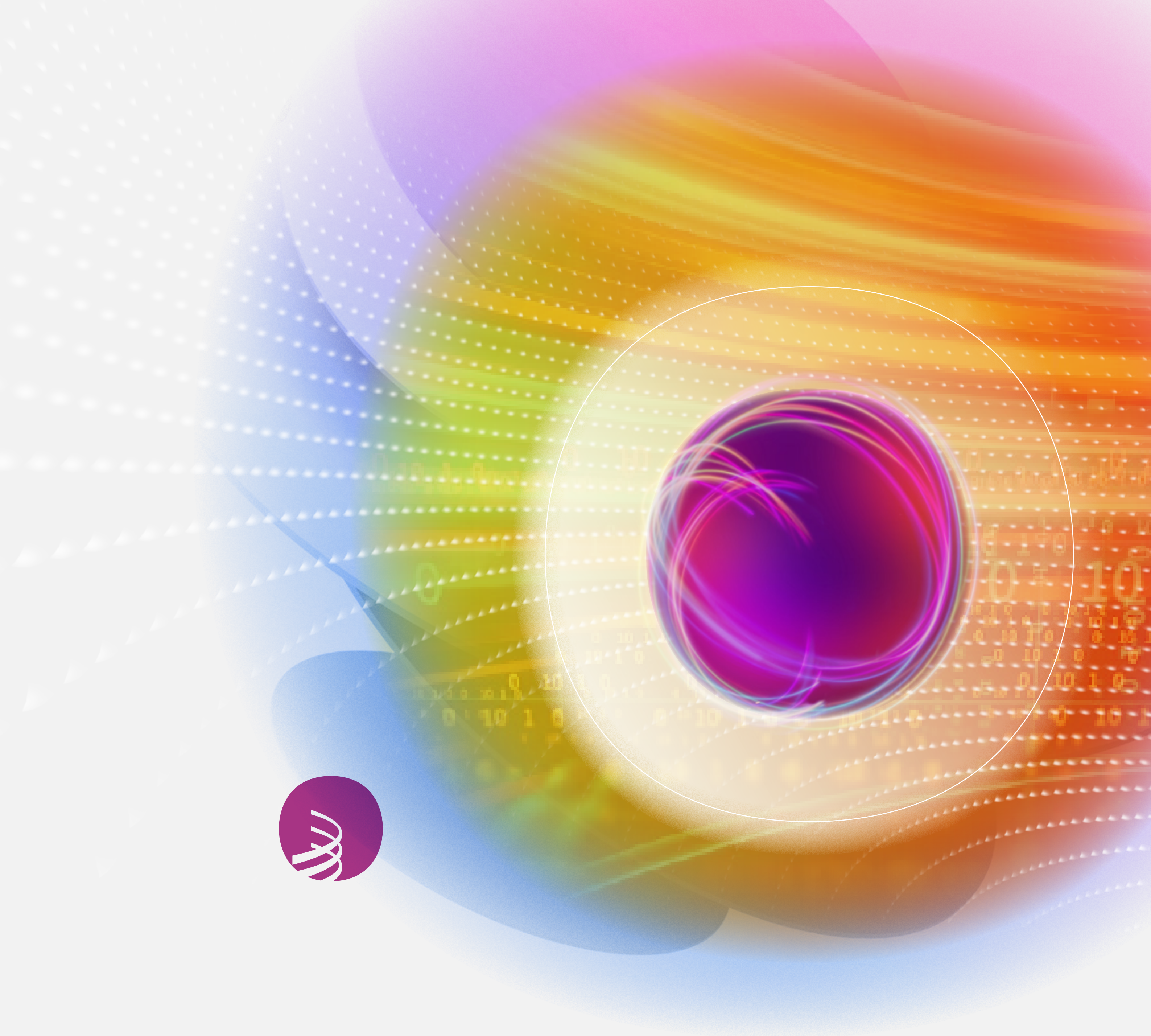
World Intellectual Property Report

Technology on the Move



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Technology on the Move

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Contents

Foreword

We all sense that the world is not just shrinking but also spinning faster. The telegraph was released in the 1840s and took decades to spread worldwide. In comparison, ChatGPT reached 100 million users in just a month.

The theme of technology diffusion is the focus of the *World Intellectual Property Report 2026*. This is important because the time and geographic lag between invention and adoption can make a big difference to the development, growth and impact of that technology on different countries as well as around the globe.

As ever, WIPO goes beyond anecdotes and stories to bring a data- and evidence-based approach to this issue. Our analysis draws on evidence spanning 250 years of technological history, as well as patent citation data over five decades, to provide detailed information on how breakthrough inventions spread.

The findings point to profound changes over the past 50 years in the speed at which technologies spread internationally. Adoption lags between invention and first use have fallen dramatically: technologies that once took decades to reach global markets now do so within years, and in some cases within days. Even more strikingly, newer technologies are no longer used only by a handful of advanced economies at scale – the gap in intensity of use has begun to close, especially in the digital domain. In addition, technological knowledge now travels across borders almost as quickly as within them, signaling a world in which ideas diffuse faster and more widely than ever before.

Nonetheless, significant challenges persist. Technological knowledge – an essential input into the diffusion process – is concentrated and retained in a small number of developed economies. Despite gains, many developing countries require faster economic growth, infrastructure investments, and institutional frameworks to speed technology adoption. At the same time, the experience of several economies, particularly in East Asia, illustrates that these barriers are not insurmountable and shows how countries can harness technology to support economic growth.

Through this report, WIPO seeks to support Member States in better understanding these dynamics and in designing policies that ensure economies benefit from technological progress. Even in a world where geography is no longer a binding constraint on knowledge flows, deliberate policy choices remain essential for translating diffusion into growth, development and actual impact.

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Chapter 1: Carsten Fink, Maria de las Mercedes Menéndez, and Julio Raffo provided the background research on "How do New Technologies Diffuse?" drew on the prior work by Diego Comin (Harvard University).

Chapter 2: Catalina Martinez (IPP-CSIC), Ernest Miguelez (University of Barcelona), Michele Pezzoni (University Côte d'Azur), Reinhilde Veugelers (KU Leuven), and Fabiana Visentin (UNU MERIT) provided the background research on "The Changing Geography of International Knowledge Diffusion."

Chapter 3: Jose Falck-Zepeda (IFPRI) provided background research on "Understanding and Characterizing the Diffusion of Agricultural Technology," and Charles de Grazia (École de Management Léonard De Vince), Nicholas Rada (USPTO) and Gregory Graff (Colorado State University) provided background research on "Diffusion of Genetically Modified Crop Technology."

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Executive summary

Introduction

The *World Intellectual Property Report 2026: Technology on the Move* reveals striking patterns in how technologies spread globally, with profound implications for economic development.

Since the Industrial Revolution, humanity has experienced unprecedented growth: global per capita income has increased more than tenfold and life expectancy has nearly doubled in developed nations. This reflects the power of creative destruction – successive waves of innovation replacing older technologies, enabling economies to produce vastly more with the same resources.

Creating innovative solutions does not automatically translate into economic growth or societal benefits. For new technologies to fulfill their potential, they must be adopted and effectively used by firms and households. This process, called technology diffusion, represents a crucial bridge between invention and impactful innovation, yet it is neither automatic nor guaranteed.

The *World Intellectual Property Report 2026* aims to provide policymakers, business leaders, and researchers with a comprehensive understanding of technology diffusion. This knowledge can inform decisions about innovation policy, IP systems, and strategies for harnessing technological progress to improve economic outcomes and address global challenges.

Do new technologies diffuse faster?

The report draws on historical data spanning 250 years and cutting-edge analysis of recent digital innovations. It uncovers several transformative trends reshaping our understanding of technology diffusion. The report also provides a deep dive on how technologies diffuse within specific contexts by looking into three case studies: agricultural technologies, clean technologies, and digital technologies.

There is a striking acceleration of global technology adoption

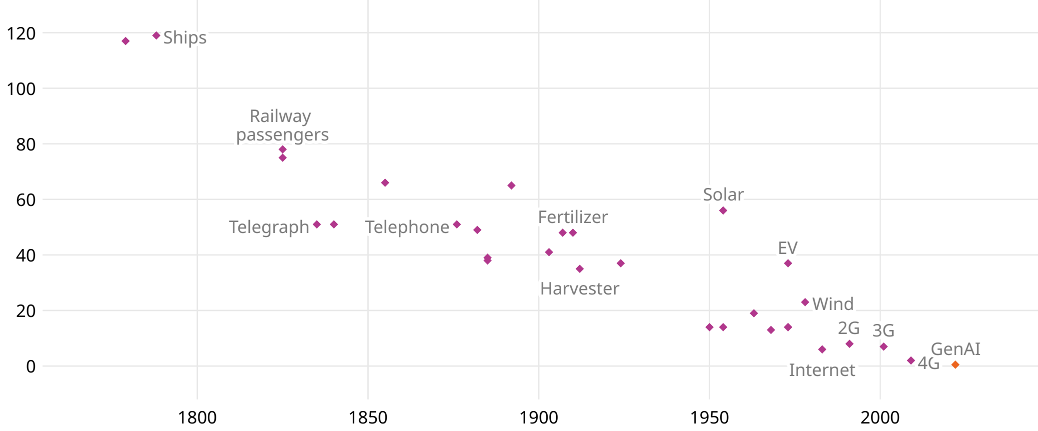
Using a historical technology database, the report reveals an unprecedented acceleration in how quickly new technologies reach global markets. There has been a remarkable compression in the time between the invention of new technologies and their first use worldwide.

Historical technologies took decades to adopt, while new digital technologies are adopted within days

The telegraph and the automobile, invented in the 19th century, took around four decades to reach countries around the world. By contrast, generative AI – exemplified by ChatGPT's release in November 2022 – had users in virtually every country within days of becoming available online (see Figure 1). This unprecedented speed of diffusion reflects a ready-made global digital infrastructure enabling immediate worldwide access.

Average technological adoption lags around the world have fallen

Figure 1 Average number of years to adopt selected technologies by year of invention, 1750–2025



Note: The sample includes 139 countries, 17 of which are advanced economies. A small average adoption lag indicates that adoption is rapid across all countries in the sample, regardless of income level.

Source: Fink, C. *et al*. (2026). How do new technologies diffuse? *WIPO Economic Research Working Paper Series No. 91*. Geneva: WIPO.

Developing economies show encouraging signs of convergence in their speed of adoption

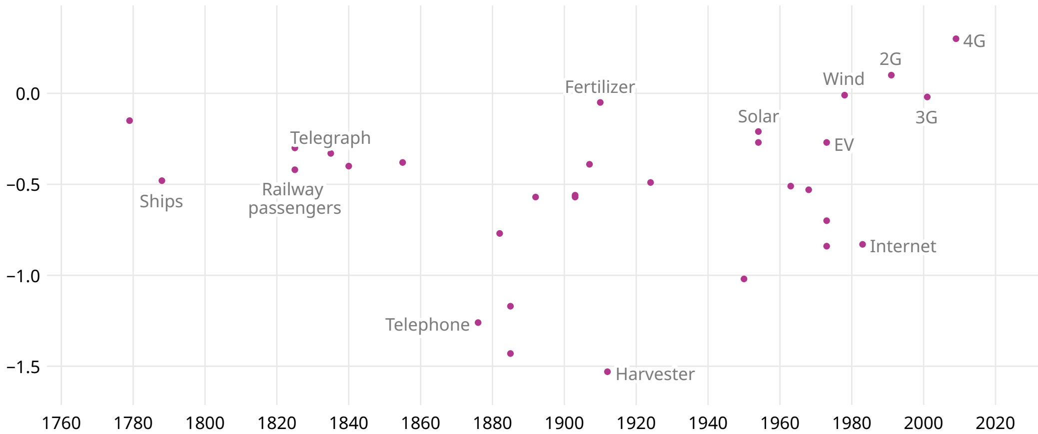
Advanced economies consistently emerge as early adopters. Historically, these economies embraced new technologies 20–80 years in advance of the global average. However, this historical advantage has diminished over time. Virtually all newer technologies demonstrate converging adoption lags between advanced and developing economies.

The gap in intensity of use was first widening, now it is narrowing

Beyond adoption time lag, the report examines how intensively technologies spread within countries after initial introduction. Studying the intensity of technology use across countries reveals a fascinating historical reversal: from the 19th through much of the 20th century, the gap in the intensity of use between advanced and developing economies generally widened, with newer technologies showing larger differences in how intensively they were used, as illustrated in Figure 2.

The gaps in usage are larger for earlier technologies

Figure 2 Gap in use intensity between advanced economies and developing economies



Notes: The intensity of use calculates relative to advanced economies (normalized to zero). Negative values indicate below-average intensity among non-advanced economies adopters. Sample includes 139 countries, of which 17 are advanced economies.

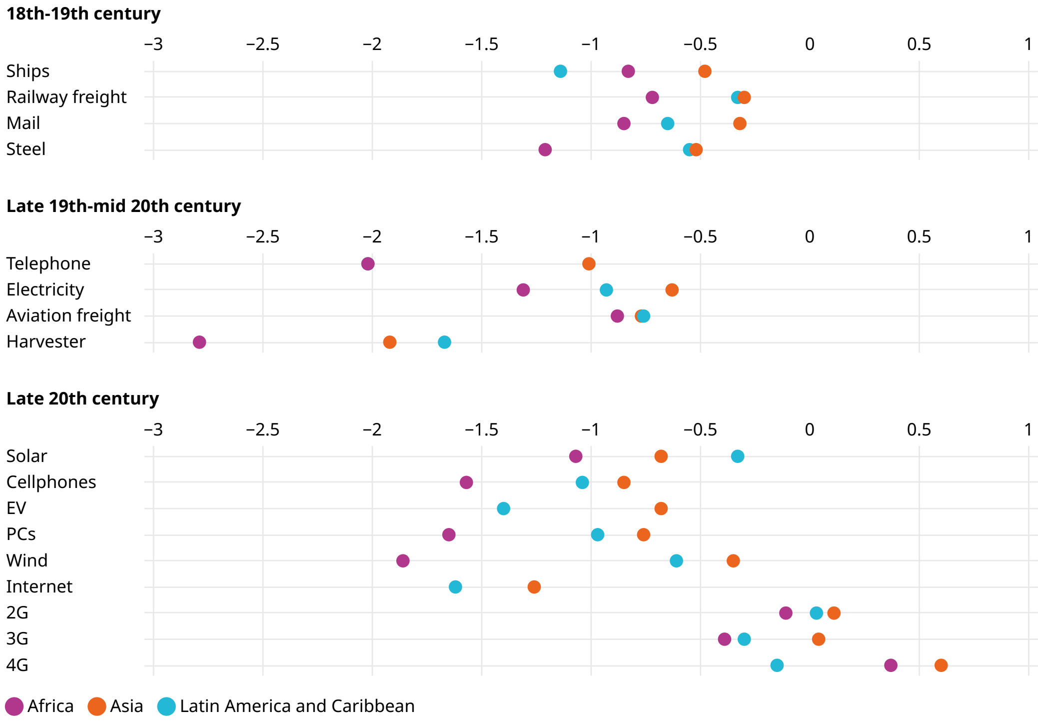
Source: Fink, C. *et al*. (2026). How Do New Technologies diffuse? *WIPO Economic Research Working Paper Series No. 91*. Geneva: WIPO.

The dramatic reversal relates to recent digital technologies revolution

Digital innovations like 3G and 4G show a converging usage intensity across countries, suggesting that today's digital technologies offer greater opportunities for developing economies to narrow historical gaps. Regional analysis reveals that while Africa exhibits the widest technology gaps, followed by Latin America and then Asia, all three regions show such gaps narrowing for recent technologies. Figure 3 shows how Asia stands out not only in having narrowed technology gaps substantially, but in some cases even exceeding advanced economy usage levels.

Asia reduces the usage gap with advanced economies

Figure 3 Intensity of use in the African, Asian and Latin American and Caribbean regions compared to advanced economies, by time period



Notes: Adoption lags are listed in deviation from the mean adoption lag for each technology. A smaller number indicates an earlier the adoption year. Advanced economies include: Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Kingdom of the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, Australia, New Zealand, Canada, the United States and Japan.

Source: Fink, C. *et al.* (2026). How Do New Technologies Diffuse?*WIPO Economic Research Working Paper Series No. 91* . Geneva: WIPO.

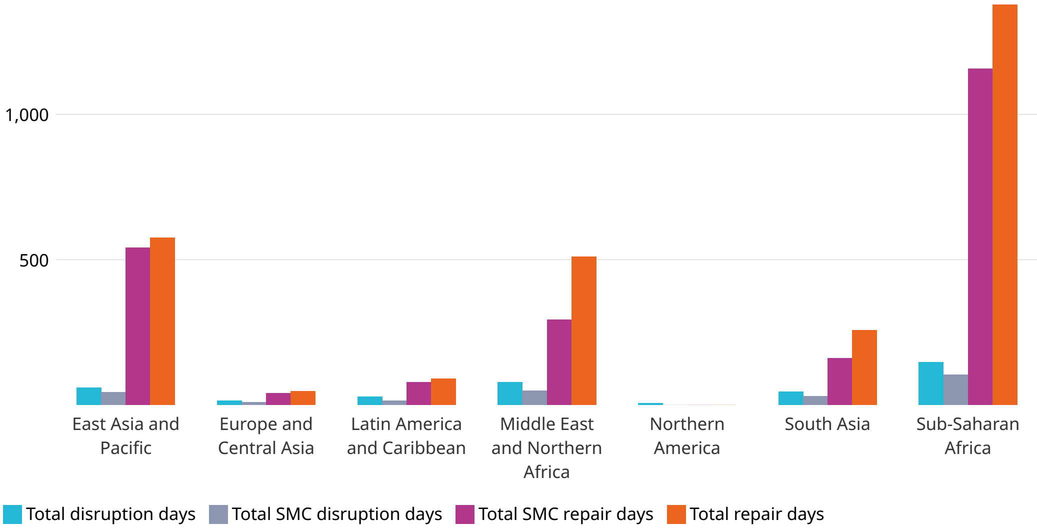
The case study on digital technologies shows that Africa managed to surf this digital wave to catalyze unique local innovations, even overcoming economic and infrastructure constraints. African innovations like mobile money services (e.g., M-Pesa in Kenya) and off-grid energy solutions have benefited global markets. The adoption of digital technologies can also improve the local socioeconomic conditions. In rural Africa, mobile connectivity has reduced gender wage gaps, narrowing when in closer proximity to 2G+ networks.

While the aggregate picture tells a positive story, especially about newer digital technologies, there are still many challenges in making technology diffusion work in developing economies. Digital inequality in developing economies operates across many dimensions: infrastructure gaps, technology quality differences, usage gaps arising from limited digital literacy, and affordability barriers. These divides create a dual digital landscape where advanced economies leverage high-value innovation while others depend on simpler solutions.

Infrastructure vulnerability and limited access to the best mobile network technology constrain Africa. High-capacity submarine cables carry over 99 percent of international data traffic connecting countries worldwide, where cable damage represents a top common cause of internet shutdowns with substantial economic losses. Africa, especially Sub-Saharan Africa, faces an infrastructure vulnerability that disproportionally disrupts the continent's connectivity (see Figure 4). Moreover, Africa still has limited access to the atest generation mobile networks, with only 12 percent of Africans having 5G access in 2023 against 74 percent of Europeans.

Submarine cable (SMC) damage causes a disproportionate level of disruption to connectivity in Sub-Saharan Africa

Figure 4 Distribution of internet shutdowns, SMC disruptions, and associated repair days by region, 2008–2020



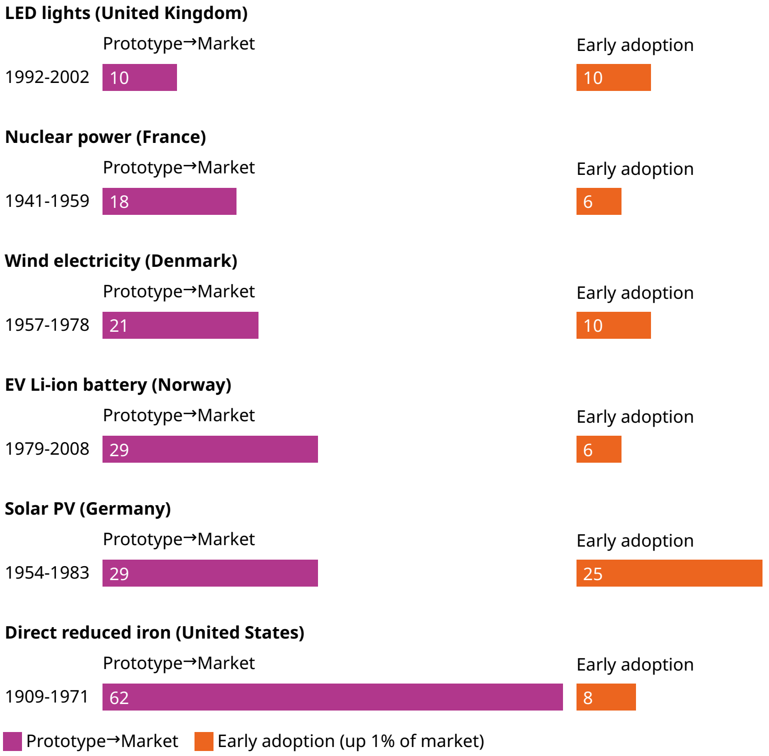
Note: Raw data drawn from the Subtel forum http://subtelforum.com/category/cable-faults-maintenance/, Akamai's reports on the "State of Internet Connectivity", and completed by manual Internet searches. The dataset is not exhaustive of all cable faults but records documented disruptions that effectively impaired Internet connectivity. SMC = Submarine cable.

Source: Cariolle, J. (2026). Digital Transformations in Developing Economies: From the First-mile Infrastructure to the End-user Fingertips. *WIPO Economic Research Working Paper Series No. 96*. Geneva: WIPO; data and calculation.

Beyond the digital revolution: technology characteristics still shape adoption timelines. Different technologies display distinct adoption patterns. Even nowadays, genetically modified crops require long development periods and must be adapted to local soil, climate and pests. On average, it takes about 16.5 years from discovery to regulatory approval. Similarly, historical evidence shows clean energy technologies typically require decades before reaching just one percent of market share. Figure 5 shows how nuclear power achieved this within 20 years in France, while direct reduced iron took a full six decades. Even solar photovoltaic (PV) needed more than half a century to reach a material market share. These differences reflect variations in modularity, capital intensity, infrastructure requirements, and regulatory frameworks, and provide caution against one-size-fits all policy approaches.

Sectoral variations in technology scaling: industrial applications demonstrate prolonged market adoption timelines

Figure 5 Time required for prototype-to-market introduction and early adoption of energy technologies, by years



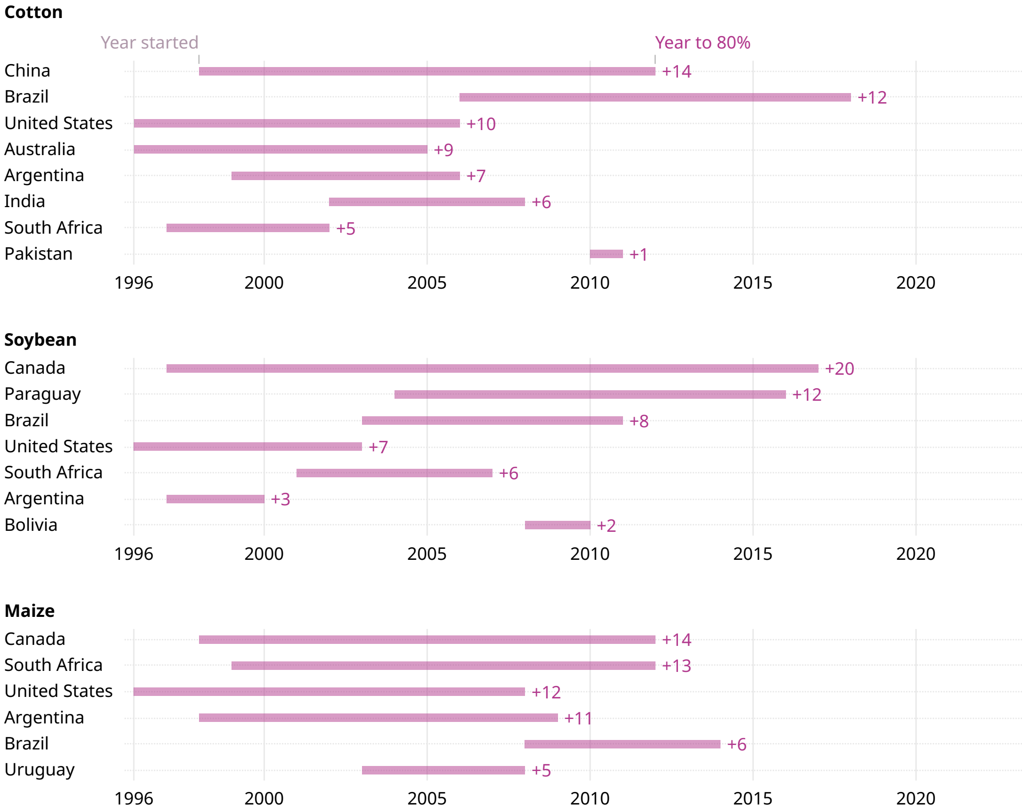
Note: Country designation applies to the early adoption phase and refers to the first countries reaching materiality for each technology.

Source: IEA (2020). Energy Technology Perspectives 2020: Special Report on Clean Energy Innovation. Paris: International Energy Agency, Figure 3.5, 76.

Regulatory frameworks are a crucial factor in the speed of technological adoption. Regulatory frameworks play a decisive role in genetically modified crop adoption. For example, genetically modified cotton reached 80 percent cropland coverage in the United States in roughly 10 years, while South Africa achieved this milestone in five years partly due to streamlined approval processes (see Figure 6).

Speed of GM crop technology adoption varies across countries and crop types

Figure 6 Time to widespread adoption (80 percent cropland) of GM crop technology for selected countries and crop types, 1996–2023



Notes: Argentina and Pakistan informally adopted GM crops earlier than recorded here

Source: WIPO based on de Grazia, C., Rada, N. and Graff, G. (2026). Diffusion of Genetically Modified Crop Technology. *WIPO Economic Research Working Paper Series No. 93*. Geneva: WIPO.

Is the technological knowledge behind new inventions spreading more internationally?

Technological knowledge is the set of problem-solving principles, techniques, and capabilities that enable the creation, improvement, and application of products, processes, or services. Innovation ecosystems with more diverse technological knowledge can produce more advanced and breakthrough inventions.

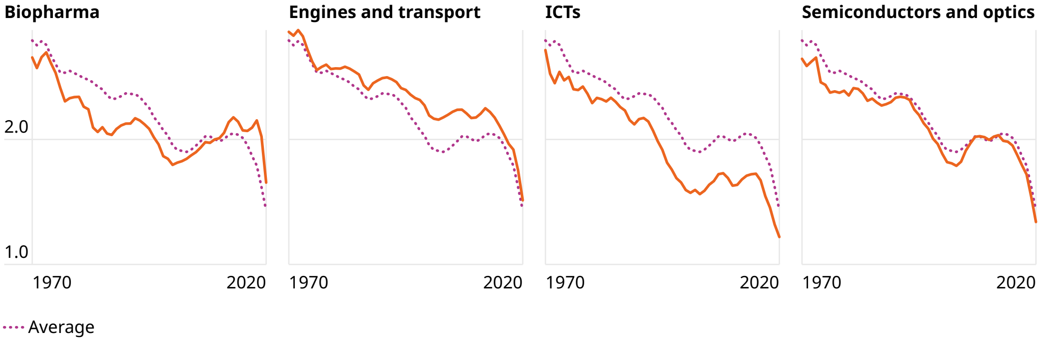
Technological knowledge flows have economic impact. Evidence shows a clear link between international knowledge spillovers – measured through indicators like patent-to-patent citations – and improvements in worker productivity, industry performance, and national income. Developing economies particularly benefit by adopting and adapting knowledge from more advanced countries, which helps narrow productivity gaps and accelerate economic development.

The report uses comprehensive analysis of patent citations, scientific references, and reuse of breakthrough inventions – novel combinations of existing technical knowledge. The report's analysis spans five decades and reveals a fundamental transformation in the diffusion of technological knowledge within the global innovation landscape.

International flows of technological knowledge have doubled in speed. The time needed for technological knowledge to spread internationally has reduced dramatically, according to every measure. Over the past 50 years, the time needed to observe the first international patent citation has halved. This systematic acceleration has occurred across all technological fields (see Figure 7).

For the past half century, the technological knowledge adoption lag has systematically decreased

Figure 7 Average adoption lag of international patent family citations, lag years, 1970–2020



Notes: Adoption lag refers to the average lag to observe a first international citation within a 5-year window from the priority application year of the cited patent family. Patent families without citations are excluded. Recent years have been omitted due to citation data truncation. For more details see the Technical annex in the full report.

Source: WIPO based on EPO Patstat, 2025, Autumn edition.

Are geographical barriers to knowledge flows at an end?

The gap between the speed of knowledge flows within countries and across countries has all but vanished. In 1988, international patent citations took on average 12 percent longer than domestic citations. By 2020, the difference between the two had essentially disappeared, suggesting that geography is no longer a meaningful barrier to knowledge flows speed.

There is a persistent dominance of innovation leaders

Despite faster global diffusion of technological knowledge, analysis reveals a striking concentration in a handful of economies. Primarily, the United States, Western Europe and Japan dominate both as contributors to and beneficiaries of international flows of technological knowledge.

Deep tech revolution takes time

There are fascinating patterns in how scientific knowledge is sourced for deep tech innovations, such as biotechnology, artificial intelligence (AI), quantum computing, and advanced materials inventions that are built upon advanced basic science. Yet, scientific articles take an average of 10 years to receive a first patent citation – much longer than patent-to-patent citations. This extended timeline reflects the complex process of transforming fundamental scientific discoveries into industrially viable deep tech applications.

Deep tech champions source globally

Scientific knowledge sourcing is even more concentrated than general patent citations, in just a handful of economies. The United States, Western Europe and Japan absorb scientific knowledge from virtually every global source available. Technologies with higher scientific content travel longer distances and are more likely to generate new inventor clusters worldwide.

The United States, Western Europe, Japan and China dominate global science sourcing for deep tech

Figure 8 Share of scientific articles with international and national patent citations, selected corridors, 2016–2022

	To Africa	To China	To Japan	To LAC	To United States	To Western Europe
From Africa	2%	10%	8%	1%	24%	36%
From China	0%	20%	9%	0%	25%	30%
From Japan	0%	8%	39%	0%	21%	23%
From LAC	0%	7%	6%	5%	26%	39%
From United States	0%	9%	7%	1%	45%	31%
From Western Europe	0%	8%	7%	1%	26%	48%

Notes: LAC = Latin America and the Caribbean, Western Europe excludes Germany. Figure data points refer to the share of scientific papers in the origin that are cited by patents from the destination. Only scientific papers with at least one patent citation are considered in the calculations. For more details see the Technical annex in the full report and Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: WIPO based on EPO Patstat, 2025 Autumn edition and Marx and Fuegi, 2020 and 2022.

China joins the exclusive group of deep tech leaders

China emerges as the most dynamic player in this space, dramatically increasing its openness to international science. Chinese citations of US scientific papers have grown from just 2.5 percent of papers published between 1985 and 1995 to 8.8 percent for papers published between 2016 and 2022 – making China more open to international science than Japan across all source regions (see Figure 8).

Only a handful of leading economies can reuse the knowledge behind breakthrough inventions

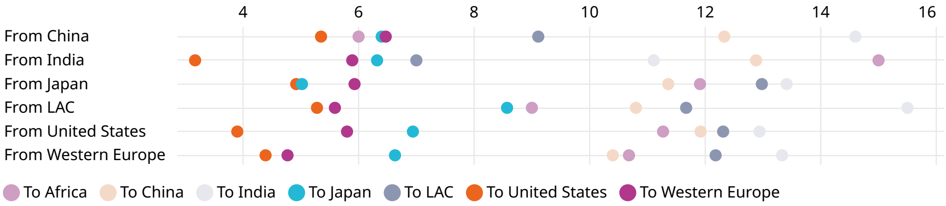
New analysis of how novel combinations of existing technical knowledge spread globally shows that most countries build primarily on domestic breakthrough inventions, but only innovation leaders demonstrate the exceptional ability to rapidly adopt and build upon foreign inventions.

Leading innovation ecosystems reuse knowledge from foreign breakthrough inventions faster

The United States is three times faster at replicating a breakthrough invention originating from India than India itself. For example, India takes on average 11 years to re-invent based on an Indian-originated invention, while it takes the United States only three years (see Figure 9).

Innovation leaders maintain their dominance through rapid reuse of knowledge behind foreign breakthrough inventions

Figure 9 Average time to the first replication of a breakthrough invention in the destination territory, in years



Notes: LAC = Latin America and the Caribbean. Western Europe excludes Germany. Figure data points refer to the average lag to observe a technological trajectory (i.e. international patent family combining pairs of IPC/CPC symbols) within a given window (from 2 to 5 years) from the first time the trajectory is observed. Technological trajectories follow the methodology by Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT) https://ideas.repec.org/p/unm/unumer/2023036.html; and Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454. For more detail see Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2025). *The Changing Geography of International Knowledge Diffusion. WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: WIPO based on EPO Patstat, Autumn 2025 edition.

Leading innovation ecosystems reuse knowledge from foreign breakthrough inventions more intensively

Even more dramatically, the United States reuses 70 percent of Chinese-originated novel technologies within five years of invention, whereas China reuses less than 5 percent of US technologies within the same timeframe (see Figure 9).

The United States and Europe dominate the early and intensive reuse of breakthrough inventions

Figure 10 Share of origin's breakthrough inventions reused by destination within 5 years of invention, selected regional corridors, 1985–2015

	To Africa	To China	To India	To Japan	To LAC	To United States	To Western Europe
From Africa	11%	2%	0%	34%	2%	70%	66%
From China	1%	8%	0%	52%	4%	70%	53%
From India	0%	4%	4%	42%	4%	88%	46%
From Japan	0%	4%	0%	69%	0%	69%	57%
From LAC	0%	2%	0%	24%	2%	60%	67%
From United States	1%	5%	1%	44%	1%	83%	59%
From Western Europe	1%	12%	1%	48%	1%	74%	71%

Notes: LAC = Latin America and the Caribbean. Western Europe excludes Germany. Figure data points refer to the share of all of the origin's technological trajectories (i.e. international patent family combining pairs of IPC/CPC symbols) being used in a given destination. Technological trajectories follow the methodology by Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454; and Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.htm. For more detail see Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: WIPO based on EPO Patstat, 2025 Autumn edition.

Developing economies struggle to benefit from global knowledge flows

While developing economies may generate innovative technologies, they show marginal participation in international technological knowledge flows. For instance, Africa has a limited ability to reuse foreign technological knowledge, whereas the technical knowledge behind African breakthrough inventions is re-used extensively in developed economies: 100 percent is reused in Western Europe, 96 percent in the United States, 92 percent in Japan, and 81 percent in Germany (see Figure 10).

Implications for global development and policy

These findings carry profound implications for global development strategies. The acceleration in diffusion speeds and convergence in usage intensity for recent technologies suggest unprecedented opportunities for developing economies to catch up or even leapfrog traditional development stages.

There are four critical factors affecting technology diffusion:

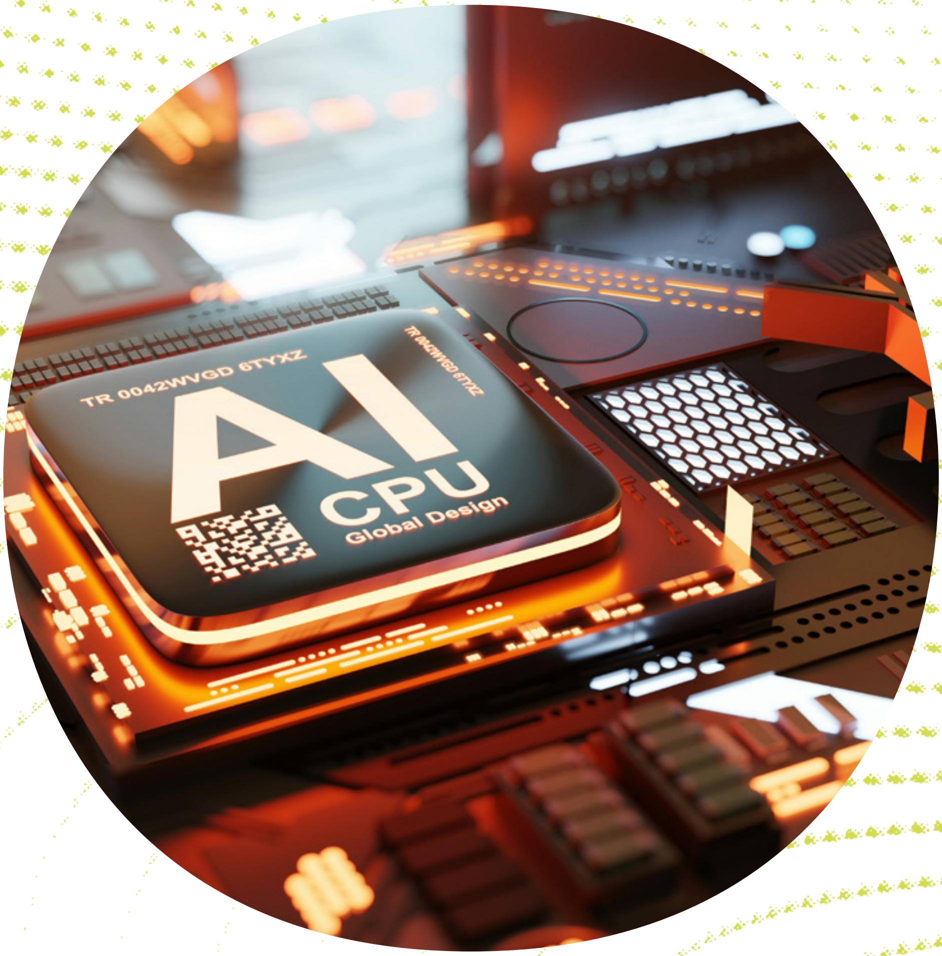
1. **Technology characteristics matter fundamentally**. Technologies with immediate benefits spread faster than complex, costly ones requiring complementary investments. Infrastructure requirements prove particularly crucial – technologies leveraging existing infrastructure (like large language model (LLMs) using the internet) diffuse rapidly, whereas those requiring new networks (like electric vehicles needing charging stations) face significant delays.
2. **Information speed has changed knowledge diffusion dramatically**. While 19^{th}-century knowledge traveled only as fast as it could be transmitted by traditional mail and newspapers, today's digital platforms enable near-instant access to technical information globally.
3. **Technology diffuses faster where it can be absorbed easily**. The absorptive capacity – the ability to understand, adapt and apply new knowledge – varies dramatically across users and contexts. Complex technologies requiring local adaptation demand substantial technical know-how, built through education, training, research institutions, and global knowledge networks.
4. **Public policy and institutions can shape diffusion**. Regulatory and institutional frameworks provide complementary infrastructure investment, standardization and interoperability frameworks, safety regulations and IP systems that balance innovation incentives with technology access.

However, realizing this potential requires addressing persistent capability gaps. Countries showing above-predicted GenAI usage demonstrate that appropriate policies and investments enable the rapid adoption of frontier technologies. Success depends on building absorptive capacity and innovation capabilities through education and skills development, investing in complementary infrastructure, and creating institutional frameworks that support technology adaptation and innovation.

For policymakers, analysis serves to emphasize that encouraging invention alone is insufficient. Equal attention must be focused on creating conditions that enable rapid, broad technology diffusion through infrastructure investment, human capital development, access to financing, appropriate regulatory frameworks, and IP systems balancing innovation incentives with technology access.

This report ultimately demonstrates that while technology diffusion has accelerated dramatically and shows encouraging convergence trends, realizing the full potential of new technologies for global development requires deliberate, coordinated policy action addressing the multiple factors that determine diffusion outcomes.

1 How do new technologies diffuse?



Technology diffusion is the process by which new ideas spread from early inventors to widespread users, and shapes economic development. This chapter highlights how diffusion is neither automatic nor uniform, and that certain efforts must be made to transform the technology into real world impact. Drawing on historical data on a wide range of technologies, it offers two insights: new innovations spread faster, and the technology use gap between advanced economies and others is narrowing for more recent technologies.

Introduction

Over the past two centuries, humanity has experienced an unprecedented improvement in living standards. Since the Industrial Revolution began more than 200 years ago, global per capita income has increased more than tenfold. Life expectancy has nearly doubled in many countries, rising from around 40 to over 80 years in developed nations. Travel that once took months now takes hours. Communication that once depended on mail carried by horseback now happens instantaneously across continents. Today, generative artificial intelligence (GenAI) can compose symphonies, write poetry, and create artwork that rivals human creativity – capabilities that would have seemed like magic just decades ago.

These remarkable gains reflect the power of innovation and technological progress. At the core of this advancement is creative destruction – the mechanism through which successive waves of innovation replace older technologies and business models, driving long-run productivity and growth, as highlighted in the work of Nobel prize-winning economists Philippe Aghion and Howitt's seminal work on the subject.[1] As the World Intellectual Property Report 2015 demonstrated, this explains why modern economies can produce vastly more – and vastly more powerful – goods and services with the same resources than previous generations.

Yet the mere invention of new technologies tells only part of the story. Creating innovative solutions does not automatically translate into economic growth or societal benefits. For new technologies to fulfill their potential, they must be adopted and used effectively by firms and households. This so-called technology diffusion process represents a crucial bridge between invention and impactful innovation. It is neither automatic nor guaranteed.

Technology diffusion faces several challenges that can slow or prevent the spread of beneficial innovations. Users often need to acquire new skills to operate unfamiliar technologies effectively. Breakthrough technologies from the internal combustion engine to information and communication technologies require substantial investments in supporting infrastructure. For instance, consider how the motor car requires not just manufacturing plants, but networks of roads, gas stations and repair services. Businesses may need to reorganize their operations or develop new management practices. Sometimes they must create entirely new business models to harness technology's full potential.

The arrival of breakthrough technologies typically spurs waves of complementary innovations. These organizational and business model innovations often prove as important as the original technological advance. New ways of organizing work, serving customers or structuring entire industries can generate major productivity gains that extend far beyond the technology itself. The internet, for example, enabled not just faster communication; it created entirely new forms of commerce, entertainment and social interaction that continue to reshape the global economy.

Multiple factors shape diffusion outcomes, including available skills, competitive dynamics, access to finance, and technical standards and regulations. These factors help explain why technologies do not diffuse seamlessly across economies. These uneven patterns contribute to persistent inequalities in economic development, living standards, health outcomes, and environmental quality.

Purpose and scope of this report

This year's *World Intellectual Property Report* seeks to shed light on the technology diffusion process. It examines what explains successful diffusion outcomes and what role intellectual property (IP) plays and how it influences the diffusion course. Intellectual property rights incentivize innovation but can also affect how quickly new technologies are diffused, creating a crucial balance for policymakers to strike.

This introductory chapter establishes the foundation for the report’s analysis by presenting the core concepts that shape technology diffusion. It reviews research examining how rapidly and extensively various technologies have spread across the globe, highlighting how diffusion patterns have changed throughout history. Building on this context, the chapter examines the key factors influencing the speed and success of diffusion.

Chapter 2 examines how technological knowledge spreads across borders – and why some economies are far better at absorbing it than others. Using patent data and citation links between inventions as its primary lens, it shows how quickly new ideas attract attention abroad, how the gap between domestic and international knowledge flows has narrowed over time, and how diffusion patterns differ across technologies and regions. The chapter also looks at how breakthrough inventions originating in one country are taken up and built upon elsewhere, revealing persistent differences in countries’ ability to identify, adapt and reuse new technologies.

Chapters 3 to 5 bring these concepts to life through three detailed case studies. They examine agricultural biotechnology, clean technologies, and digital technologies, exploring in concrete terms how diffusion processes unfold in practice. The case studies reveal the specific challenges and opportunities that arise in different technological domains. They offer insights into policy approaches that can encourage beneficial technology diffusion and illuminate the nuanced role that IP plays in shaping diffusion outcomes.

Together, these chapters aim to provide policymakers, business leaders and researchers with a comprehensive understanding of technology diffusion. This knowledge can inform decisions about innovation policy, IP systems, and strategies for harnessing technological progress to improve economic outcomes and address global challenges.

Key concepts and terminology

Technology diffusion involves multiple interconnected processes operating at different scales – from individual to industry-wide transformation. Understanding these process is important for analyzing how technologies spread and for identifying the factors that shape their outcomes. This section introduces the core concepts and the terminology that guide the rest of the report.

Technology diffusion

Technology diffusion refers to the broader spread of new technology across firms, industries, and economies as more users adopt it over time.[2] Diffusion usually follows a recognizable path. Early adopters with greater technical expertise or appetite for risk lead the way. Mainstream users follow once the technology has proven its worth and become more accessible. Even cautious users eventually adopt a technology once it has become standard.

Diffusion of technological knowledge

The diffusion of technological knowledge refers to the spread of know-how, expertise and information that makes it possible to adopt technology. This may include scientific principles, design details, production techniques, hands-on experience, or the skills needed to operate and manage a technology in practice.

The amount of knowledge that needs to spread varies according to technology. Some technologies require very little. For instance, a farmer can apply a new fertilizer without understanding its chemistry. Others demand much more. A company that adopts advanced robotics must not only purchase the machines, but also acquire the skills required to program, maintain and integrate them into production.

These differences help explain why some technologies diffuse quickly while others spread more slowly or unevenly. The way knowledge circulates, and the extent to which users can access it, often shapes the overall diffusion process.

Technology adoption

Technology adoption describes how individuals and organizations start using a new technology and integrate it into their activities. The technology may be completely new – for example, a breakthrough from a research lab – or it may simply be new to a specific user, region or economy, even if others already use it elsewhere. Note that *adoption* focuses on individual cases, whereas *diffusion* looks at the aggregate pattern.

Adoption rarely means copying a technology in its original form. Users usually adapt it to suit the conditions. Farmers may adjust a drought-resistant crop variety to different soils or climates. Manufacturers may modify a production method when relying on different inputs, machines or business models. A digital inventory system built for large supermarket chains may need major adjustments before small corner shops can afford to use it.

These adaptation needs explain why adoption takes time and why success rates vary. They also show that adoption is not a passive act of imitation, but an active, often innovative, process.

Technology transfer

Technology transfer is a particular form of adoption. It involves the deliberate sharing of knowledge, skills, methods, or technologies between parties.[3] The receiving organization then uses, adapts or develops the technology further. Contracts such as licenses, partnerships and joint ventures often govern this process.

Universities transfer technology when they license research discoveries to companies. Multinational corporations transfer technology when they share production know-how or management practices with foreign subsidiaries. Governments may facilitate transfer by linking research institutions with industry or by funding joint projects.

Knowledge spillovers

Knowledge spillovers occur when ideas, expertise or skills spread from one economic actor to another without a deliberate transfer or payment. For example, a company may introduce a new product, and competitors learn from it by observing its features or by seeing how customers respond. The original company bears the cost of innovation, but other firms also benefit from the knowledge it generates.

Note that knowledge spillovers may further technology adoption outside a formal technology transfer framework. The key distinction lies in intent: technology transfer involves purposeful and often contractual sharing of knowledge, whereas spillovers happen unintentionally with others benefitting from knowledge flows that the originator did not plan nor can control.

Stylized facts

Economists have examined technology diffusion at the level of individual innovations, as well as across industries and entire economies. Although patterns and outcomes often vary depending on the technology and context, the literature reveals several stylized facts that hold more generally. These facts offer a useful lens for understanding how technologies spread and what factors determine the extent and pace of diffusion.

Stylized facts #1: Technology diffusion often follows an S-shaped path

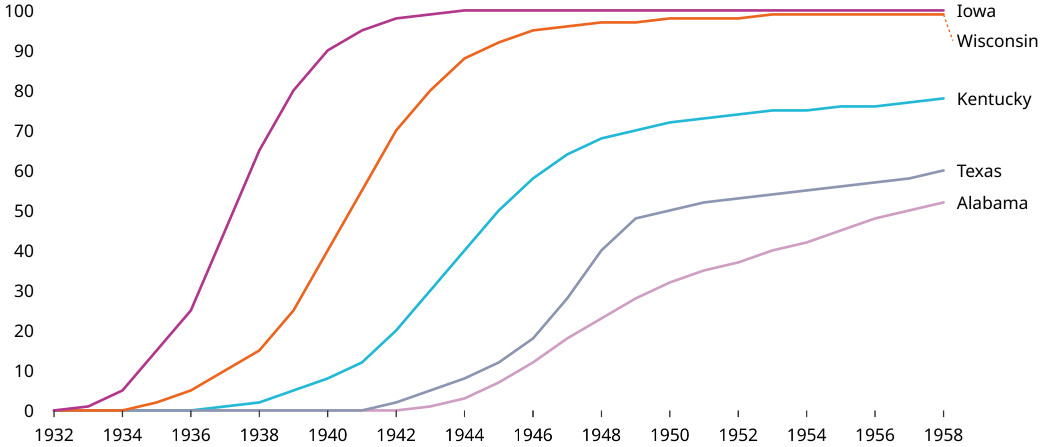
One of the first formal studies to examine how technologies diffuse after their invention is Zvi Griliches' pioneering 1957 work on hybrid corn in the United States.[4] By tracing the spread of this agricultural innovation across states, he demonstrated that many technologies follow an S-shaped diffusion path, with slow initial uptake, a phase of rapid growth, and eventual saturation (see Figure 1.1). Subsequent studies across a wide range of technologies have confirmed this pattern.[5]

What makes the S-shape important is not the curve itself, but what it reveals about the process of diffusion.[6] The slow early phase reflects that diffusion is a social process, not an automatic one. Potential adopters often wait to see how early users fare, so as to learn from their experiences, or simply to be convinced that the new technology is reliable and worth the cost.[7] Economic historians have shown that this period of hesitation can be especially long, with decades sometimes passing before a major innovation spreads beyond a small group of pioneers.[8] Moreover, the fact that a technology is technically superior does not guarantee that it will spread quickly. Even demonstrably better technologies may diffuse only slowly, held back by institutional obstacles, infrastructure requirements or behavioral resistance.[9]

Once enough adopters are on board, however, a tipping point is reached, and diffusion accelerates sharply. Policies, falling prices or improvements in complementary infrastructure can all help push a technology into this rapid-growth phase.[10] Eventually, the curve flattens once more. Some potential users remain outside the process entirely or adopt only after a long delay, so even very successful innovations rarely achieve complete saturation.[11]

Hybrid corn has not been immediately adopted everywhere

Figure 1.1 Share of total corn acreage planted with hybrid seed, selected US states, 1932-1958

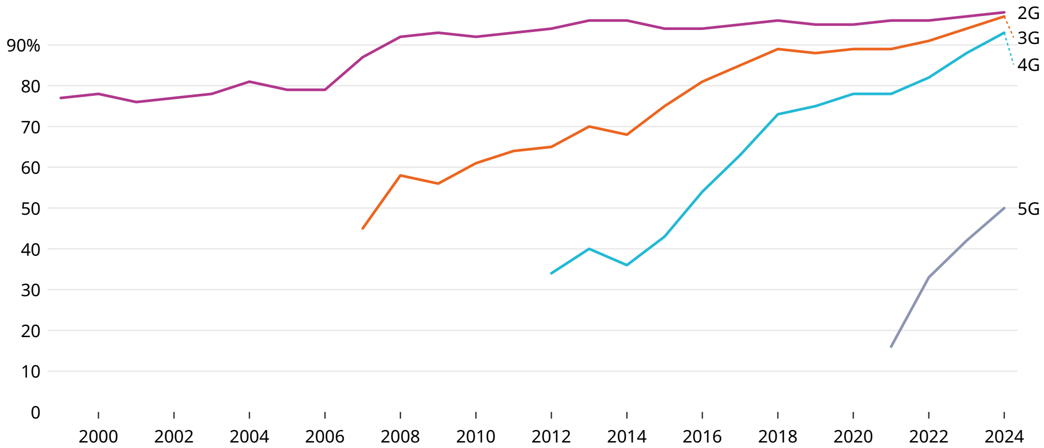


Source: WIPO's own elaboration based on Griliches, Z. (1957). Hybrid corn: An exploration in the economics of technological change. *Econometrica*, 25(4), 501–522. https://doi.org/10.2307/1905380.

Where do today's key technologies sit along the S-curve? For mobile communications, the picture is one of technologies that have reached the upper, flattening part of the curve (see Figure 1.2). Coverage for 2G, 3G and now 4G has largely levelled off as these generations approach saturation. Even 5G – despite having reached half of the world's population in under five years – will eventually slow, as the gaps that remain become harder to close. Renewable energy technologies tell a different story. Their diffusion curves still sit closer to the middle part of the S-shape, where growth is rapid and often exponential (Figure 1.3). Renewable energy generation continues to rise steeply, especially wind and solar. There is still substantial room to climb before nearing saturation, as the share of renewables in global electricity generation is projected to rise from 35 percent to 47 percent by 2030, while the share of solar and wind renewable energy sources is set to almost double to 27 percent.

50 percent of the world's population covered by 5G in under five years

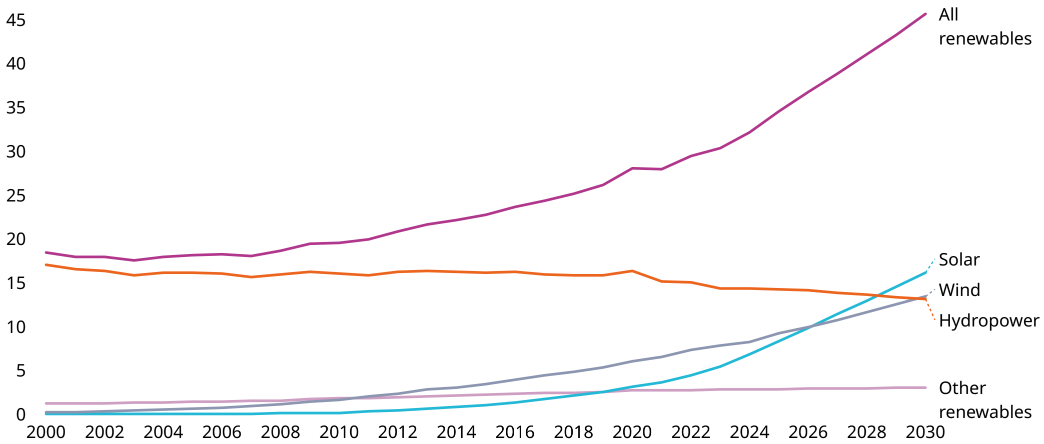
Figure 1.2 Global population coverage by type of mobile network technology, 2000–2024



Source: International Telecomunication Union (https://datahub.itu.int/data/?e=701&c=&i=100095&v=chart).

Renewable sources accounted for 35 percent of global electricity generation in 2025

Figure 1.3 Share of renewable electricity generation by technology, 2000–2030



Note: Electricity generation from wind and solar PV indicate potential generation including current curtailment rates. However, it does not project future curtailment of wind and solar PV, which may be significant in a few countries by 2028.

Source: International Energy Agency (https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2030)

While the S-curve captures an important general tendency, economists have also pointed out its limitations. Empirically, not all technologies follow a neat S-shaped trajectory. Many innovations exhibit uneven or multi-phase diffusion, with abrupt accelerations, slowdowns or successive waves, as improved versions replace earlier ones.[12] Moreover, the S-curve is essentially a descriptive tool: it fits observed data *ex post*, but does not explain the underlying drivers of diffusion – why adoption begins slowly, what triggers acceleration, or which factors determine saturation?[13] Traditional diffusion measures often lack firm-level detail, focusing on whether firms adopt a technology rather than how intensively they use it. For instance, knowing that 50 percent of firms have adopted a technology says little about its economic impact if most use it only minimally. Assessing diffusion outcomes requires an understanding both of adoption rates and usage intensity in order to assess productivity gains.

Stylized facts #2: Newer technologies are diffusing faster

Evidence suggests that the speed at which technologies reach widespread use has increased over time. One prominent study from the United States[14] examined the household adoption of 31 electrical consumer durables introduced between 1923 and 1996. It found a statistically significant and sizable increase in diffusion speed over the period studied.

In the mid-20th century United States, a product that had just begun to spread could take more than a decade to move from limited household use to near saturation. By the 1980s, this timespan had roughly halved. Innovations such as microwave ovens or personal computers reached mass adoption in half the time it had taken earlier products like washing machines or refrigerators.

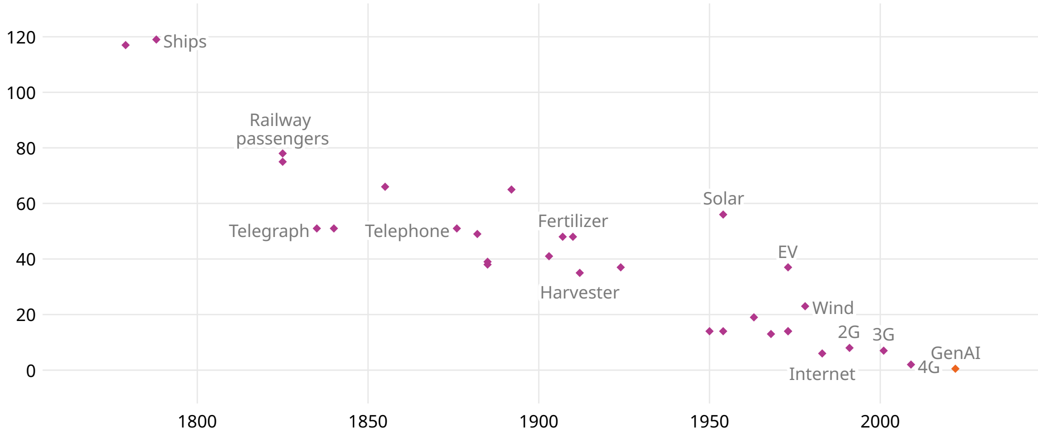
The study traced this acceleration to several broad forces. Rising incomes meant that households could afford new goods sooner, while periods of economic stability with low unemployment further supported faster uptake. Demographic changes, including urbanization and evolving household structures, expanded the pool of potential adopters. The nature of the products themselves also mattered: some benefitted from infrastructure that could be quickly built or was already available, such as broadcast networks for radios and televisions. In other cases, consumers had a choice between different versions of the same product early on. Once the technology had proved useful, this variety in formats helped to lower prices and made the product easier to obtain, encouraging faster spread – as happened with videocassette recorders and personal computers.

Stylized facts #3: Across countries, technology adoption lags are shortening

Technologies are spreading around the world faster than ever before. A useful way to measure this is through adoption lags – the number of years between the first invention of a technology anywhere in the world and its first recorded adoption in a particular country. Figure 1.4 plots the average adoption lag against the year of invention for a large set of major technologies introduced over the past 250 years. It draws on a historical dataset originally assembled by Diego Comin and Bart Hobijn, which was extended to include more recent technologies for the purposes of this report.[15]

Average technological adoption lags around the world have fallen

Figure 1.4 Average number of years to adopt selected technologies by year of invention, 1750-2025



Source: Fink, C. *et al*. (2026). How Do New Technologies Diffuse? *WIPO Economic Research Working Papers No. 91,* World Intellectual Property Organization - Economics and Statistics Division, based on Comin, D. and Hobijn, B. (2010). An exploration of technology diffusion. *American Economic Review*, 100(5), 2031–2059; Comin, D. and Mestieri, M. (2018). If technology has arrived everywhere, why has income diverged? *American Economic Journal: Macroeconomics*, 10(3), 137–178.

The pattern is striking: the newer the technology, the shorter the lag before it reaches other parts of the world. In other words, the time between invention and first use has drastically shortened.

Consider a few examples. The telegraph, invented in the first half of the 19th century, took on average almost 50 years to reach countries around the world. The automobile, emerging in the late 19th century, diffused faster, with an average lag of about 36 years. By contrast, cellphones, introduced in the 1970s, saw first use globally within less than 20 years. More recent generations of mobile technologies – 3G and 4G – have spread even faster, often reaching new markets within just a few years of their introduction.[16]

At the most extreme end of this trend are large language models (LLMs), exemplified by the release of ChatGPT in November 2022. Within days of becoming available online, users in virtually every country had accessed and experimented with the technology (see Box 1.1).[17] This unprecedented speed reflects the presence of a ready-made, global digital infrastructure – the internet – which has allowed immediate worldwide access.

Box 1.1 The rapid global diffusion of generative AI

Artificial intelligence and machine learning have been part of the technological landscape for decades. But the rise of GenAI – beginning in 2022 with tools such as ChatGPT, Claude, Gemini, Copilot, and Perplexity – has been exceptionally fast and transformative. Beyond producing text, code, images, or other content, GenAI can deliver a wide spectrum of knowledge tailored to users' individual questions and needs, with a wide array of practical applications.

Since late 2022, GenAI services have spread across the world at unprecedented speed. Early usage was heavily concentrated in the United States – more than 70 percent of global traffic at launch – but this dominance faded rapidly. Within one month, the US share had fallen to around 25 percent, and later stabilized near 20 percent, as traffic spread quickly to a wide range of economies. By mid-2023, ChatGPT alone was attracting roughly 500 million unique users a month – equivalent to about 12.5 percent of the global workforce – underscoring the breadth of early international uptake. [18]

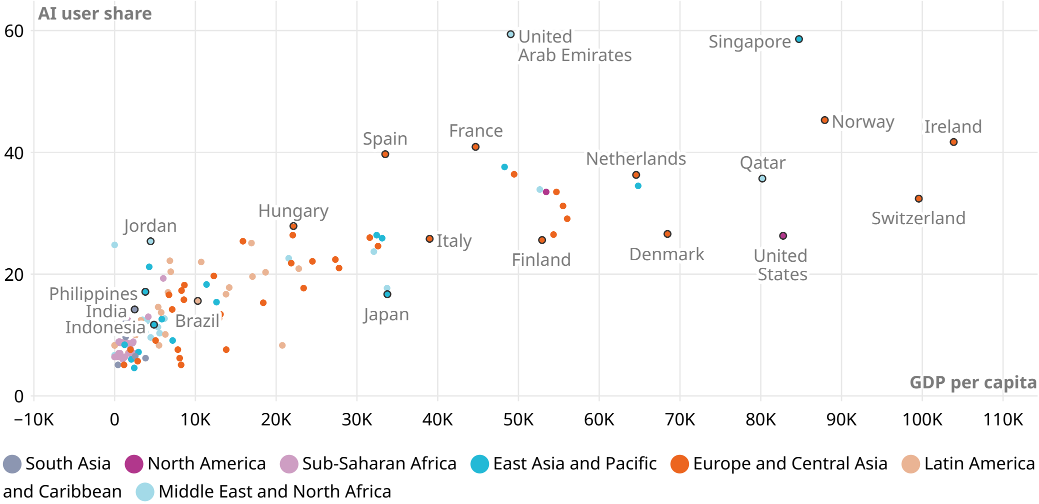
Across countries, there is a clear positive correlation between income levels and GenAI use (see Figure 1.5). Higher-income economies tend to show greater overall activity, reflecting differences in digital infrastructure, connectivity and skills [19] Yet the relationship is far from uniform. Several middle-income economies–including India, Brazil, Indonesia, the Philippines, and Mexico–have recorded GenAI usage far above what their GDP, electricity consumption, or search engine traffic levels would predict when benchmarked against the United States [20]

At the same time, many low-income economies remain in the early stages of adoption due to constraints such as limited internet access, insufficient data-center capacity, and shortages of digital and AI skills. Language coverage also shapes adoption patterns, as many GenAI systems perform strongest in English.

GenAI's rapid global spread is facilitated by the fact that it runs on existing digital devices and that many tools are available at low or no cost – reflecting intense competition among providers seeking to establish an early market foothold.[21] Although users still represent a relatively small share of the global population and workforce, early diffusion patterns suggest that GenAI is spreading across borders faster than most technologies have done in the past.

Generative AI use rises with income levels, but with wide variations

Figure 1.5 AI user share by region and GDP per capita (US) 2023



Note: AI user share represents the estimated share of the working-age population using AI. Estimates are based on aggregated and anonymized telemetry from over one billion Windows devices.

Source: Microsoft (2025). *AI Diffusion Report: Where AI Is Most Used, Developed and Built*. AI Economy Institute.

Not every technology fits this trend. Electric vehicles (EVs) stand out as a relatively new innovation with a still-longer adoption lag. Unlike digital technologies, EVs depend on extensive physical infrastructure – such as charging networks and grid capacity – that takes time and investment to build. In addition, policy incentives encouraging EV adoption have only emerged more recently, further explaining their delayed take-off.

Even so, the overall trend is unmistakable: new technologies are reaching more places faster than ever before. The world is catching up more quickly – and the distance between invention and first use is steadily shrinking.

The adoption lag data also reveals persistent patterns of technological leadership and followership across regions. Advanced economies consistently emerge as early adopters, typically embracing new technologies 20–80 years *before* the global average, while Africa shows the opposite pattern, adopting most technologies 10–50+ years *after* the global average, while Asia and Latin America show mixed patterns depending on the specific technology (see Figure 1.6). [22]

These differences matter greatly for global development. Countries that adopted technologies such as electricity, railways or fixed-line telecommunications much earlier than others accumulated decades of productivity gains – advantages that still shape today's global income gaps. Yet the data also points to new possibilities for catching up. More recent technologies, like the internet and mobile phones, have spread far more quickly across borders. This has made it easier for many developing economies to adopt new technologies sooner and, in some cases, leapfrogging older ones in the process. [23]

The adoption lag between advanced and not advanced economies has narrowed for newer technologies

Figure 1.6 Adoption lags for advanced economies and selected regions (in deviation from average adoption lag for technology), in years

Notes: Adoption lags are listed in deviation from the mean adoption lag for each technology. A smaller number indicates an earlier the adoption year. Advanced economies include: Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Kingdom of the Netherlands, Norway, Sweden, Switzerland, the United Kingdom, Australia, New Zealand, Canada, the United States and Japan.

Source: Fink, C.*et al*. (2026). How Do New Technologies Diffuse? *WIPO Economic Research Working Paper No.91.*

Stylized facts #4: A widening use gap

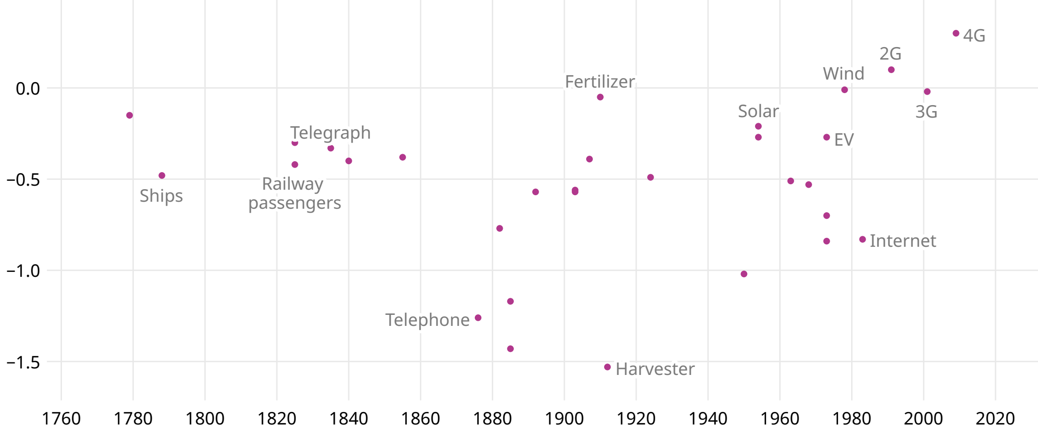
Adoption lags tell us when a country first starts using a new technology, but they do not show how quickly that technology spreads within the country once it has arrived. To understand this second part of the story, we need to look beyond the moment of first adoption and examine how widely a technology is taken up overtime.

Based on the historical database described above and following the methodology of Comin and Mestieri,[24] it is possible to estimate the technology use intensity – that is, the share of potential users who eventually adopt a given technology and the degree to which they use it – for a broad range of innovations across many economies. With these estimates, we can then examine how technologies diffuse within countries after their initial introduction, and how the intensity and overall usage patterns of each technology vary across economies over time.

Figure 1.7 illustrates how the usage gap between advanced economies and developing economies has changed over time. From the 1800s through much of the 20th century, this gap generally widened. Although the pattern varies across individual technologies, newer technologies typically saw larger differences in how intensively they were used. Comin and Mestieri[25] refer to this long-run pattern as divergence in technology-use intensity, noting that it aligns closely with the evolution of global income disparities in the 20th century.

The gaps in usage are larger for earlier technologies

Figure 1.7 Gap in use intensity between advanced economies and developing economies

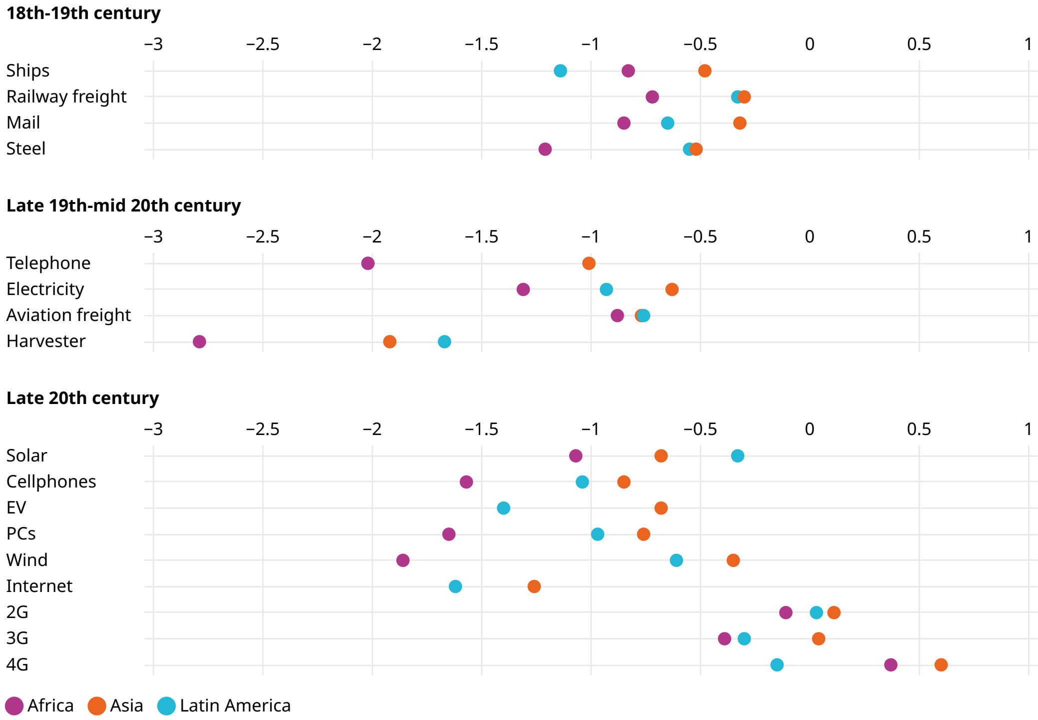


Note: Intensity is based on the number of capital units embodying new technology within a country or output volume generated using innovative technology. [26].

Source: Fink, C. *et al*. (2026). How Do New Technologies Diffuse? *WIPO Economic Research Working Paper Series No. 91*., based on Comin, D. and Hobijn, B. (2010). An exploration of technology diffusion. *American Economic Review*, 100(5), 2031–2059; Comin, D. and Mestieri, M. (2018). If technology has arrived everywhere, why has income diverged? *American Economic Journal: Macroeconomics*, 10(3), 137–178.

Asia reduces the usage gap with advanced economies

Figure 1.8 Intensity of use compared to advanced economies for selected regions



Source: Fink, C. *et al*. (2026). How Do New Technologies Diffuse? World. *Economic Research Working Paper Series No. 91.*

The picture shifts, however, once we include more recent technologies such as 3G, 4G, and wind power. For these innovations, the intensity of use has begun to converge across countries. This is an encouraging development, suggesting that today's digital and renewable technologies may offer greater chances for developing economies to narrow historical gaps.

Figure 1.8 provides a complementary perspective by comparing technology-use gaps across developing-country regions relative to advanced economies. With some exceptions, Africa exhibits the widest gaps across most technologies, followed by Latin America and then Asia.

Importantly, while all three regions show declining gaps for the most recent generations of technologies. Asia stands out: not only has it narrowed its gaps more substantially, but in some cases even displays a technology-use edge – that is, usage levels that exceed those observed in advanced economies.

How does GenAI fit into this picture? Because of its very recent emergence, GenAI is not included in the analysis underlying Figures 1.4 and 1.6–1.8, as we do not yet have the long-run data needed to estimate its potential use intensity in the same way as for earlier technologies. Nonetheless, initial indications point to a rapidly rising use intensity – particularly in several middle-income economies that appear to be adopting GenAI at levels well above what their income would predict (see Box 1.1). Much like 3G and 4G, GenAI relies heavily on preexisting digital infrastructure, suggesting that its diffusion trajectory may also show signs of convergence with advanced economies over time.

These findings need to be interpreted with care. Some of the narrowing may simply reflect differences in the characteristics of newer technologies – for example, their lower costs, greater adaptability, and ease of scaling across markets. Moreover, the set of technologies covered in this analysis is not exhaustive. Even so, given the central role of digital technologies as general-purpose technologies, the emerging signs of convergence in use intensity are a positive signal for global development.

What determines faster and wider technology diffusion?

The pace and breadth of technology diffusion vary greatly across innovations, industries and countries. While some technologies spread globally within a few years, others take decades to become widely used. Understanding what drives these differences is crucial for designing policies that accelerate beneficial diffusion. Four broad sets of factors stand out in the economic literature.

The nature of technology itself

Some technologies spread rapidly either because they are simple to use, inexpensive or immediately beneficial to a wide range of users. Others diffuse more slowly because they are costly, complex or require complementary investments. A key determinant is the price of the technology relative to the benefits it offers. Technologies that provide clear value at a manageable cost tend to spread more quickly.[27]

Another important determinant is the need for supporting infrastructure. Some innovations depend on large and costly networks – such as electricity grids, broadband cables or charging stations – that take time to develop. Others are able to leverage existing infrastructures and therefore diffuse more easily. As pointed out above, the rapid global spread of LLMs reflects the fact that the underlying digital infrastructure – the internet – was already in place worldwide. In contrast, technologies like EVs or renewable energy systems require heavy new investments in physical networks, such as charging stations, transmission grids and energy-storage facilities. Such infrastructure requirements can significantly delay adoption, even when the technologies themselves are mature and cost competitive.

The speed of information

Diffusion depends not only on the intrinsic appeal of a technology, but also on how quickly and widely information about it circulates. In the 19th century, knowledge about new inventions traveled only as fast as traditional mail and newspapers could carry it. The arrival of the telegraph, followed by the telephone, radio and fax, progressively accelerated the exchange of technical knowledge. The internet further transformed information flows, and today, digital platforms – and increasingly, AI-based systems – allow near-instant access to vast repositories of technical and scientific information.

A particularly striking recent development is the emergence of LLMs. Beyond simply granting access to large quantities of information, LLMs can process and apply that information in highly accessible ways, helping users generate or retrieve highly specific, context-relevant knowledge on demand. This capability reduces the cost and effort of finding, interpreting and adapting information, thereby lowering barriers to learning and potentially accelerating technology diffusion itself.

These advances have greatly reduced the time it takes for new ideas to reach potential adopters around the world.[28]

Absorptive capacity and local capabilities

Even when information is freely available, not all users can immediately make use of a new technology. Adoption often requires absorptive capacity, the ability to understand, adapt and apply new knowledge effectively.[29] For simple consumer technologies, limited knowledge may suffice; one can drive a car without understanding how an engine works. But more complex technologies, especially those that must be adapted to local conditions, such as biotechnology or advanced manufacturing – demand substantial technical know-how.

Building absorptive capacity depends on education, technical training, research institutions, and linkages with global knowledge networks. As the next chapter will explore in more depth, these innovation capabilities are decisive for how well economies learn from others and close the gap between invention and effective use.

Public policy and institutions

Public policy plays a pivotal role in shaping technology diffusion. Governments influence diffusion through the following multiple channels.

Complementary public infrastructure

Technology adoption by individuals or firms often depends on the presence of public goods such as roads, ports, electricity, and telecommunications networks. The success of mass-produced automobiles, for instance, relied on publicly-funded road systems. Similarly, the diffusion of digital technologies depends on the availability of affordable broadband and mobile coverage – key areas where policy intervention can accelerate adoption.

Standardization and interoperability

Standards ensure that products and systems work together, reducing uncertainty for producers and users alike. In many cases, standards emerge organically from industry collaboration. Private or industry-led standards – such as those developed by professional associations or technology consortia – often prove highly effective in promoting interoperability and market expansion. However, in other cases, government involvement in standard-setting is essential. Public standards can ensure safety, compatibility and consumer protection within sectors where coordination failures or high risks might otherwise slow adoption. Examples include railway gauges, electrical voltage, control of the radio spectrum, building codes, and automotive emission norms. Governments and regulatory authorities often set or coordinate such standards directly, sometimes through international bodies like the International Organization for Standardization (ISO) or the International Telecommunication Union (ITU).[30]

Safety and consumer protection

Regulations that guarantee safety and quality can also foster technology diffusion by building public trust. Vehicle safety inspections, aviation certification and pharmaceutical regulatory approvals ensure that new products meet minimum safety thresholds before entering the market. This helps consumers overcome skepticism toward unfamiliar technologies, enabling broader uptake.[31]

Intellectual property (IP) policy

IP systems influence how quickly and widely technologies spread by balancing a fundamental trade-off between incentives for innovation and access to new technologies. Exclusive rights encourage firms and inventors to invest in developing new ideas, while disclosure requirements and time limits ensure that others can learn from them and build on their advances. Published patent documents, in particular, form a vast global repository of technical information that supports imitation, learning and further innovation.[32]

IP rights also help turn inventions into tradable assets. By defining ownership and offering legal assurance, they make it easier for firms to license, buy or sell technologies, thus enabling markets for knowledge and facilitating cross-border diffusion. At the same time, as discussed above, adopting technologies invented elsewhere often requires adapting them to local conditions. This follow-on innovation is supported by a range of IP instruments – including utility models, design rights, and trademarks – which strengthen incentives for incremental and adaptive innovations that help technologies take root within diverse settings.[33]

Conclusion

Technology diffusion is a broad and multifaceted process at the core of economic development and human progress. For technological breakthroughs to drive economic growth, they must spread widely throughout an economy. While the pace of global technology adoption has accelerated dramatically, the benefits of new technologies remain unevenly distributed both within and across countries.

Several key insights emerge from this introductory chapter. First, diffusion is never automatic; even superior technologies face obstacles that can delay or prevent their spread, from infrastructure requirements and skill gaps to regulatory barriers and financing constraints. Second, the nature, cost and infrastructure requirements of a technology fundamentally shape its diffusion pattern. Third, the flow of information and the presence of local absorptive capacity determine whether potential adopters can effectively learn about and implement new technologies. Finally, public policy and institutional frameworks play a decisive role in creating the conditions required for successful diffusion, as the spread of technology does not of itself automatically translate into desired outcomes in economic, social and environmental terms.[34]

These insights have important implications for policymakers seeking to harness technological progress for economic development and social benefit. Solely encouraging invention is insufficient. Equal attention must be paid to creating conditions that enable rapid and broad diffusion. This includes investing in complementary infrastructure, building human capital and institutional capabilities, establishing appropriate regulatory frameworks, and designing IP systems that balance innovation incentives against technology access.

The patterns of technology use between advanced and developing economies, as highlighted in this chapter, not only emphasise the source of persistent global income gaps, but also point to the enormous potential for catch-up growth if barriers to diffusion can be reduced. Meeting today's pressing global challenges – including climate change – will depend on countries' ability to diffuse beneficial technologies rapidly and widely.

Achieving this will require close cooperation and interdependence among the many actors that make up the global innovation ecosystem. The chapters that follow build on this foundation by examining specific mechanisms through which technological knowledge spreads globally and exploring detailed case studies that illuminate these concepts in practice. Together, they aim to provide actionable insights for policymakers, business leaders, and researchers working to unlock technology's transformative potential for societal benefit.

Notes

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2 Global trends of technological knowledge diffusion

This chapter explores how technological knowledge travels across borders. It draws on patent data, scientific citations, and breakthrough technology trajectories, to reveal that knowledge now diffuses faster than ever, yet remains highly concentrated among a small group of advanced economies. Digitalization has narrowed gaps between national and global knowledge flows, yet innovation leaders like the US, Western Europe, and East Asia still dominate both the creation and absorption of new technologies. Examining channels such as trade, talent mobility, science networks, and IP, the chapter shows that diffusion is accelerating but uneven.

Introduction

This chapter explores the patterns and trends of international technological knowledge diffusion over time.[1] The chapter defines technological knowledge as the codified and embodied set of problem-solving principles, techniques and capabilities that enable the creation, improvement and application of products, processes or services.

Innovation drives technological progress. New knowledge helps companies produce goods more efficiently and create better, more varied products. This process fuels economic growth and helps countries to develop. Economic evidence shows that differences in productivity growth explain most of the income gaps between countries during the 20th century.

Why do these productivity differences persist? As discussed in Chapter 1, innovation is not equally distributed across countries or regions. However, technology spreads more easily over long distances when it is built into goods and equipment ready for use. The spread of major technologies was crucial for the Industrial Revolution's diffusion across countries and shaped the distribution of income per capita over the past two centuries.[2]

Yet, technological knowledge is not always built into physical products. Much of it remains tacit – existing as unwritten expertise rather than codified information. This makes technological knowledge harder to spread over long distances unless the people who hold this knowledge move or the knowledge gets written down and shared with others. Tacit knowledge spreads mainly through face-to-face interactions and specialized professional networks that tend to be geographically concentrated.[3]

Can new communication technologies change how quickly technological knowledge spreads? Despite advances in remote collaboration tools and long-distance communication, geographical distance still affects the diffusion of ideas, knowledge and technological change.[4]

Technological knowledge flows have economic impact. Despite barriers to cross-border movement, international knowledge diffusion plays a crucial role in shaping global economic patterns.[5] Evidence shows a clear link between international knowledge spillovers – measured through indicators like patent-to-patent citations – and improvements in worker productivity, industry performance and national income.[6] Developing economies particularly benefit by adopting and adapting knowledge from more advanced countries, which helps narrow productivity gaps and accelerate economic development.

Understanding international technological knowledge diffusion is essential for policymakers who want to promote innovation-driven growth, reduce global inequality and boost productivity. As the world evolves, the pace and direction of knowledge flows will remain central to discussions about economic development and global competitiveness.

The measurement of knowledge diffusion remains a challenge for innovation scholars.In his 1991 book *Geography and Trade*, Paul Krugman noted that knowledge spillovers "leave no paper trail by which they can be measured and tracked." This observation challenged innovation economists to find ways to measure these invisible knowledge flows, spurring decades of research to develop empirical methods for tracking knowledge spillovers.

Using intellectual property data as a lens, this chapter maps international technological knowledge diffusion and examines how patterns have changed over time. Patent documents make technological knowledge diffusion observable by recording inventions and categorizing them by technology areas through systems like the International Patent Classification (IPC).

The chapter has two main objectives: first, to map international technological knowledge diffusion and track changes over time using intellectual property (IP) data; second, to examine these findings from the viewpoint of economic literature on the main channels for international technological knowledge diffusion.

The analysis takes a global perspective and uses multiple approaches to track technological knowledge diffusion documented in patent and related data. Box 2.1 discusses methods for measuring international technological knowledge diffusion.

Box 2.1 How to measure international technological knowledge diffusion

In his 1991 book *Geography and Trade*, Paul Krugman asserted that knowledge spillovers are an agglomeration force that leave "no paper trail by which they can be measured and tracked." This statement challenged economists directly, spurring a decades-long quest to find empirical proxies for this invisible phenomenon.

Innovation economists have since developed several metrics, mostly based on patent data, to capture technological knowledge diffusion. These are the main approaches:

- **Patent locations** show where new technological knowledge appears over time by tracking the geographical origins of applicants or inventors in patent filings.
- **Patent citations** represent the most common approach for tracing technological diffusion. When a new patent cites an earlier one, this represents a potential knowledge flow from the older invention to the newer one. Patent citations dominate strategies for making invisible knowledge flows visible, despite ongoing debates about strategic considerations and institutional constraints in patent systems.[7]
- **The diffusion trajectories of breakthrough inventions** assume that novel breakthrough technologies emerge when existing components are combined for the first time in a new patent. Researchers map the knowledge diffusion trajectories using initial combinations of patent classification codes (e.g., IPC) and tracking their subsequent re-appearance over time and geography.[8]
- **Patent citations to scientific articles** track the science-to-technology pipeline that creates "deep tech" innovations.[9] These citations reveal how fundamental scientific discoveries translate into breakthrough technologies in highly science-based fields like biotechnology, artificial intelligence, quantum computing and advanced materials.
- **Patent families** trace knowledge diffusion by connecting where inventors first file patents and their subsequent international extensions.[10] These extensions reflect territories where applicants intend to enforce patent protection.
- **Specialization patterns in trade, science and patents** show that countries consistently diversify into products, technologies and scientific fields related to their existing expertise, suggesting knowledge diffusion between technologically neighboring regions.[11]
- **Other IP data** include recent experiments with trademark data and other IP indicators to map innovation geography and knowledge diffusion.[12]

Advantages of patent data: Patent data offer rich, quantifiable and publicly available records of inventive output. Patents are classified by technology, include detailed geographical information and span long time periods, allowing researchers to track innovation's geography, timing and nature globally.

Limitations of patent data: Not all innovations get patented; patenting propensity varies across industries and countries, and patent quality differs significantly. Patent citations can partially address these issues but introduce other complications, such as questions about who inserts citations in the patent documents.[13]

Despite being imperfect measures of knowledge spillovers, patents and their citations data provide useful quantifiable benchmarks that can be easily measured and analyzed. They remain the primary tool in empirical literature on knowledge diffusion, both within and across countries.

When knowledge diffusion leaves a trail in patent citations

Innovation economists often analyze how technological knowledge spreads by examining the geographic location of patents and their citations.

Patent data offer unique research advantages. Patent data provide a rich, quantifiable and publicly available record of inventive activity. Patents that cite other patents are carefully classified by technology and include detailed information on inventors and applicants. Patents are filed over long time periods, allowing researchers to track the geography, timing and nature of innovation worldwide.[14] This makes patents an invaluable, though imperfect, tool for measuring innovation and investigating what drives technological change. Patents fill a critical data gap for studying an otherwise invisible process.

Interpreting patent citations requires caution. Patent citation data have notable limitations that require careful interpretation.[15] Researchers must consider the strategic motivations of patent applicants and the institutional constraints of different patent systems.[16] However, few other data sources offer such wide international coverage with detailed individual records.

Patent-to-patent citations can reveal knowledge flows. Patent-to-patent citations represent the main empirical approach for observing the “paper trail” of international technological knowledge diffusion.[17] When a new patent cites an earlier patent, this represents a potential knowledge flow from the cited location to the citing one. For decades, economic studies have found strong positive relationships between the geographical location of research and development (R&D) activities, patents and their citations. Research on international patent citations shows that these knowledge flows correlate with major patterns of trade and foreign direct investment (FDI).

Technological knowledge is diffusing faster

Analysis of international patent citation flows clearly shows that technological knowledge spreads faster today than in the past. All patent citation measures indicate that technologies are accelerating their diffusion paths.

International adoption times have halved. Figure 2.1 shows that the international adoption lag – measured by the first international citation to an existing patent family – now takes half the time it took 50 years ago. In the early 1970s, the average patent family received its first international citation around 2.8 years after filing. By 2020, this international adoption lag had fallen to less than 2 years. The decline has been continuous, with one notable exception: from the mid-2000s to mid-2010s, the adoption lag stabilized at around 2 years. This period coincides with rapid increases in patenting by China and other emerging players, which significantly increased the number of patent documents not immediately available in English.

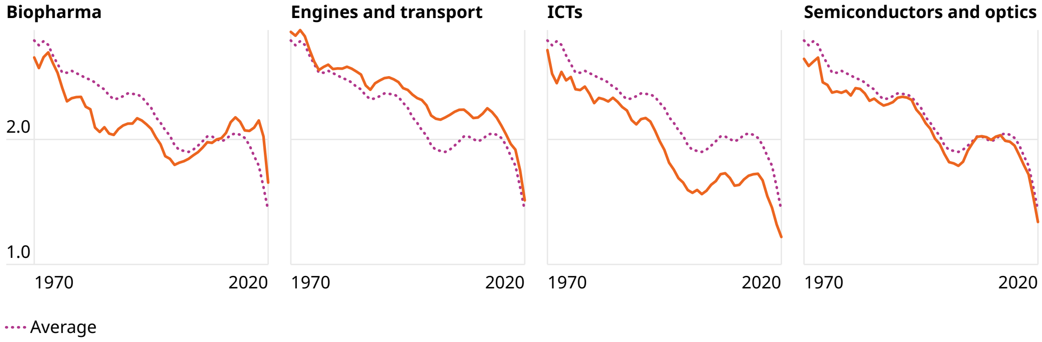
All technology fields show faster diffusion. The international adoption lag reduction occurs across all technological fields, although average lag times differ. Figure 2.1 breaks down adoption lags for four selected technology areas: biopharma; engines and transport; information and communication technologies (ICTs); and semiconductors and optics. All four follow the general trend toward faster adoption.

ICTs consistently show shorter adoption lags than average, with this advantage growing over time. The gap started at just 5 percent in 1970 and reached 15 percent by 2020. Engines and transport show the opposite pattern, with adoption lags only 2 percent slower than average in 1970 but 6 percent slower by 2020.

Biopharma technologies follow a distinctive path. They started with adoption lags 5 percent faster than average, improving steadily until the early 2000s, when they peaked at 10 percent faster. However, this trend reversed in the early 2010s, reaching a peak of 25 percent slower than average.

For the past half century, the technological knowledge adoption lag has systematically decreased

Figure 2.1 Average adoption time lag of international patent family citations, lag years, 1970–2020



Notes: Adoption lag refers to the average time lag to the first international citation within a 5-year window from the priority application year of the cited patent family. Patent families without citations are excluded. Recent years have been omitted due to citation data truncation. For more details see the Technical annex.

Source: WIPO (based on EPO Patstat, 2025 Autumn edition), https://www.wipo.int/wipr.

Advances in digital technologies can explain the faster diffusion. This long-term trend can largely be attributed to remarkable advances in communications and information technologies during the same period. Patent documents shifted from paper-only publication to primarily digital formats. Researchers and inventors gained increasing access to patent information through online databases that offered automatic translation into multiple languages. Communication methods evolved from time-consuming traditional mail and expensive phone calls to virtually free, instant video calls, messaging and file sharing on portable devices.

The gap between national and international knowledge flows is narrowing

The trends toward shorter adoption lags reflect what scholars call the beginning of a knowledge economy.[18] This new period features accelerating and unprecedented speeds at which knowledge gets created, shared and accumulated.

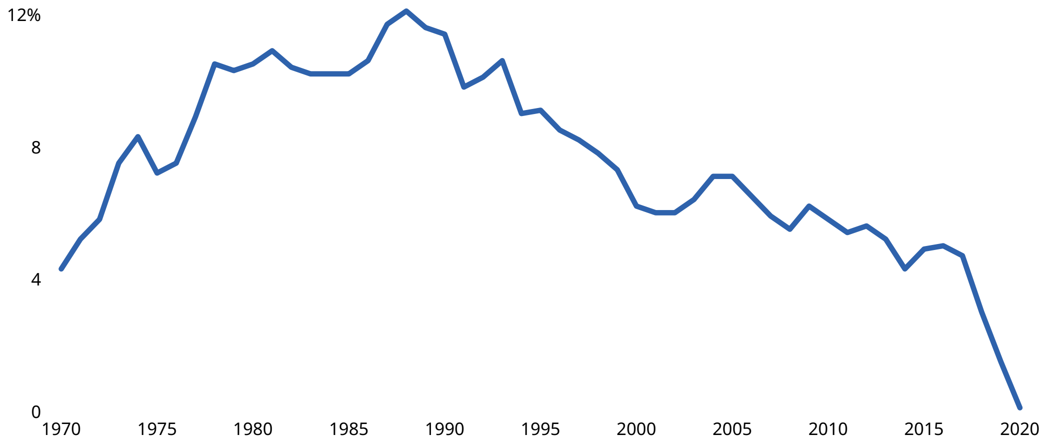
Distance still matters, but less than before. Both research theory and evidence confirm that distance affects knowledge diffusion. Knowledge spillovers occur more easily when the distance between origin and destination is shorter. Figure 2.2 illustrates this by showing the difference in adoption lags between national and international patent citations. As expected, patent citations happen faster within national boundaries than across them.

However, the international gap is disappearing. Since the late 1980s, this gap has been closing steadily. The difference peaked in 1988, when the average international adoption lag was 12 percent slower than the average national adoption lag. Since then, the gap has reduced significantly. By the early 2010s, the difference was only around 5 percent and by 2020 it appears to have virtually disappeared.

This convergence suggests that geographical barriers to knowledge diffusion are weakening over time. The same technological advances that have shortened overall adoption times have also made international knowledge sharing nearly as fast as domestic knowledge sharing.

Technological knowledge diffuses faster nationally than internationally… but the gap is closing

Figure 2.2 Average adoption time lag difference between international and national patent family citations, percent, 1970–2020



Notes: Adoption lag refers to the average lag to observe a first citation within a given window (5 years) from the cited priority application year within the family. Citation data in recent years may be incomplete. For more details see the Technical annex.

Source: WIPO (based on EPO Patstat, 2025 Autumn edition), https://www.wipo.int/wipr.

Advanced economies absorb foreign knowledge faster

Knowledge diffusion varies significantly across countries. The speed of technological knowledge diffusion is not evenly distributed globally. While international diffusion has accelerated overall, clear differences remain in how quickly knowledge moves between different countries and regions.

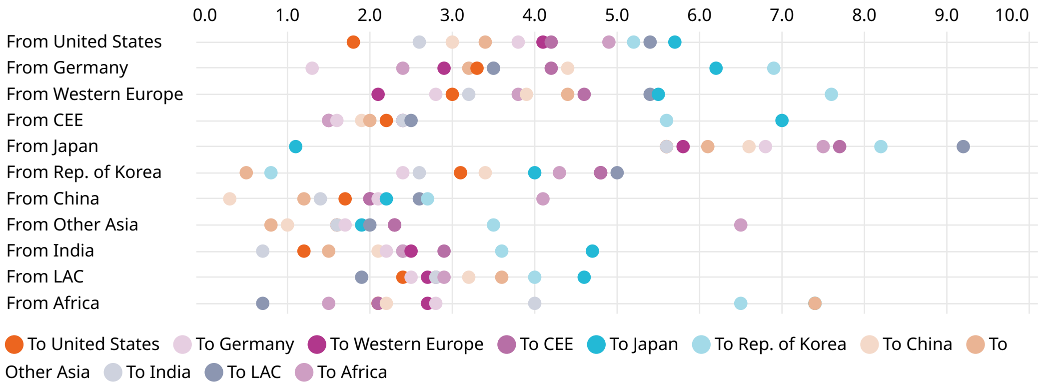
Domestic knowledge always travels fastest. Figure 2.3 shows the average time between a patent's filing date and its first citation elsewhere. Geography clearly matters. In every case, inventors cite technologies from their own country faster than foreign inventors cite the same technologies. This pattern holds even among advanced innovation economies. For example, US applicants cite their own technologies twice as fast as German or Chinese applicants cite US patent families, and three times faster than applicants in Japan or the Republic of Korea. The reverse pattern also applies. Applicants from Germany, the Republic of Korea, Japan and China cite their own technologies 2.5, 4, 5 and 6 times faster than US applicants cite technologies from these countries, respectively.

Advanced economies absorb foreign knowledge faster. Substantial differences exist in diffusion speeds along different international knowledge corridors. High-performing innovation economies – including the United States, East Asian countries and Western European nations – benefit from faster inward flows of foreign technological knowledge from almost every other region compared to how quickly the rest of the world absorbs their knowledge. In contrast, Africa, Latin American and Caribbean countries and Eastern Europe typically experience slower inward knowledge diffusion.

Knowledge flows favor leading innovation ecosystems. US applicants systematically take less time to cite technologies from other countries than those countries take to cite US technologies. This pattern suggests that leading innovation economies have developed stronger capabilities to identify, absorb and build upon foreign technological advances.

Innovation leaders benefit from faster knowledge absorption

Figure 2.3 Average adoption time lag per year, international and national patent family citations, selected corridors, 1970–2020



Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Adoption time lag refers to the average time lag to observe a first citation within a given window (5 years) from the cited priority application year within the family. For more details see the Technical annex.

Source: WIPO (based on EPO Patstat, 2025 Autumn edition), https://www.wipo.int/wipr.

A few leading countries both contribute and absorb most global knowledge

Speed does not tell the whole story about knowledge volumes. The previous analysis shows how quickly economies become aware of technologies created elsewhere, indicating their innovation development and how actively they are sourcing for specific technologies. However, it reveals little about the actual volume of knowledge that economies contribute to and receive from the global pool of technological knowledge.

A few economies dominate global knowledge flows. Only a handful of economies account for the majority of patent citations that flow internationally – both as sources and as destinations of knowledge. Figure 2.4 shows the top 10 contributors and beneficiaries during the period 1970–2020. The United States leads as the main sender of technological knowledge abroad throughout the past five decades. It also ranks as the most important receiver of knowledge during the same period.

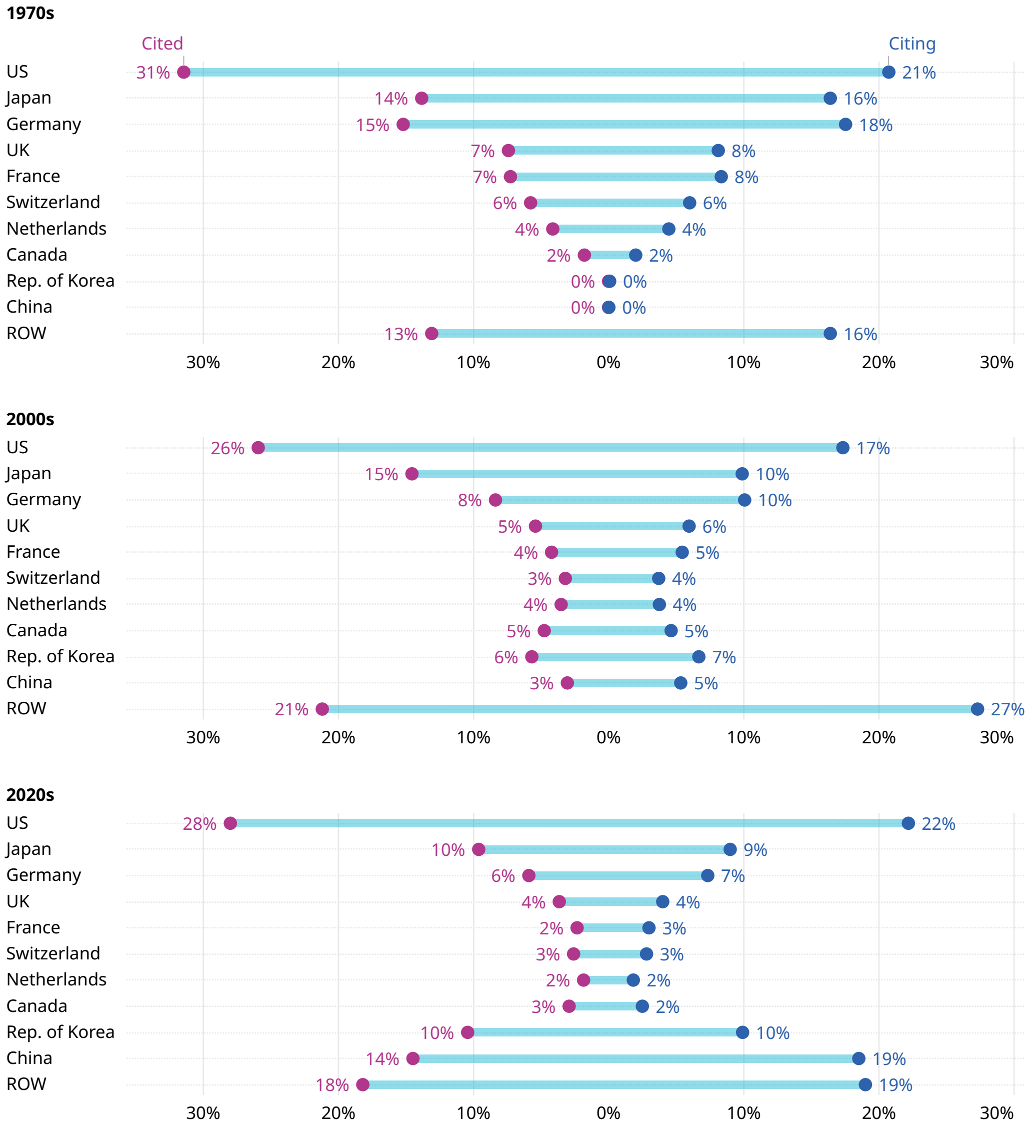
East Asian economies have joined the leaders. Historically, the United States was followed by Japan, Germany, the United Kingdom, France, Switzerland, the Kingdom of the Netherlands and Canada. In the 2000s, the Republic of Korea and China began gaining ground. By 2020, these two East Asian economies showed the largest increases of the analyzed period and joined the United States in the top three.

Contributors and beneficiaries are largely the same. All top economies show relatively similar patterns in terms of their shares as both cited and citing countries, and this balance remains consistent across time periods. The same pattern applies to the rest of the world as a whole.

Active contributors are also active absorbers. This balance indicates that economies contributing technologies that attract international attention are the same economies that find foreign technologies most interesting. Countries that generate globally relevant innovations also actively seek out and build upon innovations from elsewhere. This suggests that successful innovation systems both create and consume knowledge at high volumes.

The United States, Europe and East Asia are the main contributors and beneficiaries of technological knowledge diffusion

Figure 2.4 Share of cited and citing of international patent family citations, top 10 economies by selected periods



Notes: ROW = rest of the world. Cited and citing refer to international citations within a given window (5 years) from the cited priority application year. The period refers to the cited patent family. Citation data in recent years may be incomplete. For more details see the Technical annex.

Source: WIPO (based on EPO Patstat, 2025 Autumn edition), https://www.wipo.int/wipr.

Technological knowledge diffusion is intensifying

Not only has technological knowledge accelerated over recent decades, but also its diffusion intensity. Figure 2.5 reveals the share of bilateral knowledge flow patterns across the main economies and regions of the world. The general trend is of widespread increase in citation intensity.

Countries primarily build on their own knowledge. The largest citation shares appear along the main diagonal, indicating that all regions rely heavily on their own technological knowledge. This pattern is particularly strong for large, technologically established countries such as the United States, Japan, Germany, and other Western European economies.

The United States and Western Europe absorb knowledge on a global scale. The high citation shares for the United States and, to a lesser extent, Western Europe as destinations show that these regions cite knowledge produced from virtually all territories. The United

States and Western European economies benefit extensively from technological knowledge created worldwide.

Asian economies use foreign knowledge extensively, but they are also becoming more self-reliant. Several territories have become heavier users of their own knowledge, as shown by increasing values along the main diagonal over the decades. This trend is most notable for China and the Republic of Korea and, to a lesser extent, India. These countries are building more extensively on their own technological foundations rather than relying primarily on foreign knowledge.

Some countries rely on global sources while others turn inward for knowledge

Figure 2.5a Share of cited international patent family citations by origin and destination, selected economies and regions, 1991–2000

	To Africa	To CEE	To China	To Germany	To India	To Japan	To LAC	To Rep. of Korea	To Other Asia	To United States	To Western Europe
From Africa	27%	5%	8%	33%	4%	24%	5%	7%	2%	68%	56%
From CEE	2%	27%	5%	36%	3%	27%	2%	6%	2%	56%	49%
From China	2%	4%	28%	24%	5%	42%	3%	15%	5%	66%	42%
From Germany	1%	3%	3%	70%	1%	33%	2%	5%	1%	53%	55%
From India	3%	5%	17%	30%	27%	41%	5%	15%	5%	85%	49%
From Japan	1%	2%	6%	31%	2%	85%	1%	16%	2%	61%	40%
From LAC	3%	4%	6%	33%	4%	28%	22%	9%	2%	69%	58%
From Rep. of Korea	1%	2%	10%	20%	3%	59%	2%	48%	3%	51%	32%
From Other Asia	1%	4%	14%	28%	7%	45%	3%	15%	20%	70%	49%
From United States	2%	4%	8%	36%	4%	45%	4%	11%	3%	91%	56%
From Western Europe	1%	4%	5%	41%	2%	32%	3%	7%	2%	60%	72%

Source: WIPO based on EPO Patstat, 2025 Autumn edition, https://www.wipo.int/wipr.

Figure 2.5b Share of cited international patent family citations by origin and destination, selected economies and regions, 2011–2020

	To Africa	To CEE	To China	To Germany	To India	To Japan	To LAC	To Rep. of Korea	To Other Asia	To United States	To Western Europe
From Africa	25%	17%	48%	40%	22%	36%	11%	29%	14%	73%	66%
From CEE	3%	40%	44%	40%	16%	34%	7%	26%	9%	60%	57%
From China	1%	5%	85%	17%	10%	28%	2%	27%	7%	43%	29%
From Germany	2%	13%	38%	79%	12%	40%	6%	22%	6%	59%	64%
From India	5%	16%	58%	35%	48%	40%	8%	38%	15%	78%	58%
From Japan	1%	7%	51%	31%	10%	91%	3%	40%	7%	52%	40%
From LAC	4%	14%	42%	39%	19%	34%	34%	24%	11%	70%	60%
From Rep. of Korea	2%	7%	60%	22%	12%	47%	3%	79%	8%	53%	35%
From Other Asia	4%	12%	60%	35%	22%	44%	7%	36%	34%	73%	55%
From United States	5%	18%	64%	48%	28%	49%	11%	38%	15%	91%	70%
From Western Europe	3%	14%	46%	48%	16%	38%	8%	25%	9%	69%	79%

Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Cited and citing refer to international citations within a given window (5 years) from the cited priority application year. The period refers to the cited patent family. Citation data in recent years may be incomplete. For more details see the Technical annex.

Source: WIPO (based on EPO Patstat, 2025 Autumn edition), https://www.wipo.int/wipr.

Deep tech sourcing: when technologies leverage scientific knowledge

There is an increasing interest in “deep tech” innovations. Scholars and policymakers recognize that basic science drives technological innovation and economic growth.[19] Today’s most transformative technologies – from artificial intelligence and quantum computing to advanced biotechnology and clean energy solutions – often emerge from fundamental scientific discoveries.[20] These “deep tech” innovations represent a growing share of patent activity and economic value creation.[21]

Science creates valuable knowledge repositories. Countries and regions serve as repositories of scientific research. Investments in science and education enhance territories’ ability to develop novel technologies and breakthrough innovations.[22] However, determining how, when and where to allocate public funding and incentives remains challenging for policymakers.

New data reveal science–technology connections. Uncovering links between science and technology has attracted research attention for years. Policymakers increasingly seek evidence from the academic community to design and evaluate their policies.[23] Growing databases with detailed data on connections between scientific discoveries and technological innovation – combined with sophisticated analytical methods – have opened new research paths.[24] Meanwhile, scientific production has become increasingly team-based, international and distributed across more territories.[25]

Scientific knowledge travels further than technical knowledge. How does science affect international technological knowledge diffusion? Economic research shows that technologies with higher scientific content travel longer distances and are more likely to generate new inventor clusters, especially during their growth and maturity phases.[26]

Measurement limitations remain. Patent citations to scientific papers have limitations. This approach underestimates science's impact by capturing only the research done openly, while omitting private channels like academic consulting or public–private partnerships.[27] Like patent-to-patent citations, treating patent citations to scientific papers as direct science–technology links oversimplifies a complex relationship.[28] These limitations do not invalidate the approach but indicate that scientific knowledge flows to technologies through multiple, often indirect pathways.

Scientific knowledge takes time to become deep tech applications

Science-to-technology transformation requires patience. Analysis of global patent citations to scientific articles reveals that patents take much longer to cite scientific articles than to cite other patents. On average, scientific articles receive their first patent citation about 10 years after publication. This pattern aligns with economic studies showing that transforming scientific knowledge into industrial applications requires significant effort.[29] Deep tech innovations with higher scientific content take longer to develop but generate greater long-term impact, making patent citation analysis valuable for innovation policymaking.

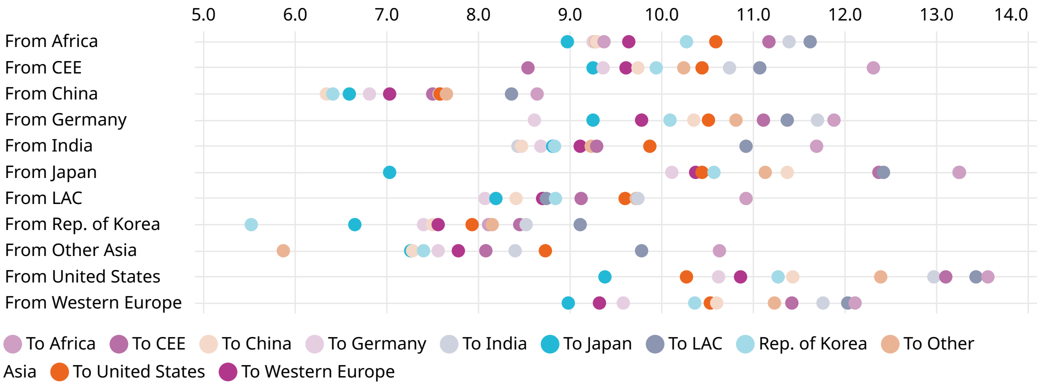
Geography affects scientific knowledge sourcing. Like patent citations, geography matters when sourcing scientific knowledge. Figure 2.6 shows how long scientific knowledge from one region takes to "diffuse" into technologies elsewhere. Patent applicants worldwide source more recent scientific knowledge nationally than from other countries or regions. This pattern exists even among advanced innovation economies like the United States, Germany and Japan, although less dramatically than for patent citations. For example, US science gets cited by US applicants only 3 and 11 percent faster than by German and Chinese applicants, respectively, and 9 percent slower than by Japanese applicants. Conversely, when citing German science, applicants from the United States, China and Japan are 22, 20 and 7 percent slower than German applicants, respectively.

Chinese scientific knowledge diffuses relatively quickly. Chinese papers get cited relatively quickly by foreign patents – within a maximum of 8 years from publication. Conversely, US papers take longer to diffuse to patents, with a minimum average time of 9 years and 4 months for Japanese patents and a maximum of more than 13 years for African patents.

These comparisons need careful interpretation. First, document volumes are not comparable since the United States produces far more cited scientific articles. Second, emerging scientific players – notably China, plus Southeast Asian, Latin American and African countries – have significantly increased their scientific publication rates recently. This means that older scientific references are more likely to originate from the United States and Europe. Finally, these adoption lags do not reveal the intensity or type of scientific knowledge being diffused.

It takes a decade for scientific knowledge to diffuse into technologies

Figure 2.6 International and national patent family citations to scientific articles, average adoption lag per year, selected regional corridors, 1985–2022



Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the average lag to observe a first patent citation from the destination to a scientific paper in the origin. Only scientific papers with at least one patent citation are considered in the calculations. For more details see the Technical annex and Miguelez, E., Pezzone, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: EPO Patstat 2025 and Marx and Fuegi (2020, 2022).

A few innovation leaders dominate global science sourcing for deep tech

Scientific knowledge sourcing is highly concentrated. More than is the case for patent-to-patent citations, reliance on scientific knowledge is heavily concentrated in a handful of regions. From virtually all global sources, the bulk of cited scientific papers flow to the United States, Western European economies and Japan.

Leading economies absorb science on a global scale. Figure 2.7 shows that among all foreign scientific papers published between 1985 and 1995 with at least one patent citation, US patents cite at least 39 percent of them. Japan, Germany and other Western European countries show similar patterns. These high-performing innovation ecosystems consistently cite scientific articles from other regions more than those regions cite their own articles. These leading economies also interact intensively with each other – about one-third of US scientific papers get cited by Western European patents, while about half of Western European scientific articles get cited by US patents.

These sourcing patterns have shown remarkable stability over the past decades. Comparing the 2016–2022 period (Figure 2.8) with earlier decades reveals only minor variations. The United States, Japan and Western Europe have continued to demonstrate openness to international science since the earliest measured years.[30]

China has emerged as a major science consumer. The most notable change over the past three decades is China's increased openness to international science. Only 2.5 percent of the oldest US papers published during the 1985–1995 period were cited by Chinese patents, but this percentage increased significantly to 8.8 percent for US papers published between 2016 and 2022. This growth has made China more open to international science than Japan across all source regions.

Local science still matters everywhere. Despite the dominance of a few high-performing innovation ecosystems in international scientific sourcing, geography still matters. Even for less scientifically advanced regions, the largest share of scientific sourcing remains domestic. This suggests that while deep tech innovations increasingly draw on global scientific knowledge, local research capabilities remain important for all regions.

United States, Japan and Western Europe dominate global science sourcing for deep tech...

Figure 2.7 Share of scientific articles with international and national patent citations, selected regional corridors, 1985–1995

	To Africa	To CEE	To China	To Germany	To India	To Japan	To LAC	To Rep. of Korea	To Other Asia	To United States	To Western Europe
From Africa	4%	2%	3%	16%	2%	15%	2%	2%	1%	46%	39%
From CEE	1%	8%	2%	18%	1%	18%	1%	2%	1%	44%	34%
From China	0%	2%	6%	14%	2%	24%	1%	3%	1%	41%	28%
From Germany	1%	3%	2%	36%	1%	17%	1%	2%	1%	43%	35%
From India	1%	2%	3%	17%	7%	19%	2%	2%	1%	41%	29%
From Japan	0%	2%	2%	14%	1%	43%	1%	2%	1%	39%	27%
From LAC	1%	3%	2%	15%	1%	13%	9%	1%	1%	40%	36%
From Rep. of Korea	0%	2%	3%	16%	1%	26%	1%	8%	1%	42%	30%
From Other Asia	1%	2%	4%	14%	2%	17%	3%	3%	4%	47%	32%
From United States	0%	2%	3%	17%	1%	17%	2%	2%	1%	63%	34%
From Western Europe	1%	2%	2%	18%	1%	16%	2%	2%	1%	47%	46%

Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the share of scientific papers in the origin that are cited by patents from the destination. Only scientific papers with at least one patent citation are considered in the calculations. For more details see the Technical annex and Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: EPO Patstat 2025 and Marx and Fuegi (2020, 2022).

... but China is ready to join the exclusive group

Figure 2.8 Share of scientific articles with international and national patent citations, selected regional corridors, 2016–2022

	To Africa	To CEE	To China	To Germany	To India	To Japan	To LAC	To Rep. of Korea	To Other Asia	To United States	To Western Europe
From Africa	2%	3%	10%	18%	2%	8%	1%	4%	1%	24%	36%
From CEE	0%	15%	8%	18%	1%	8%	1%	3%	1%	24%	34%
From China	0%	3%	20%	15%	2%	9%	0%	7%	1%	25%	30%
From Germany	0%	3%	7%	40%	1%	6%	1%	3%	1%	23%	34%
From India	0%	3%	10%	19%	11%	8%	1%	4%	1%	22%	30%
From Japan	0%	2%	8%	13%	1%	39%	0%	4%	1%	21%	23%
From LAC	0%	4%	7%	18%	2%	6%	5%	3%	1%	26%	39%
From Rep. of Korea	0%	3%	11%	13%	2%	9%	0%	23%	1%	22%	28%
From Other Asia	0%	3%	11%	16%	3%	10%	1%	5%	4%	24%	35%
From United States	0%	2%	9%	15%	2%	7%	1%	4%	1%	45%	31%
From Western Europe	0%	3%	8%	17%	2%	7%	1%	3%	1%	26%	48%

Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the share of scientific papers in the origin that are cited by patents from the destination. Only scientific papers with at least one patent citation are considered in the calculations. For more details see the Technical annex and Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: EPO Patstat (2025) and Marx and Fuegi (2020, 2022).

Technological knowledge trajectories: when breakthrough inventions spread globally

Patent citations miss part of the innovation story. Previous analyses rely on patent citations, which often do not represent the complete trajectory of technological knowledge diffusion behind the cited patents or scientific articles. Scholars have found that many patent citations do not even belong to the same technological class.[31]

Alternatively, scholars have tracked the international diffusion of technological knowledge by identifying the first appearance of a breakthrough invention and its international reuse. Recent studies examine the first and subsequent appearances of specific technologies to understand their diffusion over time and space. These studies map technological knowledge diffusion using the concept of “reuse”, which is tracked across regions and years.[32]

How can breakthrough technologies be mapped? Breakthrough technologies emerge through the novel recombination of existing technical knowledge. Following the idea that innovation stems from recombining existing knowledge components, scholars have mapped the diffusion trajectories of technologies using novel combinations of international patent classification (IPC) codes.[33]

The transgenic mouse breakthrough provides an interesting example of this process. Consider transgenic mammal technology – the foundation for genetically modified laboratory mice used to develop treatments for cancer and Alzheimer's disease. This novel technological trajectory originated in 1985 when Harvard patented the "onco-mouse," listing for the first time the patent codes for "gene isolation" and "injection of material into animals." Subsequently, multiple patents reused this same combination. For instance, Seoul National University patented the "diabetic mouse" in 1996. All inventions classified under the same combination can be assumed to belong to the same technological trajectory.

Innovation leaders rapidly adopt foreign breakthrough technologies

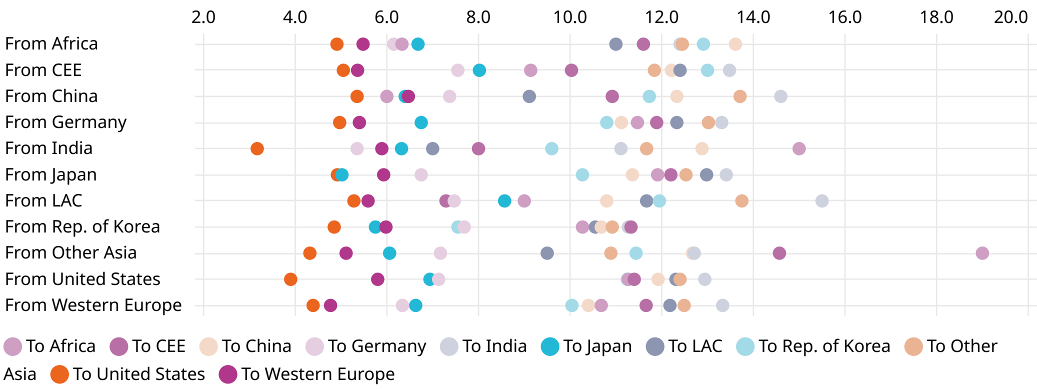
The usual suspects dominate both creation and adoption. As with patent citations, the United States leads as the top origin of breakthrough inventions generating new technological trajectories, followed by Western Europe and Japan. These same regions also rank as the top three adopters reusing these foreign breakthrough inventions. Developed countries are the most active reusers of breakthrough technologies originated elsewhere. Given the increased patenting activity over recent decades, both new technology combinations and their reuse are growing in volume.

Advanced economies excel at rapid adoption of the knowledge behind these breakthrough inventions. Geographical patterns become even more pronounced when examining the time required for technological knowledge reuse. Countries and regions like the United States, Japan, Germany and other Western European economies prove to be much faster at reusing breakthrough technologies that originated elsewhere (see Figure 2.9). For example, the diffusion trajectories of the breakthrough technological knowledge originating in India take, on average, one-third of the time to be reused in the United States compared to reuse within India itself. The United States particularly excels at rapidly adopting the knowledge behind the breakthrough inventions from abroad.

Speed differences reveal the innovation capabilities of the resuing economy. This pattern suggests that leading innovation economies have developed superior technological capabilities not just for creating new technologies, but also for quickly identifying, understanding and building upon breakthrough innovations from other regions. This rapid adoption advantage may help to explain why innovation leaders maintain their competitive positions over time.

Innovation leaders maintain their dominance through rapid reuse of foreign breakthrough technologies

Figure 2.9 Average time for first reuse of breakthrough inventions in destination region



Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the average time lag to observe a breakthrough invention (i.e. international patent family combining pairs of IPC/CPC symbols for the first time) to be reused in the destination region (within a 5 years). Figure follows the methodology by Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.htm; and Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454. For more detail see Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*, Geneva: WIPO.

Source: EPO Patstat 2025.

Developing economies struggle to reuse breakthrough technologies intensively

Domestic reuse dominates globally. Figure 2.10 shows overall technological knowledge flows across countries. Most breakthrough inventions get heavily reused in their country of origin, as shown by high values along the matrix's diagonal. For example, 99 percent of breakthrough inventions originating in the United States get reused within that country. Similarly, Germany reuses 94 percent of its homegrown breakthrough inventions, while Japan reuses 92 percent of its own breakthrough inventions.

Innovation leaders also absorb foreign breakthrough inventions actively. Despite high domestic reuse rates, leading innovation economies remain open to reuse foreign breakthrough inventions. Japan serves as a destination for about 84 percent of breakthrough inventions originating in the United States, meaning that most US breakthrough inventions eventually reach Japan. Germany demonstrates similar openness, actively reusing breakthrough inventions from abroad while maintaining high domestic reuse rates.

Regional partnerships emerge around shared technology interests. Bilateral exchanges exist between countries like China and the Republic of Korea, reflecting both geographical proximity and technological affinity. These reuse flows are concentrated in nanotechnologies and electric data processing – core activities for companies like Samsung, LG and Huawei. Geographic and technological similarities create natural partnership corridors for breakthrough invention reuse.[34]

Developing economies face challenges in reusing breakthrough inventions. Most developing economies show marginal participation in international knowledge flows based on the reuse of breakthrough technologies. Africa demonstrates limited capability to reuse foreign knowledge behind breakthrough inventions, as indicated by low reuse rates across all origins. However, African breakthrough inventions flow extensively to developed economies – all of the African breakthrough inventions are reused in Western Europe, while large shares are reused in the United States (96 percent), Japan (92 percent) and Germany (81 percent).

These patterns suggest that successful breakthrough invention reuse requires sophisticated innovation capabilities. Leading economies excel at both creating breakthrough technologies and rapidly identifying, adapting and building upon innovations from elsewhere. Developing regions may generate innovative technologies but lack the institutional infrastructure and technical capabilities necessary to maximize reuse of foreign breakthroughs.

Figure 2.10 Share of origin's breakthrough inventions reused by destination regions, selected origin regions, 1985–2015

	To Africa	To CEE	To China	To Germany	To India	To Japan	To LAC	To Rep. of Korea	To Other Asia	To United States	To Western Europe
From Africa	19%	31%	38%	81%	10%	92%	8%	46%	23%	96%	100%
From CEE	7%	30%	36%	88%	12%	81%	10%	35%	13%	97%	97%
From China	2%	14%	47%	88%	6%	89%	10%	53%	8%	96%	99%
From Germany	3%	17%	31%	94%	9%	88%	6%	36%	7%	95%	96%
From India	4%	20%	32%	80%	36%	76%	8%	40%	12%	92%	76%
From Japan	3%	17%	38%	85%	10%	95%	6%	47%	11%	94%	94%
From LAC	2%	14%	20%	84%	8%	82%	18%	37%	8%	98%	96%
From Rep. of Korea	6%	29%	63%	79%	17%	86%	11%	74%	21%	96%	93%
From Other Asia	5%	18%	47%	79%	18%	84%	16%	42%	24%	97%	95%
From United States	5%	19%	32%	84%	11%	84%	9%	37%	11%	99%	95%
From Western Europe	5%	18%	36%	89%	11%	86%	8%	40%	10%	96%	98%

Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the share os all breakthrough inventions (i.e. international patent family combining pairs of IPC/CPC symbols for the first time) being reused in the destination region. Figure follows the methodology by Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454; and Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.htm. For more detail see Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: EPO Patstat 2025.

Innovation leaders excel at rapid and intensive adoption of foreign breakthroughs

The United States and Western Europe dominate early adoption of breakthrough inventions. Figure 2.11 reveals that the United States and Western Europe excel as early and intensive reusers of foreign breakthrough inventions. These regions successfully reuse high shares of foreign technological knowledge already from their initial stages of technology development.

Geographic proximity influences adoption patterns. In early stages, Japan intensively reuses breakthrough inventions from other Asian countries but reuses less intensively from distant regions than the United States and Western European countries. This suggests that geographic and cultural proximity can facilitate faster technology diffusion, especially for nascent innovations.

Even strong patent producers struggle with early breakthrough inventions reuse. Despite their strong performance in patent citations, China and the Republic of Korea struggle to reuse breakthrough inventions intensively during early stages. For instance, China reuses less than 5 percent of US-originated breakthrough inventions within 5 years of invention. It takes 20 years for China to reach 28 percent reuse of US-originated breakthrough inventions. In contrast, the United States reuses 70 percent of Chinese-originated breakthrough inventions within the first 5 years of invention.

Developing regions face persistent reuse gaps. Regardless of the stage, India, Southeast Asian, Latin American and African countries lag significantly behind. These regions can reuse only small fractions of foreign-originated breakthrough inventions, indicating substantial capability gaps in identifying, understanding and implementing breakthrough technological knoweldge from abroad.

Speed and intensity of reuse reveal competitive advantages. The ability to quickly adopt and build upon foreign breakthroughs represents a crucial competitive advantage. Early adopters can enhance these technologies, create derivative innovations and establish market positions before slower adopters catch up. This pattern helps to explain why innovation leaders maintain their advantage over time – they excel not only at creating breakthrough technologies but also at rapidly incorporating innovations from elsewhere.

The United States and Europe dominate early and intensive reuse of breakthrough inventions

Figure 2.11 Share of origin's breakthrough inventions reused by destination within 5 years of invention, selected regional corridors, 1985–2015

	To Africa	**To CEE**	**To China**	**To Germany**	**To India**	**To Japan**	**To LAC**	**To Rep. of Korea**	**To Other Asia**	**To United States**	**To Western Europe**
From Africa	11%	2%	2%	49%	0%	34%	2%	6%	4%	70%	66%
From CEE	2%	8%	6%	42%	1%	33%	2%	2%	2%	69%	65%
From China	1%	2%	8%	42%	0%	52%	4%	10%	0%	70%	53%
From Germany	1%	3%	9%	63%	1%	47%	1%	10%	1%	68%	63%
From India	0%	4%	4%	50%	4%	42%	4%	8%	0%	88%	46%
From Japan	0%	2%	4%	46%	0%	69%	0%	9%	1%	69%	57%
From LAC	0%	5%	2%	43%	0%	24%	2%	7%	0%	60%	67%
From Rep. of Korea	1%	3%	9%	33%	3%	56%	1%	41%	3%	66%	59%
From Other Asia	0%	0%	9%	51%	0%	60%	3%	11%	6%	80%	63%
From United States	1%	3%	5%	41%	1%	44%	1%	7%	1%	83%	59%
From Western Europe	1%	3%	12%	51%	1%	48%	1%	13%	1%	74%	71%

Notes: CEE = Central and Eastern Europea, LAC = Latin America and the Caribbean, Other Asia = Central, South and Southeast Asia (excluding India), Western Europe excludes Germany. Figure data points refer to the share os all breakthrough inventions (i.e. international patent family combining pairs of IPC/CPC symbols for the first time) being reused in the destination region within five years of first invention. Figure follows the methodology by Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. Research Policy, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454; and Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.htm. For more detail see Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Source: EPO Patstat 2025.

Understanding the channels behind international knowledge diffusion

Multiple channels drive technological knowledge across borders. The patterns observed in previous sections reflect well-established channels through which technological knowledge spreads internationally. Economic research identifies several key pathways: international trade in goods, foreign direct investment, skilled migration, licensing agreements and global value chains.[35] These mechanisms allow countries to access frontier innovations without bearing the full cost of invention.

Absorption requires capabilities, not just exposure. Simply being exposed to foreign knowledge doesn't guarantee adoption. Successful absorption depends on domestic factors like human capital, institutional quality, research capacity and what economists call "absorptive capacity" – a country's ability to recognize, understand and use external knowledge. This explains why innovation leaders like the United States and Western Europe excel at rapidly adopting foreign breakthroughs or sourcing deep scientific knowledge while other regions struggle.

Knowledge travels in traded goods

Trade remains the primary diffusion channel. The most common way technological knowledge spreads is through goods that embody new technologies. Consumers access embedded innovations through their purchases while companies use imported machinery, components and materials as inputs for their own production. These flows create learning opportunities as firms reverse-engineer foreign technologies.[36]

Imports can boost domestic innovation. Recent studies show strong positive relationships between imports and patents.[37] *When countries import knowledge-rich inputs, their patenting activity increases notably. This process helps to explain why countries with higher trade integration tend to show faster technology adoption, as observed in the patent citation patterns.*

Skilled people bridge knowledge gaps

Inventors and scientists drive knowledge flows. Skilled migration – particularly of inventors and scientists – plays a crucial role in global knowledge diffusion. Historically, major technological shifts have coincided with cross-border mobility of highly skilled individuals.[38] Today's international circulation of STEM talent toward R&D-intensive economies – such as the United States and Europe – continues this tradition.

Migrants connect otherwise isolated communities. Skilled migrants act as knowledge brokers by building ties in host countries while maintaining connections to their origins.[39] This bridging role proves especially important across international borders, which represent significant barriers to knowledge circulation. Migrant inventors systematically demonstrate more global orientations than native peers – they cite more foreign prior art, receive more international citations and connect host economies to global technological frontiers.

Brain circulation can benefit all parties. Rather than creating "brain drain," skilled migration often generates "brain circulation." Even emigrants who do not return facilitate co-patenting, co-publications and technology transfer through their networks. Return migration further reinforces these processes, contributing to new technological specializations in origin countries.[40]

International business creates knowledge highways

Multinational companies transfer knowledge systematically. Foreign direct investment and multinational enterprises represent major conduits for international knowledge diffusion. These companies bring advanced production techniques, organizational practices and technological capabilities to host countries, creating potential spillovers for local firms through competition, labor mobility and supplier relationships.[41]

Local capabilities determine success. However, these spillovers are not automatic. They depend on domestic absorptive capacity – determined by R&D intensity, human capital and institutional quality. This explains why the same foreign investment can generate varying outcomes in different countries. Successful knowledge transfer requires co-evolution between global and local actors through reciprocal learning.

Global value chains expand knowledge networks. Modern production networks embed firms within international innovation systems. Foreign investment supports "knowledge upgrading" by connecting domestic companies to global production and innovation networks, although outcomes depend on complementary institutions, such as education systems, R&D incentives and intellectual property protection.

Patent protection enables technology markets

International patent systems facilitate knowledge flows. Since the 1883 Paris Convention established priority rights across patent offices, international patent protection has become crucial for reaching foreign markets with new technologies.[42] The higher an invention's expected market value, the broader its patent protection and the more important the markets where inventors seek protection.[43]

Modern treaties have expanded access. International patent protection has expanded significantly since the 1970s through treaties such as WIPO's Patent Cooperation Treaty and regional agreements establishing the European Patent Office, African Regional Intellectual Property Organization and other regional systems. These developments have made it easier for inventors to protect innovations across multiple jurisdictions.

Patents enable technology trade. Patent protection in foreign markets facilitates international technology licensing and transfer agreements. These "markets for technology" improve overall welfare and innovation by enhancing innovation activity, knowledge diffusion and the emergence of specialized inventors. Patent trade stimulates the geographical spread of technology by enabling inventors to monetize their innovations globally.

Distance still creates barriers. Despite these mechanisms, uncertainty remains higher for international technology trade than for domestic transactions. Three types of uncertainty limit technology trade's geographical reach: uncertainty about property rights, about technology value and about trading processes.[44] This explains why geographical proximity still influences patent transactions and why technology flows remain concentrated among advanced economies.

Implications for the observed patterns

Multiple reinforcing channels favor innovation leaders. The patterns observed in patent citations, scientific sourcing and the reuse of breakthrough inventions reflect these multiple reinforcing diffusion channels. Innovation leaders like the United States, Western Europe and Japan benefit from advantages across all channels – they attract skilled migrants, engage in extensive international trade, host multinational companies and maintain effective patent protection systems.

Absorptive capacity explains persistent gaps. Developing economies' limited participation in rapid and intensive technology adoption reflects constraints across these channels. Lower absorptive capacity, weaker institutions, smaller trade volumes and limited skilled migration create cumulative disadvantages that persist over time.

Policy can strengthen diffusion channels. Understanding these mechanisms suggests that countries can enhance their participation in global knowledge flows by strengthening education systems, improving institutions, expanding trade integration, attracting skilled talent and developing effective intellectual property frameworks and institutions. The economies which have been most successful at catching up have typically improved across multiple channels simultaneously.

Key insights on global knowledge diffusion patterns

This chapter has examined how technological knowledge diffuses internationally by analyzing global patterns across multiple dimensions of innovation flows. Using patent citations, scientific references and the reuse of breakthrough inventions, the analysis has mapped where knowledge originates, how it spreads and which countries benefit most from international technological knowledge transfer.

Key findings reveal persistent but evolving patterns. Patent citation analysis shows that technological knowledge spreads faster today than 50 years ago, with international adoption times dropping by half since the 1970s. The gap between national and international knowledge flows has nearly disappeared, suggesting that geographical barriers are weakening. However, advanced economies like the United States, Western Europe and Japan dominate both as contributors and as beneficiaries of global knowledge flows, while most developing regions participate only marginally.

Scientific knowledge follows different diffusion patterns. Deep tech technologies based on scientific breakthroughs take much longer to develop – about 10 years from publication to first patent citation – but create more globally relevant technologies. Most science-to-technology flows are concentrated in a handful of leading economies, with the United States, Western Europe and Japan absorbing scientific knowledge from virtually all global sources. China has emerged as increasingly open to international science, showing the fastest growth in transnational scientific citations.

The trajectories of breakthrough inventions reuse reveal adoption capabilities. Analysis of breakthrough inventions reuse demonstrates that most countries primarily build on their own technological knowledge. However, innovation leaders excel at rapidly and intensively adopting foreign breakthroughs – the United States reuses 70 percent of Chinese-originated breakthrough inventions within five years, while China reuses less than 5 percent of US breakthrough inventions in the same timeframe. This asymmetry highlights critical differences in absorptive capacity.

Three main conclusions emerge from this chapter’s wide-ranging analysis:

- First, global innovation remains highly concentrated. Advanced economies still dominate knowledge flows, although emerging economies, particularly China, are playing an increasingly important roles. This concentration reflects advantages across multiple diffusion channels rather than single factors.
- Second, science is reshaping innovation geography. Scientific knowledge increasingly underpins breakthrough technologies, particularly in fast-moving fields. Countries that effectively combine global scientific inputs with local capabilities can gain competitive advantages in deep tech innovation.
- Third, diffusion benefits remain unequally distributed. Large parts of the developing world remain excluded from rapid technology adoption, despite producing knowledge that flows to advanced economies. Geographical proximity and technological affinity influence adoption patterns, but absorptive capacity ultimately determines successful knowledge integration.

Implications for policy and future research

For policymakers, these findings emphasize that accessing global knowledge flows requires more than openness – it demands sustained investments in education, research capabilities and institutional quality. Countries seeking to participate more actively in global innovation networks must strengthen their absorptive capacity across multiple dimensions simultaneously.

For researchers, the results highlight the value of analyzing multiple diffusion indicators together. Each measure – citations, scientific references, breakthrough inventions reuse – captures different aspects of how knowledge spreads internationally. Future work should explore the causal relationships between these different diffusion mechanisms and their combined effects on economic development and global competitiveness.

Notes

1 The content of this chapter is based on the background paper by Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: World Intellectual Property Organization.

2 See Comin, D.and Mestieri, M. (2014). Technology diffusion: Measurement, causes, and consequences. In *Handbook of Economic Growth*. Elsevier, 565–622, https://econpapers.repec.org/bookchap/eeegrochp/2-565.htm; and Comin, D. and Mestieri, M. (2018). If technology has arrived everywhere, why has income diverged? *American Economic Journal: Macroeconomics*, 10(3), 137–78, https://doi.org/10.1257/mac.20150175.

3 See Storper, M. and Venables, A.J. (2004). Buzz: Face-to-face contact and the urban economy. *Journal of Economic Geography*, 4(4), 351–70, https://doi.org/10.1093/jnlecg/lbh027; and Breschi, S. and Lissoni, F. (2009). Mobility of skilled workers and co-invention networks: An anatomy of localized knowledge flows. *Journal of Economic Geography*, 9(4), 439–68, https://doi.org/10.1093/jeg/lbp008.

4 Tobler (1970) defines the Law of Geography as "Everything is related to everything else, but near things are more related than distant things". Several studies (see Holl *et al*., 2024; Kalyani *et al*., 2025) find that this "law" is still current despite the progress of communication technologies. See Tobler, W.R. (1970). A computer movie simulating urban growth in the Detroit region. *Economic Geography*, 46, 234–40; Holl, A., Martínez, C. and Casado, C. (2024). The changing geography of innovation: Comparing urban, suburban and rural areas. *Growth and Change*, 55(4), e70003, https://doi.org/10.1111/grow.70003; and Kalyani, A., Bloom, N., Carvalho, M. *et al*. (2025). The diffusion of new technologies. *Quarterly Journal of Economics*, 140, 1299–1365, https://doi.org/10.1093/qje/qjaf002.

5 See Eaton, J. and Kortum, S. (1996). Measuring technology diffusion and the international sources of growth. *Eastern Economic Journal*, 22, 401–10.

6 More recently, Berkes *et al*. (2022) estimate the causal effect of innovation induced by international spillovers (measured by patent-to-patent citations) on sectoral output per worker and total factor productivity growth in a panel of country-sectors from 2000 to 2014, as well as on aggregate income per capita since 1960, finding a strong relationship. See Berkes, E., Manysheva, K. and Mestieri, M. (2022). Global Innovation Spillovers and Productivity: Evidence from 100 Years of World Patent Data. *FRB of Chicago Working Paper No. 2022-15*. Federal Reserve Bank of Chicago, https://doi.org/10.2139/ssrn.4106645.

7 Thompson and Fox-Kean (2005) revealed that the technological classes used in Jaffe et al (1993)'s matching procedure were too coarse, potentially conflating technological proximity with geographic proximity and invalidating their findings of localization. Thompson (2006) argued that citations added by applicants (including inventors and attorneys) are more likely to represent genuine knowledge flows than those added by patent examiners. This initiated a literature focused on disentangling citation origins. However, this applicant/examiner distinction is itself problematic: applicants often act strategically, sometimes withholding citations, while examiners outside the United States operate under different rules (Lampe, 2012). See, Jaffe, Adam B., Trajtenberg, M. and Henderson, R. "Geographic localization of knowledge spillovers as evidenced by patent citations." *The Quarterly Journal of Economics* 108, no. 3 (1993): 577–98. https://doi.org/10.2307/2118401; Lampe, R. (2012). Strategic citation. *The Review of Economics and Statistics*, 94(1), 320–33, https://doi.org/10.1162/REST_a_00159; Thompson, P. (2006). Patent citations and the geography of knowledge spillovers: Evidence from inventor- and examiner-added citations. *Review of Economics and Statistics*, 88(2), 383–88, https://doi.org/10.1162/rest.88.2.383; and Thompson, P. and Fox-Kean, M. (2005). Patent citations and the geography of knowledge spillovers: A reassessment. *The American Economic Review*, 95(1), 450–60.

8 Following the assumption that breakthrough technologies emerge when pre-existing components combine for the first time (Arthur, 2009; Fleming, 2001; Verhoeven *et al*., 2016), Pezzoni *et al*. (2022, 2023) use patent classification codes (e.g. IPC or CPC codes) in patent data to build proxies for the pre-existing components at the base of a technology. See Arthur, W.B. (2009). *The Nature of Technology: What It Is and How It Evolves*. Simon and Schuster; Fleming, L. (2001). Recombinant uncertainty in technological search. *Management Science*, 47(1), 117–32, https://doi.org/10.1287/mnsc.47.1.117.10671; Verhoeven, D., Bakker, J. and Veugelers, R. (2016). Measuring technological novelty with patent-based indicators. *Research Policy*, 45(3): 707–23; Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.html; and Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454

9 See Ahmadpoor, M. and Jones, B.F. (2017). The dual frontier: Patented inventions and prior scientific advance. *Science*, 357, 583–87; Arora, A., Belenzon, S. and Suh, J. (2021). Science and the Market for Technology, *NBER Working Paper Series No. 28534*, Cambridge, MA: National Bureau of Economic Research, https://doi.org/10.3386/w28534; Marx, M. and Fuegi, A. (2020). Reliance on science: Worldwide front-page patent citations to scientific articles. *Strategic Management Journal*, 41, 1572–94. https://doi.org/10.1002/smj.3145; and Marx, M. and Fuegi, A. (2022). Reliance on science by inventors: Hybrid extraction of in-text patent-to-article citations. *Journal of Economics & Management Strategy*, 31(2), 369–92. https://doi.org/10.1111/jems.12455.

10 See Martínez, C. (2011). Patent families: When do different definitions really matter? *Scientometrics*, 86, 39–63, https://doi.org/10.1007/s11192-010-0251-3; and Martinez, C. (2010). Insight into Different Types of Patent Families. *OECD Science, Technology and Industry Working Papers No. 2010/02*. Paris: OECD Publishing,https://doi.org/10.1787/5kml97dr6ptl-en

11 See, Hidalgo, C.A., Klinger, B., Barabási, A.-L. *et al*. (2007). The product space conditions the development of nations. *Science*, 317, 482–87; Bahar, D., Hausmann, R. and Hidalgo, C.A. (2014). Neighbors and the evolution of the comparative advantage of nations: Evidence of international knowledge diffusion? *Journal of International Economics*, 92(1), 111–23, https://doi.org/10.1016/j.jinteco.2013.11.001; Balland, P.-A., Boschma, R., Crespo, J. *et al*. (2018). Smart specialization policy in the European Union: Relatedness, knowledge complexity and regional diversification. *Regional Studies*, 1–17 ; and Petralia, S., Balland, P.-A. and Morrison, A. (2017). Climbing the ladder of technological development. *Research Policy*, 46, 956–69, https://doi.org/10.1016/j.respol.2017.03.012.

12 See Castaldi, C. (2020). All the great things you can do with trademark data: Taking stock and looking ahead. *Strategic Organization*, 18(3), 472–84, https://journals.sagepub.com/doi/full/10.1177/1476127019847835; Castaldi, C. and Drivas, K. (2023). Relatedness, cross-relatedness and regional innovation specializations: An analysis of technology, design, and market activities in Europe and the US. *Economic Geography*, 99, 253–84; and Castaldi, C., Abbasiharofteh, M. and Petralia, S. (2019). *From Patents to Trademarks: Towards a Concordance Map*. EPO-ARP Programme Report.

13 The emerging consensus is that citations are a flawed and institutionally mediated measure, and their interpretation requires careful consideration of the patent office and the strategic incentives of the actors involved. At the same time, there are not many other sources with such a wide international coverage and detailed unit record data. See Belenzon, S. and Schankerman, M. (2013). Spreading the word: Geography, policy, and knowledge spillovers. *The Review of Economics and Statistics*, 95, 884–903; Duguet, E. and MacGarvie, M. (2005). How well do patent citations measure flows of technology? Evidence from French innovation surveys. *Economics of Innovation and New Technology*, 14(5), 375–93, https://doi.org/10.1080/1043859042000307347; MacGarvie, M. (2005). The determinants of international knowledge diffusion as measured by patent citations. *Economics Letters*, 87(1), 121–26, https://doi.org/10.1016/j.econlet.2004.09.011; Murata, Y., Nakajima, R., Okamoto, R. *et al*. (2013). Localized knowledge spillovers and patent citations: A distance-based approach (revised version). *GRIPS Discussion Paper No. 12–18*. National Graduate Institute for Policy Studies; and Singh, J. and Marx, M. (2013). Geographic constraints on knowledge spillovers: Political borders vs. spatial proximity. *Management Science*, 59, 2056–78, https://doi.org/10.1287/mnsc.1120.1700.

14 See Griliches, Z. (1990). Patent statistics as economic indicators: A survey. *Journal of Economic Literature*, 28(4), 1661–707.

15 In Zvi Griliches own words: "It should be noted here that patent citations differ from usual scientific citations to the work of others in that they are largely the contribution of patent examiners whose task is to delimit the reach of the new patent and note the context in which it is granted. In that sense, the 'objectivity' of such citations is greater and may contribute to the validity of citation counts as indexes of relative importance. But in another sense, they are like citations added at the insistence of the editor; they may reflect the importance that is put in the field on particular papers but are not a valid indicator for channels of influence, for intellectual spillovers. On the other hand, they bring us closer to something that might be interpreted as measuring the social rather than just the private returns to these patents." See Griliches, Z. (1990). Patent statistics as economic indicators: A survey. *Journal of Economic Literature*, 28(4), 1669.

16 Some scholars have argued that citations added by applicants (including inventors and attorneys) are more likely to represent genuine knowledge flows than those added by patent examiners. See Thompson, P. (2006). Patent citations and the geography of knowledge spillovers: Evidence from inventor- and examiner-added citations. *Review of Economics and Statistics*, 88(2), 383–88, https://doi.org/10.1162/rest.88.2.383. Other scholars find the distinction between applicant and examiner citations is also problematic, as applicants can act strategically. See Lampe, R. (2012). Strategic citation. *The Review of Economics and Statistics*, 94(1), 320–33, https://doi.org/10.1162/REST_a_00159 and Box 2.1, note 7.

17 See Jaffe, A.B. and Trajtenberg, M. (1999). International knowledge flows: Evidence from patent citations. *Economics of Innovation and New Technology*, 8(1–2), 105–36, https://doi.org/10.1080/10438599900000006.

18 On the "new economics of science" and knowledge economy, see David, P.A. and Foray, D. (2002). An introduction to the economy of the knowledge society. *International Social Science Journal (NWISSJ)*, 54(171), 9–23, https://doi.org/10/b9t653; and Foray, D. (2004). *The Economics of Knowledge*. MIT Press.

19 Macroeconomic studies have linked gross domestic product (GDP) growth in the United States to higher levels of scientific employment, as well as to increased private and public expenditures on R&D. See Sveikauskas, L. (1981). Technological inputs and multifactor productivity growth. *The Review of Economics and Statistics*, 275–82; Adams, J.D. (1990). Fundamental stocks of knowledge and productivity growth. *Journal of Political Economy*, 98, 673–702; and Mansfield, E. (1995). Academic research underlying industrial innovations: Sources, characteristics, and financing. *The Review of Economics and Statistics*, 77(1), 55–65, https://doi.org/10.2307/2109992.

20 See the seminal work by Nelson, R.R. (1959). The simple economics of basic scientific research. *Journal of Political Economy*, 67, 297–306, https://doi.org/10.1086/25817; Nelson, R.R. and Winter, S.G. (1982). *An Evolutionary Theory of Economic Change*. Cambridge, MA: Belknap Press of Harvard University Press; and Rosenberg, N. and Nelson, R.R. (1994). American universities and technical advance in industry. *Research Policy*, 23, 323–48. See also WIPO (2022). *World Intellectual Property Report 2022: The Direction of Innovation*, Geneva: WIPO, https://www.wipo.int/publications/en/details.jsp?id=4594&plang=EN for a review.

21 Tijssen, R. J.W. (2002). Science dependence of technologies: Evidence from inventions and their inventors, *Research Policy*, 31(4), 509–26, https://doi.org/10.1016/S0048-7333(01)00124-X.

22 See Balland, P.-A. and Boschma, R. (2022). Do scientific capabilities in specific domains matter for technological diversification in European regions? *Research Policy*, 51(10), 104594, https://doi.org/10.1016/j.respol.2022.104594; Catalán, P., Navarrete, C. and Figueroa, F. (2022). The scientific and technological cross-space: Is technological diversification driven by scientific endogenous capacity? *Research Policy*, Special Issue on Economic Complexity, 51(8), 104016, https://doi.org/10.1016/j.respol.2020.104016;. Hausmann, R., Yildirim, M.A., Chacua, C. *et al*. (2024). Innovation Policies under Economic Complexity.*WIPO Economic Research Working Papers No. 79*. Geneva: WIPO; Pugliese, E., Cimini, G., Patelli, A. *et al*. (2019). Unfolding the innovation system for the development of countries: Coevolution of science, technology and production. *Scientific Reports*, 9(1), 1, https://doi.org/10.1038/s41598-019-52767-5; and Stojkoski, V., Koch, P. and Hidalgo, C.A. (2023). Multidimensional economic complexity and inclusive green growth. *Communications Earth & Environment*, 4(1), 1–12, https://doi.org/10.1038/s43247-023-00770-0.

23 See Ahmadpoor, M. and Jones, B.F. (2017). The dual frontier: Patented inventions and prior scientific advance. *Science*, 357, 583–87; Arora, A., Belenzon, S., Cioaca, L.C. *et al*. (2023). The Effect of Public Science on Corporate R&D. *NBER Working Paper Series No. 31899*. Cambridge, MA: National Bureau of Economic Research, https://doi.org/10.3386/w31899; Lissoni, F., Montobbio, F. and Zirulia, L. (2013). Inventorship and authorship as attribution rights: An enquiry into the economics of scientific credit. *Journal of Economic Behavior & Organization*, 95, 49–69, https://doi.org/10.1016/j.jebo.2013.08.016; Maraut, S. and Martínez, C. (2014). Identifying author–inventors from Spain: Methods and a first insight into results. *Scientometrics*, 101, 445–76, https://doi.org/10.1007/s11192-014-1409-1; Marx, M. and Fuegi, A. (2020). Reliance on science: Worldwide front-page patent citations to scientific articles. *Strategic Management Journal*, 41, 1572–94, https://doi.org/10.1002/smj.3145; Marx, M. and Fuegi, A. (2022). Reliance on science by inventors: Hybrid extraction of in-text patent-to-article citations. *Journal of Economics & Management Strategy*, 31(2), 369–92, https://doi.org/10.1111/jems.12455; OECD (2023). *Artificial Intelligence in Science: Challenges, Opportunities and the Future of Research*. Paris: Organisation for Economic Co-operation and Development; and Stephan, P.E. (1996). The economics of science. *Journal of Economic Literature*, 34, 1199–235.

24 Motohashi, K., Koshiba, H. and Ikeuchi, K. (2024). Measuring science and innovation linkage using text mining of research papers and patent information. *Scientometrics*, 129, 2159–79.

25 See Jones, B.F. (2009). The burden of knowledge and the "Death of the Renaissance Man": Is innovation getting harder? *Review of Economic Studies*, 76(1), 283–317, https://doi.org/10.1111/j.1467-937X.2008.00531.x; Wuchty, S., Jones, B.F. and Uzzi, B. (2007). The increasing dominance of teams in production of knowledge. *Science*, 316, 1036–39, https://doi.org/10.1126/science.1136099; and WIPO (2019). *World Intellectual Property Report 2019: The Geography of Innovation –Global Hotspots, Local Networks* Geneva: WIPO, https://www.wipo.int/publications/en/details.jsp?id=4467&plang=EN.

26 See Sorenson, O. and Fleming, L. (2004). Science and the diffusion of knowledge. *Research Policy*, 33(10), 1615–34, https://doi.org/10.1016/j.respol.2004.09.008; and Gazni, A. (2020). The growing number of patent citations to scientific papers: Changes in the world, nations, and fields. *Technology in Society*, 62, 101276, https://doi.org/10.1016/j.techsoc.2020.101276.

27 See Roach, M. and Cohen, W.M. (2013). Lens or prism? Patent citations as a measure of knowledge flows from public research. *Management Science*, 59(2), 504–25, https://doi.org/10.1287/mnsc.1120.1644.

28 See a discussion in Meyer, M. (2000). Does science push technology? Patents citing scientific literature. *Research Policy*, 29(3), 409–34, https://doi.org/10.1016/S0048-7333(99)00040-2.

29 See Pezzoni, M., Veugelers, R. and Visentin, F. (2023). Technologies Fly on the Wings of Science. *MERIT Working Papers 2023-036*, United Nations University – Maastricht Economic and Social Research Institute on Innovation and Technology (MERIT), https://ideas.repec.org//p/unm/unumer/2023036.html; and Pezzoni, M., Veugelers, R. and Visentin, F. (2022). How fast is this novel technology going to be a hit? Antecedents predicting follow-on inventions. *Research Policy*, 51(3), 104454, https://doi.org/10.1016/j.respol.2021.104454.

30 More recent scientific papers have had less time to collect patent citations. For further details, see Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*, Geneva: WIPO.

31 See Jaffe, A.B., Trajtenberg, M. and Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *The Quarterly Journal of Economics*, 108(3): 577–98, https://doi.org/10.2307/2118401.

32 See Rogers, E.M., Singhal, A. and Quinlan, M.M. (2014). Diffusion of innovations. In Stacks, D.W. and Salwen. M.B. (eds), *An Integrated Approach to Communication Theory and Research*. Routledge; and Rogers, M. (1998). The Definition and Measurement of Innovation. *Melbourne Institute Working Paper No. 10/98*. Melbourne Institute of Applied Economic and Social Research.

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34 See Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2025).The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

35 For a recent survey, see Keller, W. (2021). Knowledge Spillovers, Trade, and FDI. *NBER Working Paper Series No. 28739*. Cambridge, MA, National Bureau of Economic Research, https://doi.org/10.3386/w28739. See also Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

36 Early contributions to the topic correspond to Grossman and Helpman (1995) as well as Coe *et al*. (1997). Grossman, G.M. and Helpman, E. (1995). Technology and trade. In Grossman, G.M. and Rogoff, K. (eds), *Handbook of International Economics*, 3, 1279–337; Coe, D.T., Helpman, E. and Hoffmaister, A.W. (1997). North–South R&D spillovers. *The Economic Journal*, 107, 134–49, https://doi.org/10.1111/1468-0297.00146.

37 Ayerst *et al*. (2023) investigate how technology spreads across borders through imported goods. Using patents, citations, trade and input–output data, they track knowledge embodied in imports from the United States. Their analysis shows that innovation is still heavily concentrated in advanced economies, but imports can transmit technology internationally. They find that when countries import inputs rich in knowledge, their patenting activity rises noticeably, while imports measured only by production value have a much smaller effect. The same pattern holds for diffusion outcomes: knowledge-intensive imports significantly boost links to US inventions, whereas production-weighted imports matter far less. In short, the study highlights trade in knowledge-embedded goods as a powerful driver of global technology diffusion. Ayerst, S., Ibrahim, F., MacKenzie, G. *et al*. (2023). Trade and diffusion of embodied technology: An empirical analysis. *Journal of Monetary Economics* 137, 128–145.

38 From the spread of Huguenot craftsmen in early modern Europe to the forced migration of Jewish scientists to the United States during the 1930s. See Hornung, E. (2014). Immigration and the diffusion of technology: The Huguenot diaspora in Prussia. *American Economic Review*, 104(1), 84–122, https://doi.org/10.1257/aer.104.1.84; Scoville, W.C. (1951). Minority migrations and the diffusion of technology. *The Journal of Economic History*, 11(4), 347–60; and Moser, P., Voena, A. and Waldinger, F. (2014). German Jewish émigrés and US invention. *American Economic Review*, 104, 3222–55, https://doi.org/10.1257/aer.104.10.3222.

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41 Keller, W. (2010). International trade, foreign direct investment, and technology spillovers. In Hall, B.H. and Rosenberg, N. (eds), *Handbook of the Economics of Innovation*. Elsevier, 793–829.

42 Harhoff, D., Scherer, F.M. and Vopel, K. (2003). Citations, family size, opposition and the value of patent rights. *Research Policy*, 32(8), 1343–63, https://doi.org/10.1016/S0048-7333(02)00124-5; Martínez, C. (2011). Patent families: When do different definitions really matter? *Scientometrics*, 86, 39–63, https://doi.org/10.1007/s11192-010-0251-3; and Martinez, C. (2010). Insight into Different Types of Patent Families. *OECD Science, Technology and Industry Working Papers No. 2010/02*. Paris: OECD Publishing, https://doi.org/10.1787/5kml97dr6ptl-en.

43 Putnam, J.D. (1996). The Value of International Patent Rights. Yale University: PhD dissertation.

44 Arora, A. and Gambardella, A. (2010). The market for technology. In Hall, B.H. and Rosenberg, N. (eds), *Handbook of the Economics of Innovation*, Vol. 1. Elsevier, 641–78.

3 Technology diffusion in agriculture

Technological diffusion in agriculture can transform farms and livelihoods worldwide. This chapter focuses on two agricultural technologies, genetically modified crops and precision agriculture technologies, to identify factors that facilitate their diffusion and barriers that slow their adoption across countries and farms. The chapter shows that while modern tools can boost productivity, profits, and sustainability, uneven access risks widening gaps between countries and between large and small farms.

Introduction

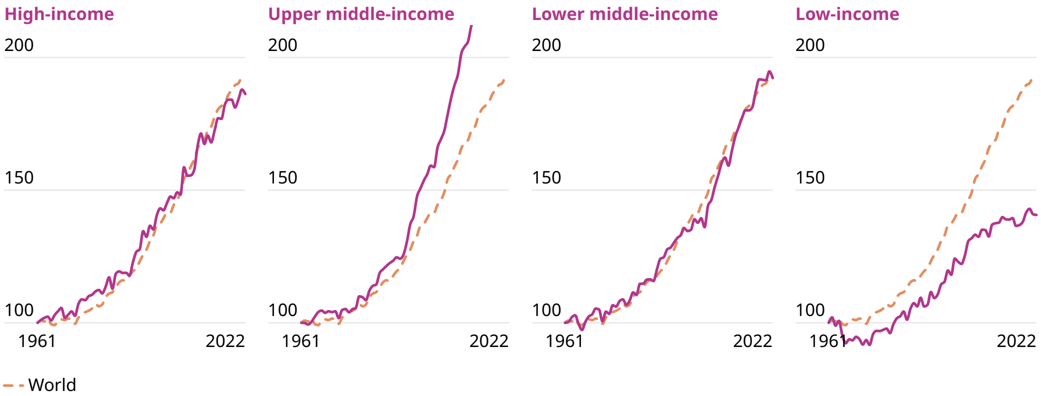
Advances in agriculture have played a major role in reducing poverty, improving food security, and raising living standards around the world.[1] New crop varieties, better farming tools, and improved practices have helped farmers grow more food and earn more income. One study found that adoption of improved food crop varieties has generated economic welfare gains of USD 213 per hectare each year in countries across Asia, Africa and Latin America.[2] Another study estimated that modern crop varieties increased the value of agricultural production in Sub-Saharan Africa by USD 6.2 billion annually and boosted regional productivity by 47 percent over three decades from 1980 to 2010.[3]

These improvements are part of a wider trend where global agriculture is becoming more productive. One way of measuring this productivity is total factor productivity (TPF). TFP compares how much output farmers produce with the amount of land, labor, machinery, and other inputs they use.[4] When TFP grows, farmers produce more output from the same bundle of inputs. This reflects technological progress, which includes improvements in input quality, better management practices, and institutional changes.[5] It represents an efficiency gain in how agricultural resources are allocated and used.

Since 2000s, global agricultural TFP grew by nearly 2 percent per year.[6] Some countries have made fast progress, while others have seen slower gains. Since productivity often grows when farmers adopt new technologies, the gap between high-performing and low-performing countries suggests that technologies have spread unevenly (see Figure 3.1).[7] If this difference continues, it risks widening the productivity divide between the richer and poorer economies.

Agricultural productivity is growing, but at an uneven pace across income groups

Figure 3.1 Average TFP growth by income group, 1961–2022 (baseline = 1961)



Notes: TFP (total factor productivity) is estimated by the ratio of agricultural outputs to the resources (land, labor, capital, and inputs such as seeds and fertilizers) used to produce them.

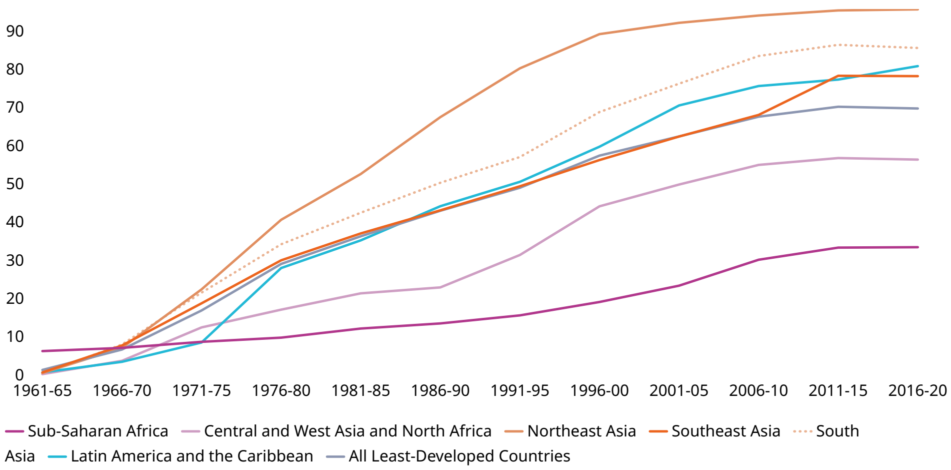
Source: USDA (2024). International Agricultural Productivity, October. U.S. Department of Agriculture, https://www.ers.usda.gov/data-products/international-agricultural-productivity.

In addition, farmers face constant challenges in maintaining and increasing crop yields due to pests, diseases, and climate change. Thus, consistent adoption of improved crop varieties is essential. Figure 3.2 shows how farmers in developing economies across Asia, Africa, and Latin America and the Caribbean have adopted new crop varieties over the period 1961–2020, regardless of whether the improvements were developed by public research institutions, universities, or private companies.

More importantly, the figure tells a similar story on the uneven adoption of new technologies. In particular, countries in Sub-Saharan Africa are lagging significantly behind other regions in adopting improved crop varieties.

Farmers in Sub-Saharan Africa lag behind others in adopting improved crop varieties

Figure 3.2 Share of improved crop varieties adoption by region, 1961–2020



Notes: New improved crop varieties include those from all types of technology source. Crops with GM technology were introduced in the mid-1990s.

Source: Fuglie, K.O. and Echeverria, R.G. (2024). The Economic Impact of CGIAR-related Crop Technologies on Agricultural Productivity in Developing Countries, 1961–2020. *World Development*, 176, 106523. https://doi.org/10.1016/j.worlddev.2023.106523.

These patterns raise two important questions. Firstly, why do some countries adopt new agricultural technologies more quickly than others? And secondly, what conditions help the technologies spread?

This chapter examines how agricultural technologies spreads across countries and what drives their adoption. It focuses on two major modern technologies, namely crops with genetically modified (GM) technologies and precision agriculture technologies (PATs).[8] These technologies can increase farmers' profits and help them use water, fertilizer, seeds, and land more efficiently. They also come with unique questions about intellectual property (IP) and data uses.

The section that follows examines what factors determine how agricultural technologies are diffused. It shows that successful diffusion requires interaction between three factors: namely, decisions made by farmers (demand-side), the innovation ecosystem producing the technology (supply-side), and the enabling environment. The third section of this chapter expands on the role of IP.

Three main lessons emerge. First, technology does not spread automatically. Farmers' characteristics, national innovation capabilities, infrastructure, and policy choices all play a role. Second, many different factors affect adoption. Farm size is one example. Larger farms often adopt new technologies faster than smaller farms. Third, IP plays a complex role. It encourages private companies to invest in developing new technologies, but it can also affect affordability and availability in different ways depending on the country and technology.

Determinants of technology diffusion in agriculture

Many factors shape how agricultural technologies spread. These factors can be loosely categorized into three connected elements: demand-side factors, supply-side factors, and the enabling environment. Demographic shifts, pest and disease outbreaks, and consumer preferences also influence adoption and dis-adoption.

Demand-side factors: farmer decisions

Factors that influence a farmer's willingness to pay for new technologies are demand-side factors. Farmers face uncertainty regarding the performance of new crops, therefore have to weigh the upfront costs, learning requirements, financing constraints and market signals against the expected returns.

Farmers are willing to pay for new technologies, even if more costly, when they are shown to outperform what they currently have.

Supply-side factors: innovation capabilities

Agricultural technologies are agro-ecological and context specific. This is where the supply-side factors influencing technology diffusion are important. Strong innovation ecosystems are able to adopt, adapt and generate new technologies for local conditions.

Figures 3.3a and 3.3b show that advanced economies benefit the most from the diffusion of new to the world type of innovation and scientific knowledge. Northern America and Europe, followed closely by Asia, are the leading beneficiaries of technology diffusion in agriculture. These three regions produce 75 percent of new agricultural technologies based on novel patented technologies and nearly 95 percent based on novel scientific knowledge.[9]

Advanced economies lead in the absorption and reuse of novel agricultural technologies worldwide

Figure 3.3a Share of new patented agricultural technologies at destination that cite novel technologies from origin by region, 1985–2022

	To Africa	To Asia	To Europe	To LAC	To Northern America	To Oceania
From Africa		33.3%	33.3%		33.3%	
From Asia	3.6%	24.3%	26.3%	8.0%	26.3%	11.6%
From Europe	3.5%	23.2%	26.9%	5.9%	25.8%	14.7%
From LAC	3.2%	22.6%	22.6%	9.7%	22.6%	19.4%
From Northern America	3.5%	22.9%	25.8%	7.9%	25.9%	14.0%
From Oceania	1.1%	21.1%	25.6%	7.8%	25.6%	18.9%
Share of total (at destination)	3.4%	23.1%	26.3%	7.1%	25.9%	14.3%

Source: Miguelez, E. , Pezzoni, M., Visentin, F.*et al*. (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

… and for novel scientific knowledge worldwide

Figure 3.3b Share of new patented agricultural technologies at destination that cite novel scientific knowledge from origin by region, 1985–2022

	To Africa	To Asia	To Europe	To LAC	To Northern America	To Oceania
From Africa	2.8%	12.9%	41.2%	2.3%	38.1%	2.8%
From Asia	0.4%	27.5%	28.5%	1.5%	39.2%	2.9%
From Europe	0.5%	13.0%	39.6%	1.5%	42.3%	3.2%
From LAC	0.9%	12.7%	36.3%	11.5%	35.6%	3.1%
From Northern America	0.3%	12.3%	28.2%	1.5%	54.6%	3.0%
From Oceania	0.6%	12.3%	30.6%	2.2%	40.0%	14.3%
Share of total (at destination)	0.4%	14.8%	32.2%	1.7%	47.5%	3.4%

Notes: LAC = Latin America and the Caribbean. Blank indicates no data.

Source: Miguelez, E. , Pezzoni, M., Visentin, F.*et al*. (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

Enabling environment: institutions, markets and infrastructure

Supportive policies reduce risks and transaction costs in the diffusion of appropriate technologies. Infrastructure, functioning markets and appropriate IP frameworks enable diffusion. In addition, evidence shows that support for trusted intermediaries, such as extension services, farmer networks, suppliers, and cooperatives, play an important role in facilitating the use of new technologies.[10] They also help train and equip farmers with the advanced and specialized knowledge required to use them.[11]

Diffusion varies according to the technology

The local adaptation needs of crops with GM traits and the modularity of PATs drive their respective diffusion patterns.

Genetically modified crops

GM crops are plant varieties that scientists have genetically altered using genes taken from other species, or by synthetic construct, in order to make crops more robust and tolerant of specific farming challenges. Scientists can modify crops to resist pests, tolerate herbicide, extend shelf life, and/or produce higher yields, to name a few of the commonly found GM traits.

GM technologies must first be adapted to the local agro-ecological conditions through local R&D before they can be adopted by farmers.[12] This implies combining the genetically modified traits with local high-performance plant varities, which are then tested in local conditions to ensure stability (in the expression of the trait introduced) and for yield performance, and finally sent for regulatory approval for cultivation in the country concerned.[13]

Developing new crops can be lenghty. One study found that it can take about seven to ten years to develop stable lines using conventional breeding technique for fruits. [14]. For GM technology, it takes an average of 16.5 years to discover, develop and get authorization to sell crops with new (GM) trait, depending on the crop type.[15]

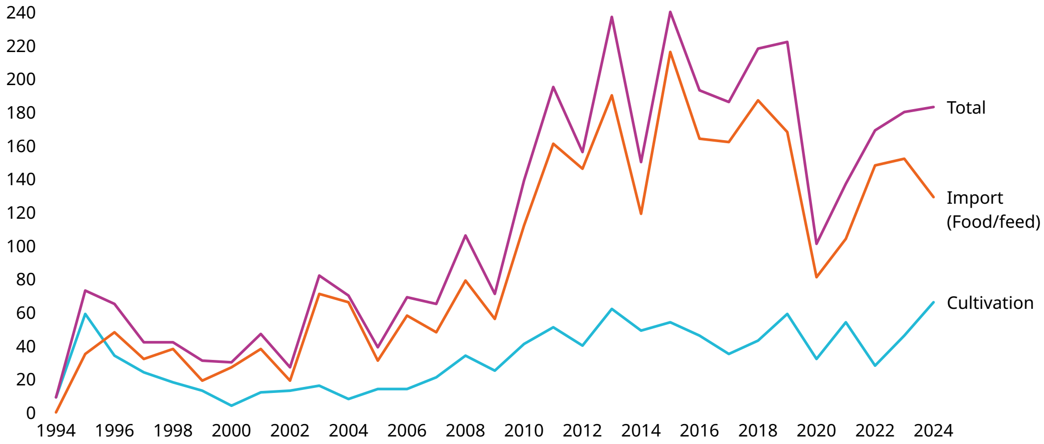
Institution/regulation: Regulation shapes the diffusion of GM crop technologies. Most countries regulate both the farming and the importation of crops with GM traits. Crops with GM technology must first be approved by the regulators before importation or cultivation.

Approval assures food safety and environmental protection of the locally adapted GM crop for consumption and cultivation.

However, obtaining regulatory approval can be expensive. Developing a crop with GM traits from discovery to commercialization costs USD 64.2 million on average. Regulatory approval per country costs an additional USD 43.2 million, which accounts for 37.6 percent of the total cost (i.e., from discovery to commercialization to regulatory approval).[16]

Regulatory approvals for GM crop cultivation suggest adaptation efforts

Figure 3.4 Total count of regulatory approval events for crops with GM traits worldwide by year, 1994-2024



Source: de Grazia, C., Rada, N., and Graff, G. (2026). Diffusion of Genetically Modified Crop Technology. *WIPO Economic Research Working Paper Series No. 93*. Geneva: WIPO.

Figure 3.4 shows more approvals for GM crop importation than for cultivation. This suggests that countries may be more willing to import GM crops than to allow farmers to grow them domestically. However, several countries have simplified the approval process whereby approval extends to both importation and cultivation, including Argentina and South Africa.

Regulatory approval does not guarantee adoption by farmers in a country. Pricing, input availability, farmer awareness, and infrastructure also matter.

Availability: Countries with strong innovation ecosystems are more likely to generate, adapt and adopt GM technologies for their local agro-ecological conditions. Argentina, Brazil, Canada, India and the United States are the largest adopters of GM technologies.[17] They also have strong innovation ecosystems, which consist of a private sector and a national agriculture research system (NARS), as well as universities.

Affordability: Crops, trees and plants with GM technologies tend to be more expensive in comparison to improved varieties developed using conventional seed technology. Nevertheless, farmers might be convinced to purchase the more expensive GM technology if the expected profit outweighs the cost (see Table 3.1 for comparison of GM trait seed's technology costs and the average gross farm income from using the seed for cotton, soybean and maize crops).

GM seed prices may be higher than conventional seeds, but the expected benefits are even higher

Table 3.1 Comparison of the technology cost and average gross farm income benefit for selected GM crops and countries, USD ($) per hectare

	GM HT cotton		GM HT soybean (1st gen)		GM HT maize	
Country	**Cost of technology ($/ha)**	**Ave. gross farm income benefit ($/ha)**	**Cost of technology ($/ha)**	**Ave. gross farm income benefit ($/ha)**	**Cost of technology ($/ha)**	**Ave. gross farm income benefit ($/ha)**
Argentina	10–30	48.4	2–4	22.6*	13–33	101.9
Brazil	26–54	53.1	7–25	32.4	10–32	21.6
Canada			20–48	20.6	17–35	12.4
Colombia	34–96		63.7		14–24	14.2
Mexico	29–79	297	20–47		40	
Paraguay			4–10	16.6*	11–17	2.4
South Africa	12–32	31.9	2–30	9.4	9–18	4.9
United States	13–82	16.2	15–57	33.5	15–30	30.5
Uruguay			2–4	22.5	6–17	2.8

Notes: HT = herbicide tolerant. * Includes second crop benefits of USD 294/ha for Argentina, and USD 311/ha for Paraguay.

Source: Brookes, G. (2022). Farm Income and Production Impacts from the Use of Genetically Modified (GM) Crop Technology 1996-2020. *GM Crops & Food*,13(1), 171–95.https://doi.org/10.1080/21645698.2022.2105626.

Another cost farmers take into consideration is the price and availability of plant protection products. In Kenya, a survey of farmers on the adoption of hybrid maize and fertilizers found that changes in the price and availability of these inputs played an important role in determining whether they adopted the technologies or not.[18]

Awareness and training: Farmer extension services and stewardship programs play an important role in demonstrating the efficacy GM crops to farmers and helping maintain the performance of the crops over its life cycle.[19] This is because crops with GM traits can lose integrity over time. Training programs are often organized in collaboration with firms, local public research institutions, regulators, and farmers and farmers' associations.[20]

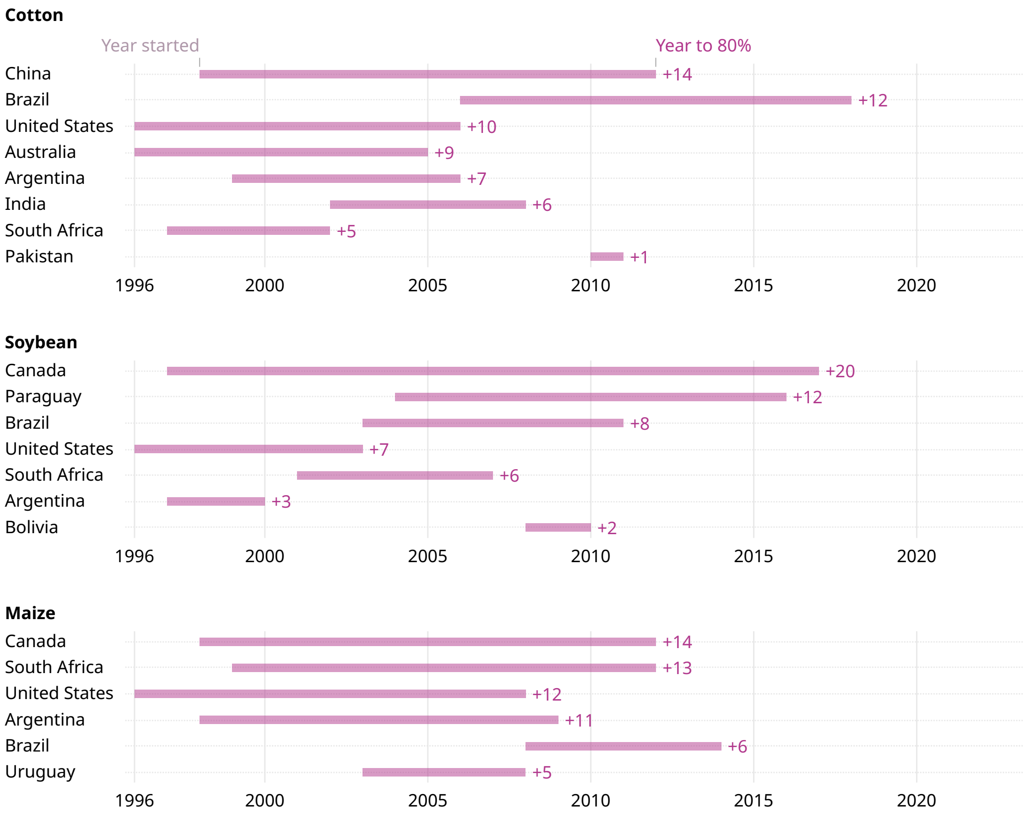
Familiarity with technology increases the speed of adoption. In India, farmers familiar with hybrid cotton cultivation adopted GM cotton faster. This same pattern was also seen in the case of China, Mexico and the US.

Infrastructure: Access to seeds with GM traits is important for farmers in rural areas. Kenya's poor infrastructure, namely access to and availability of seed and fertilizer distributors, has contributed to a low adoption rate for hybrid maize and fertilizer among farmers, even when the estimated gross returns to adopting the technology were high.[21]

Figure 3.5 shows how long it took for specific crops with GM technology to achieve widespread diffusion within selected countries, defined as 80 percent cultivation of the cropland. While the United States developed the GM technology, some developing economies reached widespread adoption faster, such as GM cotton in South Africa, GM soybean in Argentina and GM maize in Brazil.

Speed of GM crop technology adoption varies across countries and crop type

Figure 3.5 Time to widespread adoption (80 percent cropland) of GM crop technology for selected countries and crop types, 1996–2023



Notes: Argentina and Pakistan informally adopted GM crops earlier than recorded here.

Source: de Grazia, C., Rada, N. and Graff, G. (2026). Diffusion of Genetically Modified Crop Technology. *WIPO Economic Research Working Paper Series No. 93*. Geneva: WIPO.

Several factors can explain this. In Argentina, local pricing, input availability and institutional support help explain why its farmers were able to adopt the GM technologies quickly.[22] South Africa's streamlined regulatory approval process on GM technology could explain why it was relatively quick to approve and subsequently cultivate GM cotton. In addition, some farmers had access to the GM seeds informally. In Brazil, for example, farmers imported GM seeds even before the Brazilian national regulatory gave their approval.

Meanwhile, consumer hesitation and regulatory caution slowed the adoption of GM technologies in the United States, particularly in the case where the GM crops were meant for food.

Precision agriculture technologies

PATs use sensors, satellite navigation, and data analytics to optimize farming operations. In general, there are three broad categories for PATs: (i) the data collection (sensors, satellite navigation), (ii) the data processing and/or analysis (yield monitoring, soil mapping), and (iii) the decision-making guidance (auto-steering tractors, variable-rate applications of fertilizers and pesticides).[23]

Farmers in Australia, Canada, Europe and the United States lead in the adoption of PATs.[24]

The US pioneered PATs in the 1980s, with adoption accelerating once global positioning systems (GPS) became widely available after 1983.[25] Most of the technologies used were related to grid sampling, fertilizer mapping, and pH as well as yield measurement. Since the 2000s, American farmers have been adopting auto-guidance system and variable rate technologies (VRTs) to reduce the cost of managing their farms.[26]

However, the adoption of PATs remains gradual. Studies show that farmers typically adopt individual PAT components rather than a complete system.[27] This is partly due to the high upfront cost of purchasing PATs.

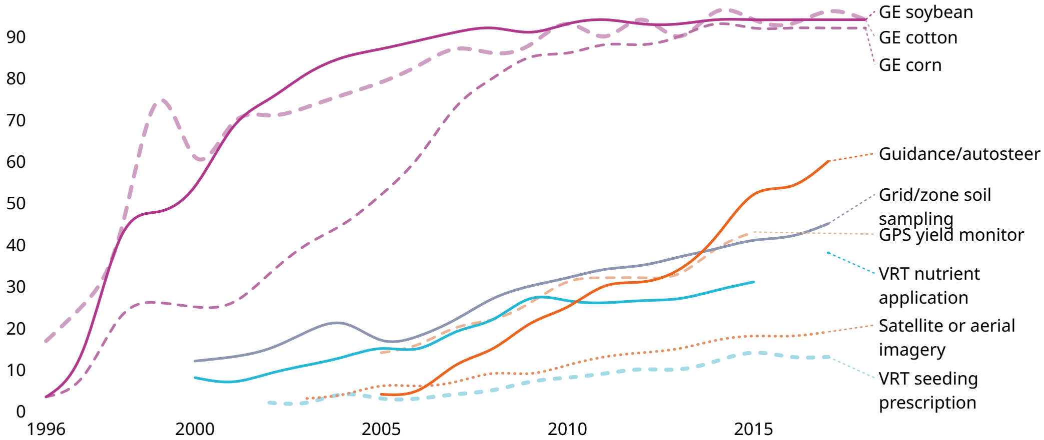
Less than one-third of US farmers use any PAT tools whatsoever and adoption occurs in modules rather than complete systems.[28] In Europe, for example, entry level PATs include automatic milking systems, digital field records and automatic steerage systems.[29]

In addition, the PATs predominantly adopted vary according to agricultural need. Water scarcity led to the adoption of micro-irrigation in India, for example, whereas farmers in the US and Australia focus more on adopting guidance systems for large-scale cropping.

Figure 3.6 illustrates how farmers in the US are slower at adapting PATs in comparison to GM crops. It also shows how farmers can adopt the PAT in separate components, such as auto-guidance and VRTs.

American farmers adopt PATs more gradually than they adopt crops with GM technology

Figure 3.6 Share of agricultural technology adoption by US farmers for selected GM technology and PAT components, 1996–2018



Notes: GE = genetically engineered, GM = genetically modified, PAT = precision agriculture technology, VRT = variable rate technology.

Source: Alston, J. M., P. G. Pardey, P.G., Serfas, D.*et al.* (2023). Slow Magic: Agricultural versus Industrial R&D Lag Models. *Annual Review of Resource Economics,* 15(1), 471–93. https://doi.org/10.1146/annurev-resource-111820-034312 .

Availability: Due to the modularity of PATs, compatibility with existing as well as new machinery matters. Farmers risk being locked into a single vendor ecosystem without interoperability standards.

Affordability: Cost and complexity are key barriers to PAT adoption. PATs require upfront investments in hardware, software and connectivity. Table 3.2 compares the cost of using three different mapping technologies to analyze crop health and manage plant protection inputs accordingly for vineyard crops. It shows the different PAT components needed: a platform, sensing device and a satellite navigation system corrector (RTK-GNSS) across the technologies. Regardless of their farm size, farmers face costs starting at over EUR 16,500 to implement any one of these mapping technologies. Yet, as shown in Table 3.2, the per-unit cost of adopting any of these technologies declines as farm size increases.

High fixed cost of PATs limits adoption

Table 3.2 Cost of mapping systems to assess vegetation characteristics, Euro (€)

	LiDAR-based (€)	Kinect-based (€)	UAV (€)
System cost			
Platform	8,000	8,000	1,500
Sensing devices	2,500	165	Integrated
RTK-GNSS	1,500	15,000	15,000
Total fixed cost	**25,500**	**23,165**	**16,500**
Costs (per ha)			
Sampling cost	23	23	3
Processing cost	33	30	27
Fuelling cost	1	1	0
Depreciation (0.1% material)	−11	−8	−2
Maintenance	2	2	1
Other costs (per ha)			
Variable-rate applicator cost	30	30	30
Mapping cost	73	68	33
Personnel cost	22	22	22
Total variable cost (per ha)	**173**	**168**	**114**
Total cost (2 ha)	25,847	23,499	16,728
Cost per ha (2 ha)	**12,923**	**11,750**	**8,364**
Total cost (20 ha)	28,968	26,514	18,775
Cost per ha (20 ha)	**1,448**	**1,326**	**939**
Total cost (200 ha)	60,178	56,655	39,248
Cost per ha (200 ha)	**301**	**283**	**196**

Notes: LiDAR = light detection and ranging, RTK-GNSS = real-time kinematic global navigation satellite system, UAV = unmanned aerial vehicle. The costs of mapping are associated with the platform, sensing devices, operating personnel for data acquisition and data processing and the depreciation and maintenance of the operating devices.

Source: Andújar, D., Moreno, H., Bengochea-Guevera, J. M. *et al.*. (2019). Aerial Imagery or On-ground Detection? An Economic Analysis for Vineyard Crops. *Computers and Electronics in Agriculture* 157, 351–58. https://doi.org/10.1016/j.compag.2019.01.007.

In some countries, farmers have abandoned using PATs because of a lack of profitability.[30]

Awareness and training: Skills and training influence the use of PATs. A survey of farmers in Europe found PATs not to be user-friendly and this and a lack of support in using the technologies are two of the main barriers to adoption.[31]

Nevertheless, those farmers who have adopted certain entry-level PATs are more likely to adopt other PAT components. For example, the widespread adoption of GPS for auto-steering tractors can also be used to guide agricultural input applications, such as variable rate fertilizers. This probably explains why variable rate fertilizer technology has only been modestly adopted.[32]

Infrastructure: Infrastructure limits the adoption of PATs. This agricultural technology is highly dependent on the physical and digital infrastructure present within a given country, such as having reliable electricity and cellular or satellite connectivity for data flows.

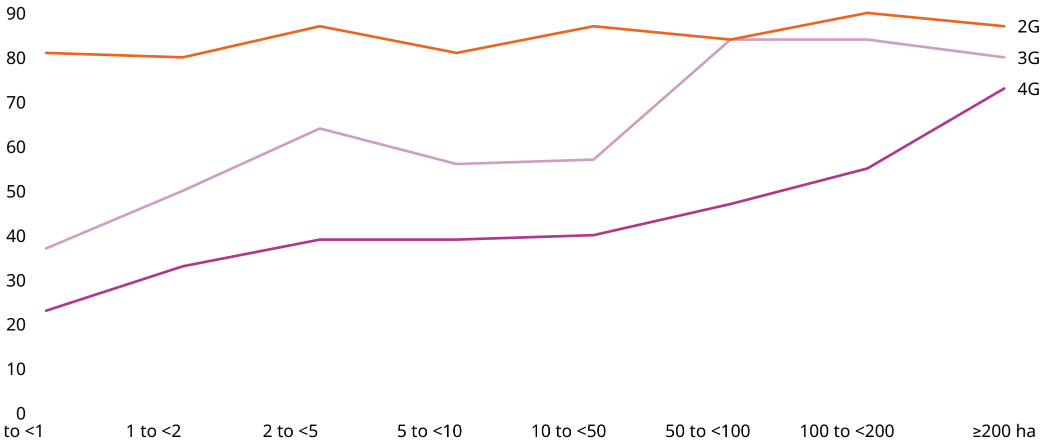
PATs that rely on the latest broadband and wireless technology 5G will not work in areas where the electrical and digital connectivity is weak.[33] For example, European farms located in areas with poor connectivity are between 40 and 60 percent less likely to adopt data-intensive PAT systems.[34]

Figure 3.7 illustrates the infrastructure challenge globally. Most large farms have access to 4G connectivity, whereas the majority of small farms are connected to the older technology, 2G.

The spread of mobile technologies can facilitate access to PAT, especially when tailored to digital connectivity constraints. India, for example, is investing in R&D to adapt PATs for local farmers in regions with weak digital connectivity.

Most small farms are connected to 2G digital technology

Figure 3.7 Data coverage by cellular technology type across different farm sizes



Source: Mehrabi, Z., McDowell, M.J., Ricciardi V. *et al*. (2021). The Global Divide in Data-driven Farming. *Nature Sustainability*, 4(2), 154–60. https://doi.org/10.1038/s41893-020-00631-0.

Diffusion varies according to farm size

Large farms adopt GM crops and PAT faster than their small-sized counterparts because they are abe to spread fixed costs over more output and have better access to finance and information.[35]

By contrast, small farms face credit constraints, higher per unit costs, and lack awareness of new technologies and their use. These factors affect profitability and increase the risks and uncertainty that arise from adopting new technologies.

Most farms worldwide are small-sized

Figure 3.8 Global shares of farms by size and farming area

Note: Small-sized farms are defined as farms operating on an area less than 2 hectares. The sample consists of 92 countries, which represents 80% of world's farms.

Source: Lowder, S.K., Sánchez, M.V. and Bertini, R. (2021). Which Farms Feed the World and has Farmland Become More Concentrated? *World Development*, 142(June), 105455. https://doi.org/10.1016/j.worlddev.2021.105455.

This divide is present within countries, especially in relation to PATs. Large farms in Australia and the US report a higher usage of guidance auto steering due to their farms requiring large-scale cropping. Ten percent of large farms in Argentina, occupying 78 percent of total agricultural land, use advanced PATs.

A similar pattern appears in other regions.[36] In South Africa, for example, small farms face more barriers to the adoption of new technologies than do their larger counterparts. Costs, access, and their suitability for the context are some of the factors preventing smallholders from adopting new technologies.

Globally, small farms – less than two hectares – are the majority by number, but occupy only a small share of total farmland.[37] Figure 3.8 shows the distribution of farm sizes across regions. Most farms are small-sized across all regions, defined as farms occupying less than 2 hectares of land.

Technological disparity across farm sizes affects lower income farmers disproportionately. Table 3.3 summarizes the different determinants of GM and PATs technology diffusion. For small farms these factors can be more acute and pose a bigger barrier to adopting these new technologies.

A slower adoption of new technologies implies a slower gain in productivity, and a lower increase in income levels.

Without targeted support, technological progress can widen income gaps and reduce inclusiveness.[38]

Both supply- and demand-side factors affect the adoption of new agricultural technologies

Table 3.3 Selected supply-side and demand-side factors shaping technology diffusion of GM crops and PATs

Factor	GM technology	PAT
Supply-side		
Affordability	GM technology is expensive to develop. From discovery to commercialization (before regulatory approval) costs USD 64.2 million.	Varies. Technology providers rely on underlying technologies and platforms that range from privately owned and proprietary, to publicly available.
Infrastructure	Requires substantial investment in infrastructure to develop new seed varieties, including research, development, deployment, and testing in importing countries.	Often require advanced and instantaneous wireless technology connectivity for optimal function.
Human capital and skills	Highly capital and knowledge intensive.	Varies by component.
IP	Facilitates cross-licensing and collaboration for further innovation. However, potential patent thicket issue in case technologies needed are owned by many different IP holders.	Potential cross-licensing and patent thicket issues. Access to standard essential patents may be needed, especially for components requiring interoperability across devices owned by different entities.
Institution/regulation	Most countries require demonstration that the technology causes no harm to the environment or human health. Obtaining cultivation approval costs approximately USD 43.2 million, or 37.6 percent of total costs from discovery to regulatory approval.	Currently limited but evolving. Some countries restrict technology providers from certain origins for national security reasons. Others have laws governing data collection and ownership.
Demand-side		
Affordability	Seeds with GM technology usually cost more than conventional seeds, due to the cost of the new technology. However, relative to total production costs, the price premium may be manageable.	Expensive upfront costs and may be unaffordable for smallholder farms.
Infrastructure	Farmers may require access to seed distribution networks to obtain seeds with GM technology. In addition, availability to use the technology may also require complementary inputs such as fertilizers, pesticides, and herbicides.	Highly dependent on physical and digital infrastructure and requires interoperability between different tools and techniques in the PAT system.
Human capital and skills	Some training is needed to ensure crops with GM technology maintain their performance and efficacy.	Farmers may require training to use the technology effectively.
IP	IP holder may restricts unauthorized use of the proprietary technology. However, IP holder is incentivized to continuously innovate to maintain leadership and market share.	Data ownership issues may prevent farmers from aggregating farm data for useful insights and analysis.
Institution/regulation	Most countries regulate importation and cultivation of crops with GM technology.	Ownership rights over farming operation data remain unclear.

Notes: GM = genetically modified, PAT = precision agriculture technology.

Source: WIPO, based on elaboration by Falck-Zepeda, J. (2026). Understanding Technology Diffusion in the Agricultural Sector. *WIPO Economic Research Working Paper Series No. 94*. Geneva: WIPO.

Diffusion happens faster within a supportive environment

Government support through policies, regulations and funding schemes can narrow the technology diffusion adoption divide. Even industry-led initiatives help technology diffuse faster.

Regulation sets the boundary conditions for diffusion

GM crops require risk assessment for human health and the environment. Efficient, transparent processes reduce uncertainty and speed safe adoption. Where processes are slow or unpredictable, firms delay investment and farmers wait.

Policies actively promote adoption

Many governments help fund new technology purchases or demonstrations, support local adaptation research, and invest in extension. In GM technologies, the public sector has been an active enabler of the technology diffusion of yield-improving crops through farmer extension services and training.

They may also set sustainability targets to encourage PATs use. For example, farmers in Brazil and Canada have benefitted from public-support programs and policies designed to encourage the adoption of PATs. In the US, various funding schemes and public–private partnerships help increase PAT uptake.

The private sector, as well as farmer-led initiatives, also plays an important role in the speed and spread of GM crops and PATs among farmers. In some countries, the agricultural technology producing firms engage with the public sector to provide extension farmer services, as well as training to help maintain GM crop integrity over its life cycle. For example, industry-led initiatives have facilitated PATs use by farmers in Australia.

Infrastructure matters

Governments also play an important role in providing the right infrastructure for the adoption of GM crops and PATs, and across farming in general. For example, irrigation infrastructure provides an important and stable growing condition that has supported the adoption of GM cotton in China, Mexico and the US. In the case of PATs, the lack of or weak physical and digital connectivity limits the usability of PATs across and within countries.

Standards and competition policy matter

For PATs, open standards enable interoperability across devices and brands. Standard essential patents (SEPs) licensed on fair, reasonable and non-discriminatory (FRAND) terms can unlock compatibility and reduce switching costs (see Chapter 5 for a discussion of SEPs).

Competition oversight can deter anti-competitive bundling which locks farmers into proprietary ecosystems.

The role of intellectual property

IP protection has a nuanced impact on agricultural technology diffusion. It provides incentives for private R&D investment, but can create barriers to access proprietary technology and to develop follow-on inventions. The effects vary according to technology, country context and market structure.

IP protection drives innovation

IP protection provides a temporary exclusive right to restrict the use and sale of protected technologies.

In plant innovation, much of the progress historically has come from public-sector breeding programs. This remains largely true across many developing economies. But in some economies, such as the United States, private investments in plant innovation have surpassed public spending.[39] This shift is largely attributable to legislative changes that have extended IP protection to plant innovation (see Box 3.1).[40]

Box 3.1 Evolution of IP in agriculture in the US

Technological advances in plant breeding can be protected using the following intellectual property (IP) instruments in the US:

- Plant Patent Act (1930): provides exclusive rights over asexually reproduced plants, including ornamental plants and fruits.
- Plant Variety Protection (PVP) Act (1970): provides protection for plant varieties of sexually reproduced crops, which include oilseed crops, grasses and grains.
- Patents (utility patents): The US Supreme Court decision on *Diamond v. Chakrabarty* (1980), and the United States Patent and Trademark Office (USPTO) Board of Patent Appeals and Interferences (1985) decision on *Ex parte Hibberd* extended that jurisdiction's patent protection system to include seeds, parts of plants, plant varieties, genetically engineered organisms, and gene products.

These gradual changes in how innovation in plant breeding can be protected made innovation in the area attractive to the private sector.

Source: Pardey, P.G., Alston, J.M. and Chan-Kang, C. (2013). Public Agricultural R&D over the Past Half Century: An Emerging New World Order. *Agricultural Economics*, 44(s1), 103–13. https://doi.org/10.1111/agec.12055.

For private firms, IP rights make it possible to capture returns on R&D investments, thereby creating stronger incentives to innovate.[41] This is especially critical in high-cost and high-risk fields such as GM technology. The commercialization of crops with GM technology entails significant expense, about USD 115 million on average when factoring in regulatory approval.[42]

In addition, the field is risky due to high attrition rates and no guarantee of success. One study found that only five genetic traits were eventually commercialized for farmers out of the 560 genetic traits identified in an R&D process.[43] Additionally, firms investing in the development of early-stage genetic-trait technology may not see any returns to profit until 10 years from the initial discovery, if any.[44]

The public sector uses IP protection. For example, public research institutions in the United States file for patent protection on agricultural innovation to enable technology transfer to private firms and to facilitate its commercialization.

However, the public sector does not rely on IP protection to the same extent as the private sector. In many instances, the scope of agricultural innovations is different, with the private sector focusing on those inventions that are scalable, while the public sector focuses on region-specific types of inventions.[45]

IP protection shapes collaboration. Licensing agreements and joint ventures give local firms and NARSs access to foreign technologies, enabling them to adapt innovations to local germplasm and strengthen domestic capabilities. It also helps to build the innovation capabilities of the local innovation ecosystems of countries. In many cases, private companies have partnered with public research institutions to tailor GM technology to specific agro-ecological conditions, thereby building stronger local innovation ecosystems.

Yet IP can restrict access

Technologies protected by IP rights can be costly to access, affecting both the development of new innovations and their eventual use.

Farmers often seek crop varieties that combine multiple desirable traits, such as pest resistance, drought tolerance, and high yields. Developing such multi-trait seeds can be expensive for seed producers, particularly when the traits are owned by different IP holders. Negotiating licenses with multiple parties can lead to "stacked" royalty fees, with each rights holder seeking a significant share. These cumulative costs can squeeze margins for seed producers, and discourage the commercialization of seeds with optimal trait combinations.

In the case of crops with GM technology, one study indicates that royalty rates account for more than half of the total markup on seeds.[46] Despite these added costs, IP protection has not appeared to hinder innovation or the international spread of GM technology — as shown by the global adoption of GM crops in Figure 3.6.[47]

Concerns about IP protection in plant innovation have instead focused on broader societal and ethical issues. Questions have been raised about whether biological materials should be subject to private ownership, and whether IP restrictions limit access to agricultural technologies, particularly in ways that may conflict with humanitarian objectives. A notable area of tension lies between patent holders on one side, and farmers' privileges on the other, reflecting ongoing debates over how to balance innovation incentives with equitable access (see Box 3.2).

Box 3.2 On patent rights and farmers' privilege

In 1996, Monsanto (now part of Bayer) developed *RoundUp Ready* GM soybeans—genetically modified to tolerate the company's Roundup herbicide. Farmers adopted this GM technology quickly due to its proven efficacy and performance.

However, between 2007 and 2023, the company faced several lawsuits regarding how it enforced its patent rights.

Typically, farmers pay technology fees when purchasing improved crop varieties. In many countries, this purchase exhausts the patent holder's rights, allowing farmers to use the technology as they wish, including saving unused seeds for the following season.

Monsanto took a different approach. When commercializing its GM technology, the company required seed producers, grain companies, and farmers to sign technology licensing agreements that prohibited farmers from saving and replanting purchased seeds beyond one season. This restriction contradicted farmers' traditional practice of seed saving.

Farmers who used seeds containing GM traits—knowingly or not—were required to pay indemnity fees based on their harvest. This led to lawsuits against Monsanto in countries such as Brazil, Canada, and the United States, among others.

In Brazil, farmers argued the indemnity fees "hurt the collective rights of millions of farmers" and filed a class action lawsuit on April 9, 2009. After years of legal proceedings, the Brazilian Appeals Court ruled in favor of Monsanto in 2019, determining that farmers' privilege to save seeds do not apply to patented technologies.

Source: WIPO based on Peschard, K.E. (2022). *Seed Activism: Patent Politics and Litigation in the Global South*. The MIT Press. https://doi.org/10.7551/mitpress/14484.001.0001.

For PATs, the absence of interoperability standards can slow adoption. PATs' modular design means farmers can purchase each component separately. However, farmers may encounter compatibility problems between hardware and software (digital) elements. In addition, they may face challenges integrating PAT systems with existing farm equipment.

Many digital components in PATs rely on overlapping and complementary proprietary technologies, which can be costly to license. This could be solved with agreed-upon interoperability standards. If PAT providers adopted standards enabling seamless integration between PAT systems and existing machinery, adoption could accelerate. This would mirror successful standardization in other digital technology sectors (see Chapter 5 on standard essential patents).

But, unclear IP ownership creates its own barriers

While IP protection may raise the issue for the adoption of new technologies in agriculture, a lack of certainty as toIP ownership can also create a barrier by complicating commercialization and limiting the potential benefit of the innovation.

In advanced plant breeding, unresolved ownership rights concerning foundational technologies can create tension for follow on innovators. A prominent example is the ongoing licensing dispute involving the CRISPR Cas9 gene editing tool. This technology allows scientists to make highly targeted changes to the genetic code of plants, animals, and other organisms, correcting genome errors or introducing beneficial traits. CRISPR Cas9 has gained rapid popularity due to its relative ease of use, efficiency, and flexibility, enabling development of improved traits roughly twice as fast as older breeding technologies.

The dispute centers on overlapping patent claims and unclear licensing rights for follow-on inventions. Two foundational patents underpin CRISPR Cas9: one filed by Jennifer Doudna and Emmanuelle Charpentier at the University of California, Berkeley, and the University of Vienna, and another filed by Feng Zhang at the Massachusetts Institute of Technology on behalf of the Broad Institute. Both patents cover CRISPR Cas9's use, but apply to different classes of DNA-based organisms. The Doudna/Charpentier rights are licensed to Corteva; Zhang's patent is held by the Broad Institute.

Because the claims appear to overlap, each rights holder could, in theory, prevent the other from commercializing follow on inventions that infringe on their patents. This creates serious licensing uncertainty — potential innovators may not know which party to approach for commercialization rights.

The complexity deepened when the U.S. Court of Appeals for the Federal Circuit sent the case back to the Patent Trial and Appeal Board to determine priority of invention, prolonging resolution. [48]

Some researchers avoid the licensing gridlock by turning to alternatives such as CRISPR 3.0 technologies, including CRISPR Cms1 and CRISPR C2c2, owned by Benson Hill Systems. While these tools may not match CRISPR Cas9's efficiency, they provide a clearer path to commercialization because patent ownership is well established.

Similar ownership uncertainty also affects PATs, particularly concerning farm level data. Sensors embedded in PAT systems collect millions of data points daily, covering soil conditions, input usage, weather patterns, and other farm specific metrics. Aggregated at regional or national levels, this data could be critical for improving farm management practices and guiding agricultural investment decisions.

However, ownership and access rights of this farm level data remain poorly defined. For instance, who controls this data — the farmer, the PAT manufacturer, the provider of specific system components, the cloud service operator storing the information, or the sensor developer that initially captured it?

Potential solutions include data cooperatives and data trusts, which establish governance frameworks for data use while ensuring farmers share in the benefits. By clarifying ownership and usage rights, such structures could unlock the full potential of farm level data for both individual and regional agricultural improvement.

Notes

1 This chapter is based on the background reports prepared by Jose Falck-Zepeda (International Food Policy Research Institute) and Charles de Gracia (École de Management Léonard da Vinci), Nicholas Rada (United States Patent and Trademark Office) and Gregory Graff (Colorado State U.

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4 Diffusion of clean technologies: patterns, mechanisms and future challenges

Clean technologies are reshaping the global energy landscape, but uneven adoption across economies is slowing the fight against climate change. This chapter examines solar panels, electric vehicles, and hydrogen technologies to explore why some scale quickly while others lag. It highlights how factors such as cost, modular design, industrial policy, infrastructure, finance, and political economy can accelerate or hinder diffusion. The analysis shows that speeding the spread of clean technologies depends not only on innovation itself, but also on aligning markets, strengthening institutions, and fostering global cooperation.

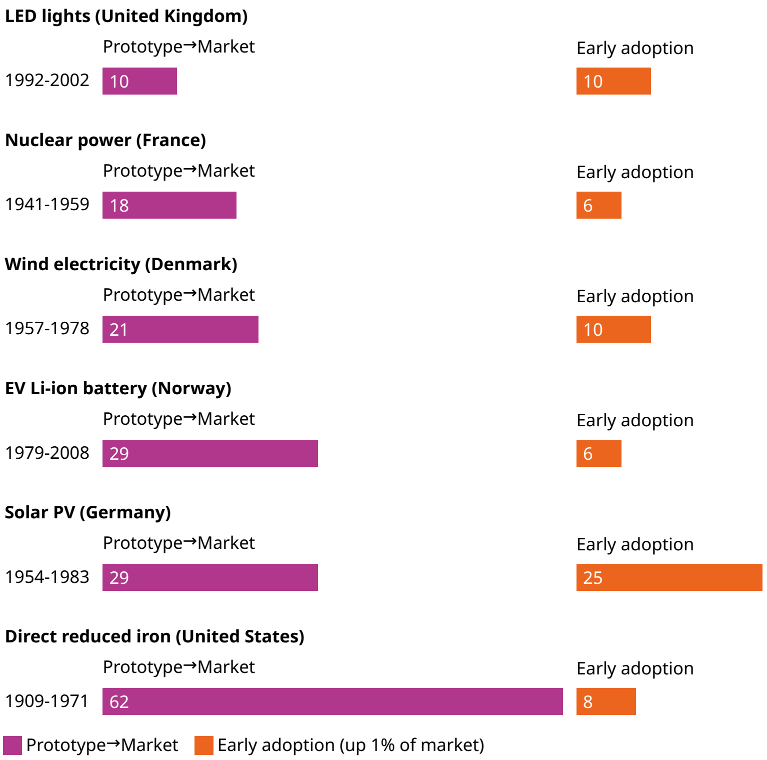
Introduction

Climate change is imposing economic damage through extreme heat, shifting rainfall, rising seas, and disruption to ecosystems and societies.[1] Limiting these impacts requires a deep and sustained cut in greenhouse gas emissions, and such a reduction depends on the innovation and diffusion of clean technologies.

Clean technologies have not diffused uniformly, nor have they spread at the same speed across different contexts. Figure 4.1 shows the time required for energy technologies to move from prototype to market introduction and early adoption, defined here as reaching 1 percent market share. For instance, nuclear power scaled from prototype to early adoption within 20 years of its invention in France, while direct reduced iron took six decades. Even recent success stories illustrate slow progress: solar photovoltaic (PV) needed more than half a century to reach material market share.

Sectoral variations in technology scaling : industrial applications demonstrate prolonged market adoption timelines

Figure 4.1 Time required for prototype-to-market introduction and early adoption of energy technologies, by years



Note: Country designation applies to the early adoption phase and refers to the first countries reaching materiality for each technology.

Source: IEA (2020) *Energy Technology Perspectives 2020: Special Report on Clean Energy Innovation*. Paris,: International Energy Agency, Figure 3.5, 76, https://iea.blob.core.windows.net/assets/04dc5d08-4e45-447d-a0c1-d76b5ac43987/Energy_Technology_Perspectives_2020_-_Special_Report_on_Clean_Energy_Innovation.pdf.

Recent experience highlights several broad trends in clean technology diffusion. Rapid cost declines have been achieved through early research and development (R&D), subsidies, feed-in tariffs, and large-scale manufacturing, driving steep learning curves. Production and adoption have shifted toward Asia, with China's industrial strategy reshaping supply chains, lowering prices and enabling uptake across middle-income economies. Yet diffusion has stalled at the margins: low-income countries and hard-to-abate sectors remain far behind. The policy challenge is now twofold – mobilizing capital, infrastructure and skills, so cost declines reach the poorest adopters, and driving industrial technologies down their cost curves through targeted R&D, demonstration and early-market creation.

This chapter examines how clean technologies have spread, why adoption is uneven, and what this implies for the next phase of diffusion. It focuses on mitigation technologies, with an emphasis on deployment over the last two decades rather than early scientific discovery.

First, it identifies key mitigation technologies and assesses their maturity across sectors and regions, with special attention paid to China's influential position in the global landscape. Next, it presents three instructive case studies: solar (PV), electric vehicles (EVs), and hydrogen.

Solar PV illustrates a complete diffusion journey from early R&D to worldwide deployment; EVs demonstrate how technological competition can be resolved through policy support and industry coordination; and hydrogen highlights strategies for overcoming complex market formation challenges requiring simultaneous infrastructure and demand development. These carefully selected cases reveal common patterns as well as specificities in how clean technologies successfully navigate infrastructure barriers, incumbent resistance, and coordination challenges. The analysis identifies critical success factors, potential policy interventions, and strategic approaches to overcome adoption barriers. Finally, the chapter examines emerging risks and opportunities, including geopolitical tensions, supply chain vulnerabilities, and the financing challenges that will define the next phase of global clean technology diffusion.

Mitigating climate change requires targeted innovation in technologies that reduces the environmental impact of economic activity. Clean technologies, also known as low-carbon technologies, serve multiple critical functions: reducing greenhouse gas emissions, enhancing energy efficiency, optimizing resource utilization, minimizing waste generation, and promoting reuse and recycling. These technologies generate significantly lower CO_2 emissions compared to conventional fossil fuel alternatives.[2]

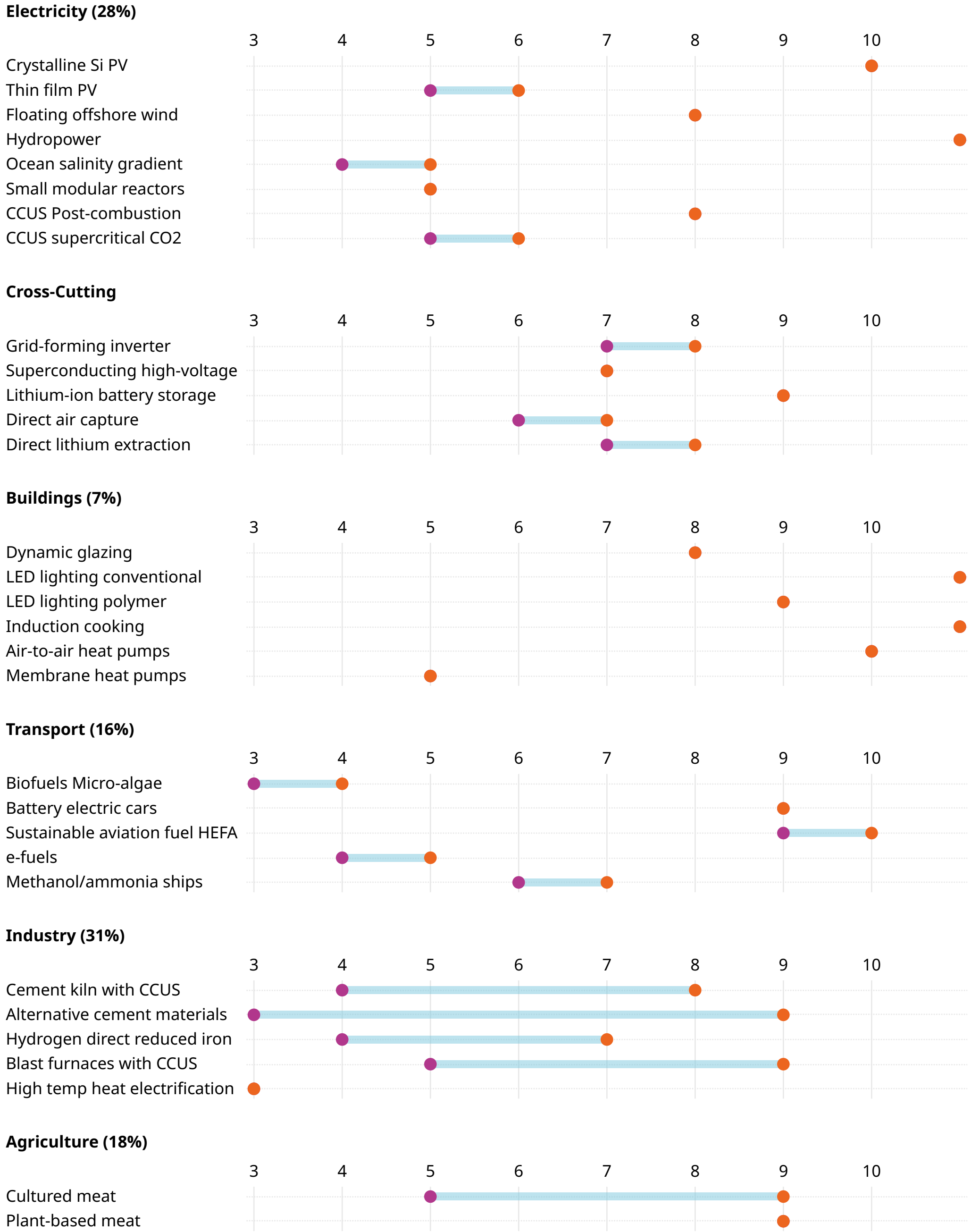
Understanding which clean technologies are most needed requires examining where global greenhouse gas emissions originate, how they are distributed across economic sectors, and which technologies can effectively reduce them.

Table 4.1 provides a comprehensive overview of these mitigation options. It links each sector's emission share to available and emerging technological solutions, revealing that the global clean technology transition has progressed unevenly over the past two decades. The table includes technology readiness levels (TRLs) to indicate each solution's market maturity.[3] TRLs provide a standardized measure of technological maturity across a spectrum from early research to full market transformation.[4] Although the distinctions between TRLs 9, 10, and 11 may appear subtle, since all refer to technologies considered mature, they are important for understanding diffusion. Technologies that have only a niche deployment fall below TRL11; TRL 11 corresponds to a broad pattern of diffusion across the market.

Innovation rarely proceeds linearly through these different TRL stages: feedback loops, reversals and redesigns are common. Still, the TRL scale is valuable because it highlights the types of barriers that typically arise at different points. At low TRLs, technical and financing risks dominate; at intermediate levels, demonstration and early adoption hinge on supply chains, certification and early demand; and at prominent levels, the main challenges concern integration into energy systems, infrastructure and markets.

Technology readiness levels demonstrate heterogeneous progress across decarbonzation sectors

Table 4.1 Clean technologies: Technology Readiness Level (TRL) by sector emissions (%)



Note: Si PV = silicon photovoltaic, CCUS = carbon capture, usage and storage, LED = light-emitting diode, HEFA = hydroprocessed esters and fatty acids.

Source: Largely based on the Cooperative Patent Classification. Data on the shares of global GHG emissions are from Rhodium Group and available at https://rhg.com/research/global-greenhouse-gas-emissions-2021. Information on specific technologies and their technology readiness level (TRL) was sourced from the IEA Clean Energy technology Guide available at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

Technology maturity varies widely across sectors

First, mature technologies already address a significant share of emissions, particularly in power generation and buildings, where solutions have achieved broad market deployment. Power generation has led this transition, beginning with wind power in the mid-2000s, supported by pioneering policy frameworks like Denmark's feed-in tariffs and industrial support measures. Solar PV followed later, achieving exponential growth after the late 2000s as module costs fell dramatically and policy support mechanisms expanded globally. Together, wind and solar dominated renewable capacity additions throughout the 2010s, driven by learning effects and increasingly competitive auctions.

Second, hard-to-abate sectors, like heavy industry and long-distance transport, remain critically dependent on technologies still at the prototype, demonstration, or early adoption stages, presenting both urgent innovation needs and substantial investment risks. Industry accounts for about one-third of global CO_2 emissions and is among the hardest sectors to decarbonize. Some progress can be made through efficiency improvements and electrification of low- to medium-temperature heat, which is already commercially available. But most high-temperature processes, such as those in steel, cement and chemicals, depend on technologies that are still at pilot or demonstration stage. Options include hydrogen-based steelmaking, alternative cement binders, and electrified processes in chemicals and aluminum. Carbon capture and storage can also play a role, though it remains costly and infrastructure intensive. Overall, deep cuts in industrial emissions hinge on advancing and scaling technologies that are not yet fully commercial.

Third, cross-cutting enablers such as grid infrastructure, energy storage, hydrogen, and carbon management systems play essential roles across multiple sectors, yet span a wide range of technological maturities, creating complex interdependencies in the transition pathway. For example, the transportation sector transition lagged significantly behind, with EVs remaining marginal until the late 2010s. The subsequent rapid growth in EVs was primarily driven by policy mandates in key markets – particularly China, Europe and the United States. By the early 2020s, EVs had achieved double-digit market shares in major markets, as automakers committed to large-scale battery platforms.

This framing makes clear that deep decarbonization requires both the rapid diffusion of mature options and a sustained effort to pull lower-TRL technologies through to market. However, the specific challenges vary significantly by sector. In some sectors, the main challenge is not the cost of the technology itself, but systems integration, which spans TRLs from early adoption to widespread deployment. Deep cuts in industrial emissions depend on advancing and scaling technologies that are not yet fully commercial.

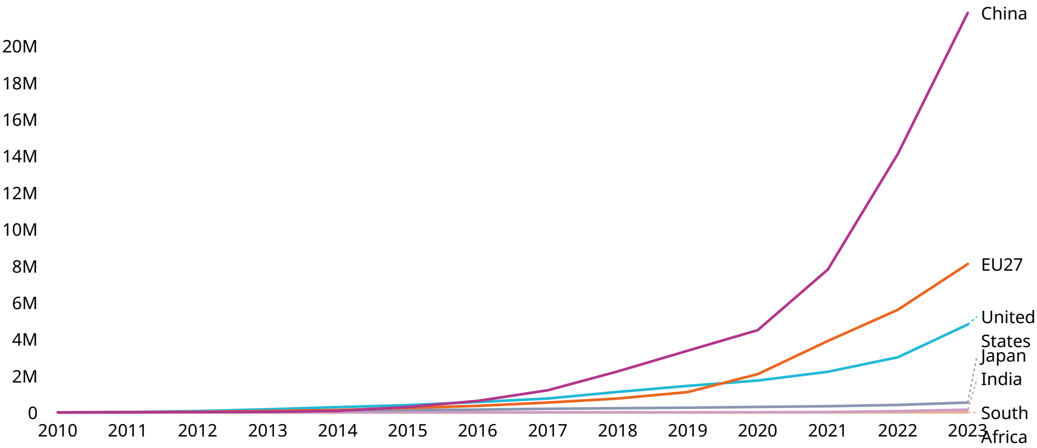
The cross-cutting enablers present a particular complexity: their diversity of maturity levels highlights the critical importance of developing enabling infrastructure – grids, CO_2 pipelines, storage basins, and hydrogen networks – without which specific technologies cannot scale effectively. Meanwhile, in buildings, the main barriers are not technical feasibility, but diffusion challenges including upfront costs, building codes and retrofit logistics. In agriculture, while a broad technical toolkit is available, adoption relies heavily on policy support, consumer behavior and institutional capacity rather than technological development.

Clean tech in the past 20 years: where and how much?

Having mapped the landscape of available mitigation technologies and their maturity levels, the question is how far these options have diffused. Over the past two decades, clean technology has moved from the margins to the center of the global energy system (see Figures 4.2 and 4.3). Solar PV, wind turbines and EVs have scaled from negligible levels in the early 2000s to hundreds of gigawatts of installed capacity and millions of annual sales today (see Chapter 1).

Electric vehicle deployment is accelerating globally

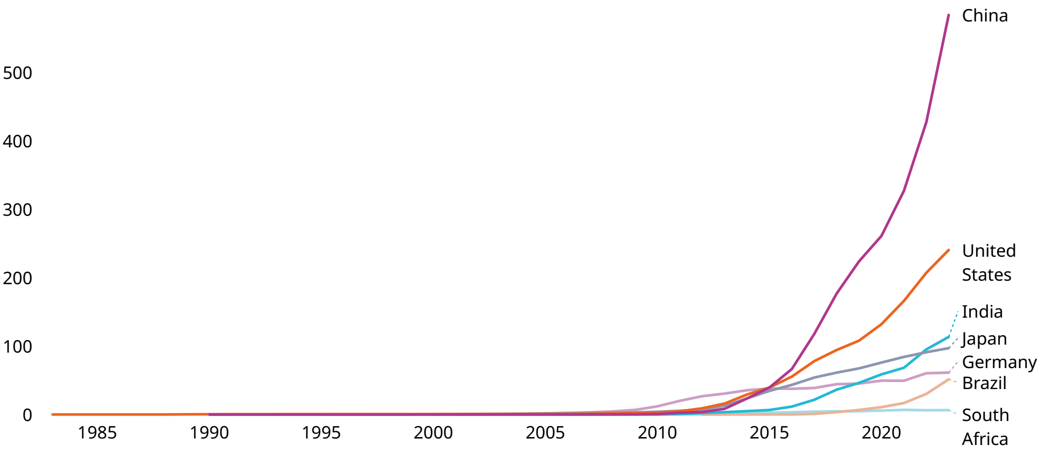
Figure 4.2 Stock of electric vehicles in China, India, Japan, South Africa, the European Union and the United States,, 2010–2023



Note: Estimations consider BEV = battery electric vehicles and PHEV = plug-in hybrid vehicles. Includes passenger cars only.
Source: IEA (2025). *Global EV Outlook 2025*. Paris: International Energy Agency.

Solar PV deployment is accelerating globally

Figure 4.3 Solar capacity/generation in Brazil, China, Germany, India, Japan, South Africa and the United States, 1985–2023



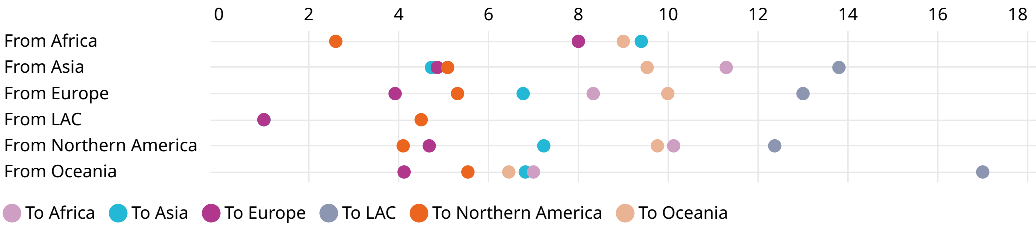
Sources: 2024 Energy Institute Statistical Review of World Energy.https://www.energyinst.org/statistical-review/resources-and-data-downloads

These parallel patterns of deployment and innovation frame this subsection.

Figure 4.4 reveals significant disparities in how quickly green technology trajectories reach destination territories, with flows ranging from 1 to 17 years. Latin American clean technology trajectories diffuse to Asia and Europe within one year, yet the region experiences protracted delays of 12–17 years when receiving technologies from most other territories, with the Oceania-to-Latin America pathway exhibiting the maximum temporal barrier of 17 years. In contrast, Northern America demonstrates consistently efficient absorptive capacity, integrating incoming trajectories within 2.6–5.5 years of irrespective origin. This might reflect the presence of robust institutional frameworks and well-established collaborative networks.

Time to first reuse of clean technologies: regional and cross-regional disparities revealed

Figure 4.4 Average time to first reuse of green technologies in destination regions, by years



Note: LAC = Latin America and the Caribbean. Northern America includes United States and Canada.

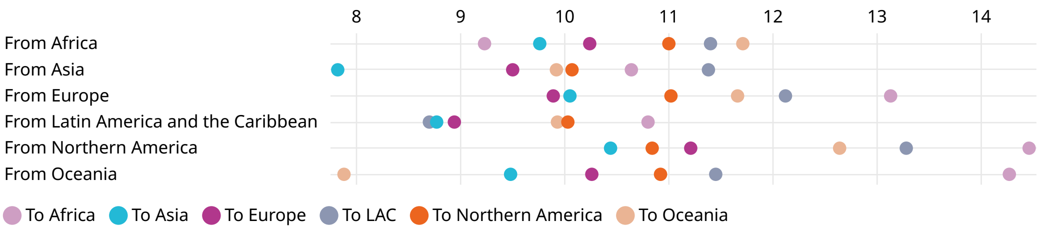
Source: WIPO; and Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO

Clean technology diffusion from scientific publications to patents takes between 8 and 14 years, with clear regional patterns (see Figure 4.5). The fastest conversions occur within regions: Asian science reaches Asian patents in 7.82 years, while Latin American and Oceanian science converts to domestic patents in approximately from 8 to 9 years. This is confirmation that co-location matters.[5] In fact, the highest proportional values lie on the diagonal of the matrix to indicate that the largest share of science produced in a country fuels national technology.[6]

Cross-regional knowledge flows are consistently slower, typically requiring between 10 and 13 years. Africa faces the most significant delays, with scientific papers taking between 13 and 14 years to be cited by African patents regardless of origin, suggesting weak links between research and innovation infrastructure rather than poor science quality. In fact, African and Latin American research is cited relatively quickly by patents in other regions (9–11 years), indicating that these regions produce valuable knowledge, but lack the institutional capacity to rapidly convert external science into local innovation. Northern American science takes longest to reach developing region patents (13–14 years), possibly reflecting relevance gaps or access barriers.

African and Latin American clean technology research faces the longest patent citation delays, highlighting critical knowledge transfer gaps

Figure 4.5 Average number of years for novel scientific knowledge to be used in new inventions by destination territories for clean technologies, by years



Note: LAC = Latin America and the Caribbean.Northern America includes United States and Canada.

Source: WIPO; and Miguelez, E., Pezzoni, M., Visentin, F. *et al.* (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO

Several factors underpin this rise, notably the structural shifts across the three development phases of China's solar PV strategy.[7] Domestic policies created large, predictable markets, first through subsidies and feed-in tariffs and later through auctions and EV mandates. Scale manufacturing lowered costs, while intense competition among local firms led to consolidation and the emergence of global champions such as BYD in EVs and CATL in batteries.[8] These firms now dominate supply chains and compete globally in terms of price and technology. China now dominates manufacturing and much of the upstream supply chain, from mining to the refining of critical minerals, while the United States and European Union (EU) remain important but smaller hubs. China's expanding role has, in turn, reshaped global policy debates, placing industrial strategy and supply chain security at the center of clean-energy policymaking.

Second, adoption outside of high-income countries remained limited until the early 2020s, though recent trends suggest this may be starting to change. Innovation trends mirror this transformation. Clean technology adoption has been concentrated in high-income economies and China, with middle- and low-income countries playing a much smaller role. This imbalance is beginning to shift as middle-income markets expand deployment through auctions, concessional finance and grid investments, and as some low-income countries see early projects. Surplus manufacturing capacity in China has further lowered global solar prices, making solar panels more accessible in regions such as Africa.[9] Diffusion remains highly uneven, but the growing participation of middle- and low-income countries points to the possibility of a broader global expansion. The following section examines the barriers and drivers that shape these patterns in more detail.

Drivers and barriers of clean tech diffusion: the case of solar photovoltaics, electric vehicles, and hydrogen

Multiple interconnected factors drive clean technology diffusion: inner technological characteristics, affordability and cost trajectories; supporting infrastructure networks; technical standardization; workforce capabilities; organizational absorptive capacity; and institutional and regulatory frameworks. These factors both create virtuous cycles that accelerate adoption as well as erect barriers that impede market penetration. This section examines how these factors specifically influence solar PV, EVs, and green hydrogen, illustrating distinct diffusion pathways and revealing transferable insights for accelerating the clean energy transition across diverse technological and market contexts.

Affordability

The deployment of wind, solar and EVs has been inseparable from the massive cost declines these technologies have experienced. Cost declines in clean technologies emerge from several reinforcing mechanisms: R&D delivers fundamental improvements; learning-by-doing reduces costs as firms gain production experience and economies of scale lower unit costs as output expands. These processes, often amplified by knowledge spillovers and growing markets, underpin the steep learning curve observed across many clean technologies. Nonetheless, a caveat of very rapid learning effects, as the ones observed in renewable energy, is that users may prefer to adopt a "wait-and-see" behavior, delaying diffusion if they anticipate cheaper and more efficient products will be soon available on the market.

For any technology to diffuse, it must meet the cost and quality requirements of specific users and applications, and compete effectively with incumbent alternatives. In the context of clean technologies, what matters for diffusion is whether clean technologies are able to compete on an equal basis with dirty (fossil-based) technologies. In practice, however, due to unpriced environmental externalities and established market dominance, fossil-based incumbents benefit from a competitive advantage. The absence of carbon pricing means that the social costs of pollution are not reflected in market prices, distorting investment decisions.

Solar PV

For instance, for solar PV, mass production for the Chinese market contributed to accelerating learning-by-doing and economies of scale, leading to a significant cost decline in solar PV prices as cumulative capacity increased, as depicted. The speed and extent of scale economies were greatly facilitated by the modular design[10] of solar PV in manufacturing, which makes solar cells affordable even at a small scale (e.g., 100 W) by contrast to other energy technologies (e.g., coal or nuclear power plants, the minimum scale is in the range of hundreds of millions of watts).[11]

Regarding solar PV, trade restrictions imposed by the United States since 2014 and Europe over the 2013–2018 period have increased the cost of importing solar PV, leading to reduced solar adoption. There is evidence that following the 2014 US tariffs, prices for solar PV in the United

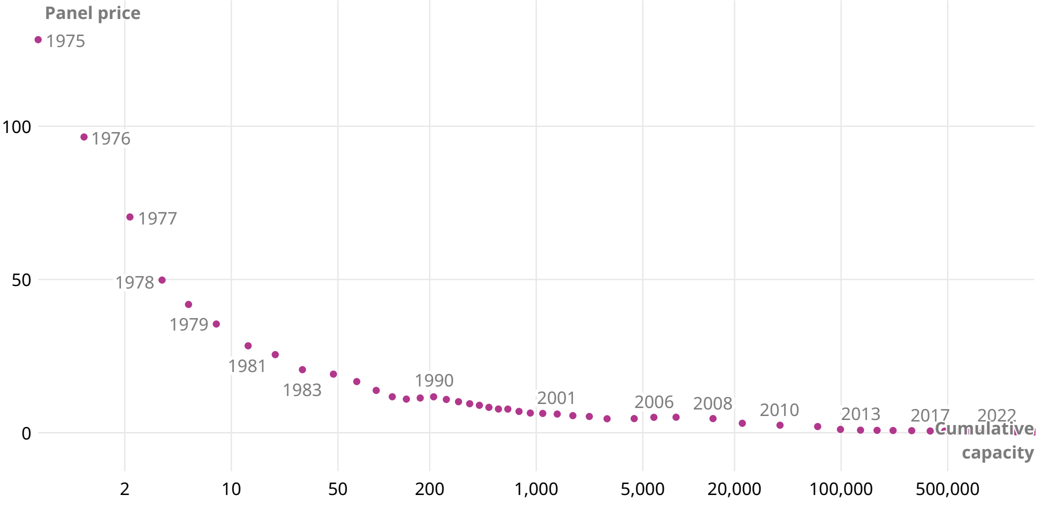
States increased by about 10 percent relative to other markets, and by 20 percent following the 2018 tariffs, leading to reduced adoption of solar panels in that country.[12] On the producer's side, even in the absence of trade tariffs, and despite low levelized cost of energy (LCOE) costs, there are still important financial risks to investing in solar PV projects, as they are typically highly capital-intensive and financed via project finance.[13] On the consumer side, credit constraints can affect the ability of consumers to install solar PV. In developed economies, even if the costs of solar system hardware (modules, inverters) have fallen, there remain important "soft" costs hampering the deployment of solar PV.

EV

Affordability remains one of the most persistent barriers to broad-based EV adoption. While lifetime costs are often favorable, the purchase price of battery-electric cars in Europe and the United States remains between 10 and 50 percent higher than for comparable internal-combustion models, dampening uptake outside high-income households.[14] Loan rates and availability are typically less favorable for subprime borrowers, creating another barrier for lower-income groups. Innovative instruments such as zero-interest loans, on-bill financing tied to utility accounts, or co-investment by public green banks could help overcome these gaps by reducing capital costs and risk. Norway illustrates how a stable package of demand-side measures can drive rapid uptake. The Government combined high taxes on petrol and diesel cars with generous exemptions for EVs, producing the world's highest market share.[15] Crucially, this policy mix has remained consistent across successive governments, and the absence of a domestic automaker lobby removed opposition to high fuel taxes. China's EV expansion is the clearest example of how coordinated industrial policy can transform a sector. Since the early 2010s, national and local governments have combined consumer subsidies, purchase-tax exemptions, and public procurement with non-price measures such as license-plate advantages in major cities. At the same time, public investment has expanded charging networks, while industrial plans have supported battery production through credit, land and permitting. These instruments have since been consolidated into a dual-credit system linking support to vehicle efficiency and range. Subsidies were gradually reduced as volumes expanded and costs fell, and scale and learning effects had driven a decline of more than 90 percent in EV battery costs between 2010 and 2020.[16]

Over time, solar PV prices have declined significantly, as cumulative capacity has increased

Figure 4.6 Solar PV panel prices vs cumulative capacity, 1975–2024



Notes: Solar module costs are from OWID *et al*. (2025), incorporating earlier series from Nemet[17] and Farmer and Lafond,[18] and are expressed in constant 2024 USD/W. Deployment data refer to installed PV capacity from IRENA,[19] accessed via Our World in Data. The learning curve shows the decline in module prices from over USD 100/W in 1975 to below USD 0.5/W in 2024, plotted against cumulative global capacity. Each doubling of deployment has driven significant cost reductions, underscoring the role of learning-by-doing and economies of scale in modular clean technologies.

Source: Reproduced from Our World in Data (https://ourworldindata.org/grapher/solar-pv-prices-vs-cumulative-capacity).

Hydrogen

By contrast, integral, site-specific systems in heavy industry – such as steel, cement or large reactors – face higher capital costs, longer project cycles, and fewer opportunities for iteration, which may help explain their slower and more uneven spread.

Cost is the primary constraint on clean hydrogen diffusion. Renewable and other low-carbon hydrogen remain several times more expensive than hydrogen produced from unabated fossil fuels ("grey" hydrogen), creating a persistent "green premium" (the higher production cost of low-carbon hydrogen relative to grey hydrogen). The gap is driven by three main factors: (i) electricity prices and electrolyzer utilization, (ii) capital intensity and stack durability, and (iii) midstream costs for compression, storage and transport. Electricity is the dominant cost component, but recent evidence also points to higher-than-expected electrolyzer costs. While falling renewable power costs improve the long-term outlook, the post-2022 decline in natural gas prices has reduced grey and blue hydrogen costs, widening the cost gap in the near term. Overcoming this premium will require more than subsidies alone; it calls for sustained R&D to improve efficiency, durability and catalyst design; demonstration programs to bring emerging pathways such as methane pyrolysis and nuclear electrolysis to market; and a scale-up of manufacturing and system integration to capture learning effects and economies of scale. In the case of green hydrogen, currently more than 99 percent of global hydrogen is produced from grey hydrogen, while low-carbon "blue" and renewable "green" pathways are still at the demonstration stage or at the early commercialization scale.[20]

Infrastructure

In the diffusion of clean technologies, "systemic failures"[21] can arise because the widespread adoption of a new technology may require near-simultaneous investments in complementary infrastructure.

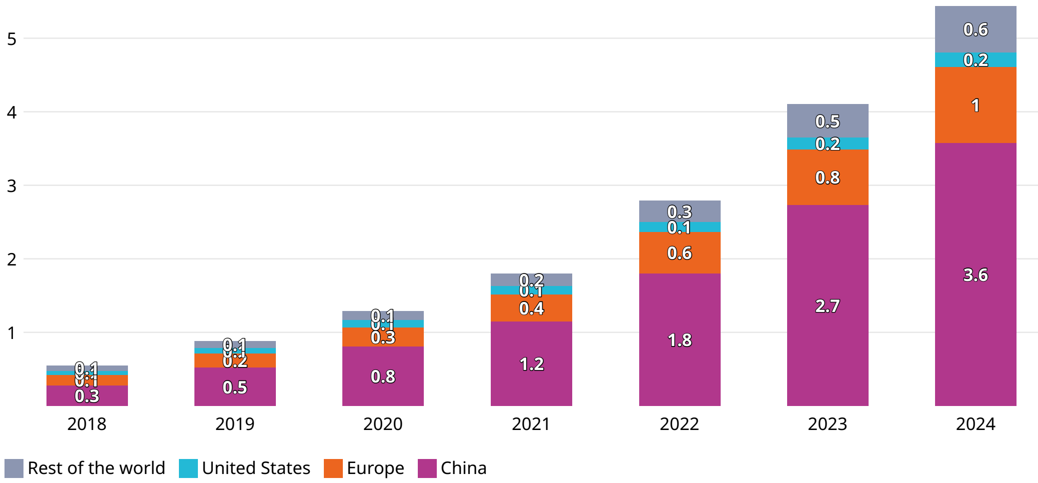
Indeed, the availability of complementary technologies and infrastructure is a constraint to solar diffusion ensuring the reliability of the electricity grid. Many complementary investments in high-voltage transmission lines, transmission networks (i.e., improving interconnections with other regions), grid stability equipment (i.e., voltage control equipment, advanced inverters), net metering systems (e.g., when prosumer policies allow consumers to inject the surplus of energy into that network), and improved distribution network (e.g., smart grids, sensors) are required to manage fluctuating supply and demand locally. Failure to invest fast enough in grid infrastructure impedes the efficient integration of solar PV systems.

In developing countries, a lack of complementary infrastructure to accommodate renewables into the electricity grid is particularly challenging. With a growing population gaining access to energy-using goods, demand for electricity across the developing world is projected to rise sharply in the coming decades, and choices of energy infrastructures in developing countries today will have significant implications both for economic development and global climate change.[22] This view, however, must be nuanced as mini-grid and off-grid systems may not be sufficient to meet the growing electricity needs of households without complementary investments.[23] For instance, once basic needs are met, households aspire to high-wattage appliances (refrigerators, television) that cannot be accommodated within home solar systems, unless possibly when coupled with sufficient investments in batteries.[24] Meeting the electricity needs of schools, hospitals, businesses, and industries will generally require a grid connection. Hence, complementary investments – such as transmission and distribution upgrades – will be essential to integrate solar energy into the grid and facilitate economic development in developing countries.

EVs require a dense network of charging infrastructure before mass adoption becomes viable, yet charging providers hesitate to invest before there is sufficient EV uptake. Charging infrastructure is a critical bottleneck for EV diffusion. As shown in Figure 4.7, the global stock of public charging points expanded from under 1 million in 2018 to more than 5 million by 2024. Most of the growth has been in slow chargers, though fast and ultra-fast options are increasing rapidly. Ultra-fast chargers (>USD 150~kW) are becoming more common, having grown by about 50 percent in 2024, but they still account for only around 10 percent of public fast-chargers worldwide. Cross-country comparison shows that those markets with a denser charging network achieve higher EV shares, highlighting the central role of infrastructure in enabling adoption. As shown, Norway's success reflects generous incentives and sustained investment in public charging.

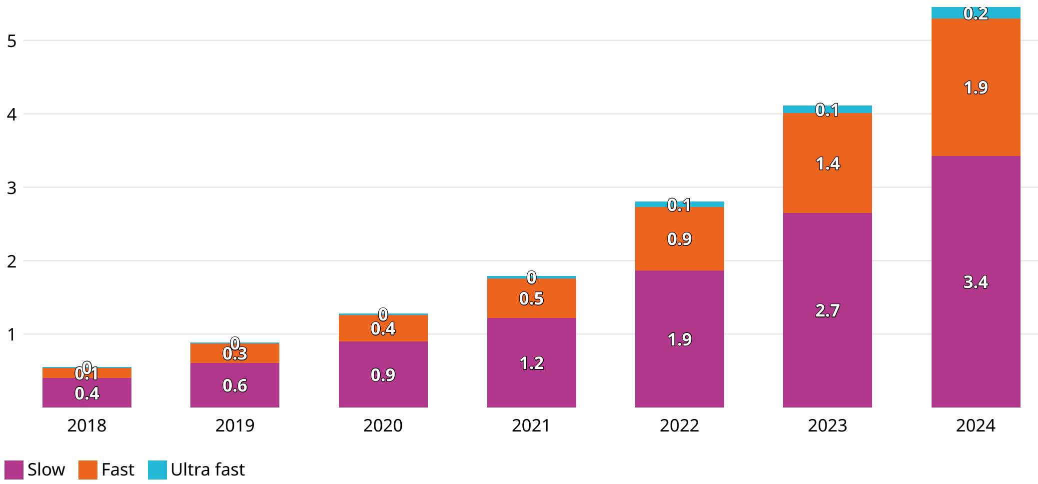
The global stock and speed of public charging points have increased dramatically

Figure 4.7a Global stock of public charging points, by selected region, 2018–2024 (millions)



Source: Based on IEA (2025). *Global EV Outlook 2025*. Paris: International Energy Agency.

Figure 4.7b Global stock of public charging points, by speed, 2018–2024 (millions)



Source: Based on IEA (2025). *Global EV Outlook 2025*. Paris: International Energy Agency.

Hydrogen requires the building of new pipelines, and solar and wind energy can only scale if accompanied by investments in grid flexibility, storage and transmission. Dedicated pipelines, storage facilities and port infrastructure are scarce. Of the 56 countries with a hydrogen strategy, 43 consider infrastructure to be the most critical barrier.[25] Limited midstream capacity constrains scale-up, and the lack of common technical standards hampers cross-border trade. CO_2 transport and storage could lower blue hydrogen costs, but such investments are proceeding slowly.[26] Options to move hydrogen indirectly – as ammonia, methanol or liquid organic carriers – require large-scale facilities and raise environmental and safety concerns.[27]

Human capital and skills

Technology adoption depends on the availability of the skilled workers, engineers, and technicians who enable firms to absorb the tacit knowledge embedded in new innovations. Evidence shows that the mobility of scientists facilitates technology diffusion.

Beyond scientists and engineers, clean technology deployment requires a skilled workforce for installation, maintenance and repair. The spread of solar PV in the United States accelerated only after qualified installers became available.[28] Many leaders in China's solar PV industry were trained abroad.[29] Policies that promote researcher mobility, field switching (e.g., from fossil to clean technologies), and inventor entry into green innovation can strengthen human capital and diffusion.[30] In developing countries, limited technical capacity constrains adoption, as shown by a decline in the use of clean cookstoves in India due to inadequate maintenance and training.[31] Recent evidence has highlighted a rapid growth in green jobs, with US solar and wind job postings having more than tripled since 2010, reflecting expanding clean energy capacity.[32]

Training programs, vocational education, reskilling, and workforce transition policies greatly contribute to expanding the pool of workers in clean technology sectors. In the context of developing countries, the key challenge is to build a base of skills that would allow these countries to leapfrog directly to clean technology adoption. Yet attracting workers in green jobs will depend crucially on job quality (i.e., level of informality, pollution exposure and wages) and may require complementary institutional changes to labor regulations, as well as the building up of specific education and training institutions.[33]

Adopter behavior plays a critical role in clean technology diffusion.[34] In the case of EVs, charging behavior can help identify coherent policy mixes, but policymakers require more than behavioral data alone. Local conditions – including grid capacity, parking availability and existing infrastructure – must inform infrastructure roll-out strategies. This point is especially important for systems where consumers act as prosumers by simultaneously generating and storing energy.

Empirical evidence reveals substantial differences in the socio-demographic profiles of solar PV and EV adopter groups, which in turn shape distinct regional diffusion patterns. Spatial mismatches have significant implications for smart energy system integration. Scenarios examining regional EV–solar PV integration show that vehicle-to-grid (V2G) systems may not be viable in every region, as the geographical distribution of EV adoption does not necessarily align with areas of high solar PV deployment. This underscores the need for place-based approaches that account for local adopter characteristics, infrastructure constraints, and energy system configuration when designing policies to support clean technology diffusion.

Intellectual property

Intellectual property (IP) is a double-edged sword in the diffusion of clean technologies. Patents and related rights create incentives for firms to undertake costly R&D by offering temporary monopoly protection, but they also restrict access by design. In the climate context, this trade-off is especially acute: each year of delay in diffusion translates into higher cumulative greenhouse gas (GHG) emissions. The asymmetry lies less in the urgency of climate action – which is high everywhere – than in the geography of ownership and resources. Most clean-technology patents are held by entities in high-income countries, while lower- and middle-income countries face the great need for financial support and technology assistance to implement mitigation and adaptation at scale. This imbalance has made IP a recurrent point of contention in international climate negotiations.

Yet exclusivity also creates barriers. Licensing negotiations are costly, access is restricted, and adoption can be delayed. For developing countries, these challenges are compounded by limited financial resources and absorptive capacity. The solar sector illustrates the implications: namely, that as markets have matured and competition has intensified, disputes over incremental but valuable innovations have proliferated. First Solar's recent lawsuits against rivals for alleged infringement of the "TOPCon cell" patents are emblematic of a broader rise in litigation;[35] observers note that such disputes reflect both the commercial significance of small efficiency gains and the growing density of "patent thickets" in mature segments of clean tech.[36]

Patent pledges have also attracted attention as an alternative to traditional exclusionary practices, but their practical impact on diffusion remains uncertain. Tesla's 2014 announcement that it would not initiate lawsuits against good-faith users of its EV patents is the most prominent example. While hailed as a bold move to accelerate market growth, scholars debate whether such pledges represent genuine commitments, strategic branding or attempts to position one's own technology as the dominant standard.[37] Tesla's behavior underscores the complexity: even as it has released parts of its patent portfolio, the company has continued to guard its most valuable process innovations – such as advanced battery manufacturing – through trade secrets.

Most clean innovation over the past two decades has concentrated on electricity generation, storage and grids, with especially strong growth in the batteries and smart-grid technologies that underpin both power and transport. In contrast, innovation for hard-to-abate sectors remains small: CCS patenting, although growing, remains at roughly 100 patent families per year, and hydrogen activity was relatively strong in the early 2000s, but declined once lithium-ion batteries became dominant in transport.

Institutions, regulations and competition

The diffusion of clean technologies does not occur within a political vacuum. Because they displace entrenched industries, clean technologies generate both winners and losers, shaping the incentives of powerful actors to either support or resist change. Fossil fuel incumbents have strong incentives to defend existing revenue streams and protect sunk capital. Utilities, coal producers, and oil and gas majors have historically lobbied against carbon pricing, emissions standards and subsidy removal.[38]

Environmental and land-use impacts of large solar farms further complicate deployment, especially in densely populated regions where local opposition is expressed through "Not In My Backyard" movements.[39] The most cited reasons for opposing large solar farms are visual impact, financial impacts on property values and potential impact on wildlife, agriculture or soil quality. Yet reductions in property values are only modest for houses located in the vicinity of solar farms, in contrast to wind parks, where impacts are more important. Nonetheless, when allocating permits for solar farms, planning decision-makers seem to be particularly responsive to local factors, especially in wealthier areas, leading to inefficiencies in the deployment of solar power.[40]

Political economy and trade

Political and industrial factors also shape how widely EVs are adopted. In the United States, EV adoption is highly polarized – meaning it is concentrated in certain political areas. About half of all new EVs registered between 2012 and 2023 were bought in just the 10 percent most Democrat-leaning counties. One-third were in the top 5 percent of the most Democratic-leaning counties. [41] This correlation persists even after controlling for income, population density and gasoline prices, underscoring the role of ideological preferences as a barrier to widespread diffusion. The Inflation Reduction Act (2022) ties federal EV tax credits to domestic assembly and critical-mineral sourcing, generating only about USD 1.02 of benefit per dollar spent compared with a no-credit scenario and provoking objections from trading partners.[42] Increasingly, trade policies are diverging across major markets. The United States maintains 100% tariffs on Chinese electric vehicles, while Canada is pursuing a negotiated reduction of its tariffs through bilateral trade agreements. The European Union is developing its own framework based on minimum import prices and investment commitments. Incumbent automakers also influence outcomes. Retooling factories and supply chains for EV production is costly, and firms may resist or lobby against stringent zero-emission mandates.[43]

Global EV overcapacity is beginning to distort markets. Aggressive expansion within China has pushed production beyond domestic demand, triggering intense price competition. In early 2024, average EV transaction prices fell by about 10 percent, as Tesla and BYD cut prices to protect market share. While this benefits consumers in the short run, prolonged price wars could erode profitability and discourage investment in further innovation.[44]

Emerging policy tools: hubs and equity

Because technologies like rooftop solar and EVs are typically purchased by higher-income households, early subsidy programs disproportionately benefited the well-off. Policy design must therefore anticipate distributional consequences. The Inflation Reduction Act in the United States addressed this by linking EV tax credits to income and vehicle price thresholds, while electricity tariff reform or renewable support schemes in developing countries also need to balance equity and political feasibility.

Hydrogen hubs have emerged as a prominent policy idea, though more in theory than in practice. The concept is that co-locating production facilities, midstream infrastructure, and end-users within a single region could accelerate deployment. By synchronizing investment timelines and sharing assets, hubs are expected to help projects move from pilots to commercial scale. In this framing, the hub serves as a coordination device – reducing first-mover risk and providing a setting for technological learning.

The central question is whether hubs will prove effective in addressing the barriers outlined above. In principle, they are designed to reduce production costs through shared infrastructure, create credible demand signals via anchor off-takers, accelerate the build-out of pipelines and storage, and provide greater regulatory clarity through demonstration and certification. Yet at this stage the evidence base is thin. Most hubs are still at the announcement or early implementation stage, and it is too soon to know whether these mechanisms will work in either practice or at scale.

These uncertainties highlight the need for systematic evaluation as hubs move from concept to operation. Careful design will be essential: engaging communities, ensuring transparent emissions accounting, and aligning projects with long-term decarbonization goals. Comparative evidence across regions will be particularly valuable for assessing whether hubs deliver on their promise or simply repackage existing barriers in a new form.

The case studies of solar PV, EVs, and hydrogen illustrate the common mechanisms, as well as specificities, in the diffusion of these technologies . Early R&D and targeted demand–pull policies in lead markets initiated diffusion. China's industrial strategy then scaled production, delivering steep cost reductions. Complementary inputs – grids, charging infrastructure, finance, and skills – were critical to sustaining adoption. Political economy headwinds slowed, but did not prevent progress where credible policy frameworks were in place.

Table 4.2 Overview of enablers and barriers in the diffusion of solar photovoltaic, electric vehicles, and hydrogen technologies

Factor	Solar PV	Electric Vehicles	Hydrogen
Affordability	Massive cost declines via learning-by-doing, scale economies, and R&D. Modular design enabled rapid reduction.	Battery costs fell 90% (2010-2020); scale and learning effects.	Green Hydrogen 2-5× costlier than grey. Green premium widening post-2022.
Infrastructure	Grid lags generation capacity, bottleneck to diffusion,especially in developing countries.	Global charging stock: <1M (2018) to 5M+ (2024); uneven distribution; ultra-fast (<10% of fast chargers).	Scarce dedicated pipelines, storage facilities,and port infrastructure.
Human Capital & Skills	US deployment accelerated only after qualified installers available, job postings tripled since 2010. International training key (China example). Knowledge transfer and workforce mobility policies accelerate diffusion.	Charging behavior + local conditions (grid, parking) determine viability; spatial mismatch with PV adopters limits V2G in many regions.	Limited workforce for complex system maintenance; skills gap in hard-to-abate sectors; specialized technical expertise scarce.
Intellectual Property	Rising patent thickets and litigation over marginal improvements (First Solar TOPCon).	Strong battery/smart-grid patenting; innovation concentrated in storage systems.	Strong early 2000s; declined post-Li-ion dominance; limited hard-to-abate innovation.
Institutions & Regulation	Demand-pull policies, renewable standards, feed-in tariffs; fossil lobby resists carbon pricing/standards.	Chinese overproduction triggers price competition; polarized geographic diffusion.	Hubs coordinate production-infrastructure-demand; 35+ strategies; mostly announcement stage; thin evidence.

Note: Note: PV = photovoltaic, R&D = research and development, V2G = vehicle-to-grid.

Source: Based on Dugoua, E. and Noailly, J. (2026). Diffusion of Clean Technologies: Patterns, Mechanisms, and Future Challenges. World Intellectual Property Organization – Economics and Statistics Division.

Looking ahead: challenges and risks for the next phase of diffusion

This chapter reviewed how clean technologies have spread, why adoption has been uneven, and what this implies for the next phase of diffusion. Four stylized facts stand out.

- Deployment has been rapid in power and light transport, but remains limited in hard-to-abate sectors.
- China has become the central actor in both innovation and deployment.
- Modularity has been decisive in driving cost declines and scaling.
- Adoption outside high-income economies has begun only recently, though the potential is large.

The case studies of solar PV, EVs, and hydrogen reveal common patterns as well as specificities in how clean technologies successfully navigate infrastructure barriers, incumbent resistance, and coordination challenges.

There are pressing challenges that will shape the next phase of clean technology diffusion. Beyond the urgent task of accelerating adoption across developing countries, several risks are emerging. Heightened vulnerabilities in the supply of critical minerals raise new concerns about costs and affordability, while uncertainty around the transformative – and potentially disruptive – impacts of artificial intelligence (AI) introduce both opportunities and risks for clean innovation and deployment. At the same time, geopolitical tensions are redefining the global landscape and could redirect the trajectory of clean technology diffusion in unforeseen ways.

Future diffusion will hinge less on breakthroughs than on managing systemic risks. Mineral scarcity, AI expansion and political headwinds could raise costs and fragment markets, but innovation, diversification and credible policy can offset them. The balance is uncertain: in some contexts, these pressures may slow adoption, in others, they may catalyze new investment and coordination. Whether clean technologies keep scaling at the speed required will depend on how effectively institutions provide stability, openness and resilience.

Notes

1 See Auffhammer, M. (2018). Quantifying economic damages from climate change. *Journal of Economic Perspectives*, 32(4), 33–52; and Carleton, T., Duflo, E., Jack, B.K. and Zappalà, G. (2024). Adaptation to climate change. In Barrage, L. and Hsiang, S. (eds), *Handbook of the Economics of Climate Change*, Volume 1. Elsevier, 143–248.

2 See more in WIPO (2022). *World Intellectual Property Report 2022: The Direction of Innovation*. WIPO, https://www.wipo.int/publications/en/details.jsp?id=4594&plang=EN.

3 Technologies are classified using the technology readiness level (TRL) framework, originally developed by NASA in the 1970s and subsequently adapted by the International Energy Agency (IEA) for energy technologies. The classification employed in this analysis draws from the IEA Clean Energy Technology Guide. The IEA TRL data tool is available at https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

4 TRLs range from: concept (including TRL1-Initial idea, TRL2-Application formulated and, TRL3-Concept needs validation); small prototype (including TRL4-Early prototype); large prototype (including TRL5-Large prototype and TRL6-Full prototype at scale); demonstration (including TRL7-Pre-commercial demonstration and TRL8-First of a kind commercial); market uptake (including TRL9-Commercial operation in relevant environment and TRL10-Integration needed at scale); mature (including TRR11-Proof of stability reached).

5 See Jaffe, A.B., Trajtenberg, M. and Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *The Quarterly journal of Economics*, 108(3), 577–598.

6 See Miguelez, E., Pezzoni, M., Visentin, F. *et al*. (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

7 See Yap, X.S., Truffer, B., Li, D. and Heimeriks, G. (2022). Towards transformative leapfrogging. *Environmental Innovation and Societal Transitions*, 44, 226–244.

8 See UN Environment and DIE (2017). *Green Industrial Policy: Concept, Policies, Country Experiences*. Geneva and Bonn: UN Environment and German Development Institute (DIE); and Aranca (2025). *Charging Forward: China's Rise to Dominance in the Global EV Market*, https://www.aranca.com/assets/docs/Charging-Forward-Chinas-Rise-to-Dominance-in-the-Global-EV-Market.pdf.

9 See Jones, D. (2025). The first evidence of a take-off in solar in Africa. Ember, https://ember-energy.org/latest-insights/the-first-evidence-of-a-take-off-in-solar-in-africa.

10 Modular technologies are composed of standardized components with clear interfaces, which enable mass production, parallel innovation and flexible deployment. See Baldwin, C.Y. and Clark, K.B. (2000). *Design Rules: The Power of Modularity*. The MIT Press. See Pia, A. and Dumas, M. (2025). *Decarbonising a Complex System*. https://dx.doi.org/10.2139/ssrn.5317836. This architecture accelerates iteration and diffusion: each additional output reduces costs through process refinements, supply-chain specialization and downstream learning.

11 See Nemet, G.F. (2025). *How Solar Energy Became Cheap: Pathway to a Solar-centric Economy*. Taylor & Francis.

12 See Gerarden, T.D., Reguant, M. and Xu, D.Y. (2025). The role of industrial policy in the renewable energy sector. In Kotchen, M.J., Deryugina, T. and Wolfram, C.D. (eds), *Environmental and Energy Policy and the Economy*, Volume 7. University of Chicago Press.

13 By contrast to fossil power plants, which tend to be financed via the balance sheet of utilities.

14 IEA (2025). *Global EV Outlook 2025.* Paris: International Energy Agency.

15 See IEA (2023). *Global EV Outlook 2023: Catching up with Climate Ambitions*. Paris: International Energy Agency; and Nolan, S. (2025). Norway's EV dominance: A roadmap for global success. EV Magazine, https://evmagazine.com/news/norways-ev-dominance-a- roadmap-for-global-success.

16 See IEA (2023). *Global EV Outlook 2023: Catching up with Climate Ambitions*. Paris: International Energy Agency.

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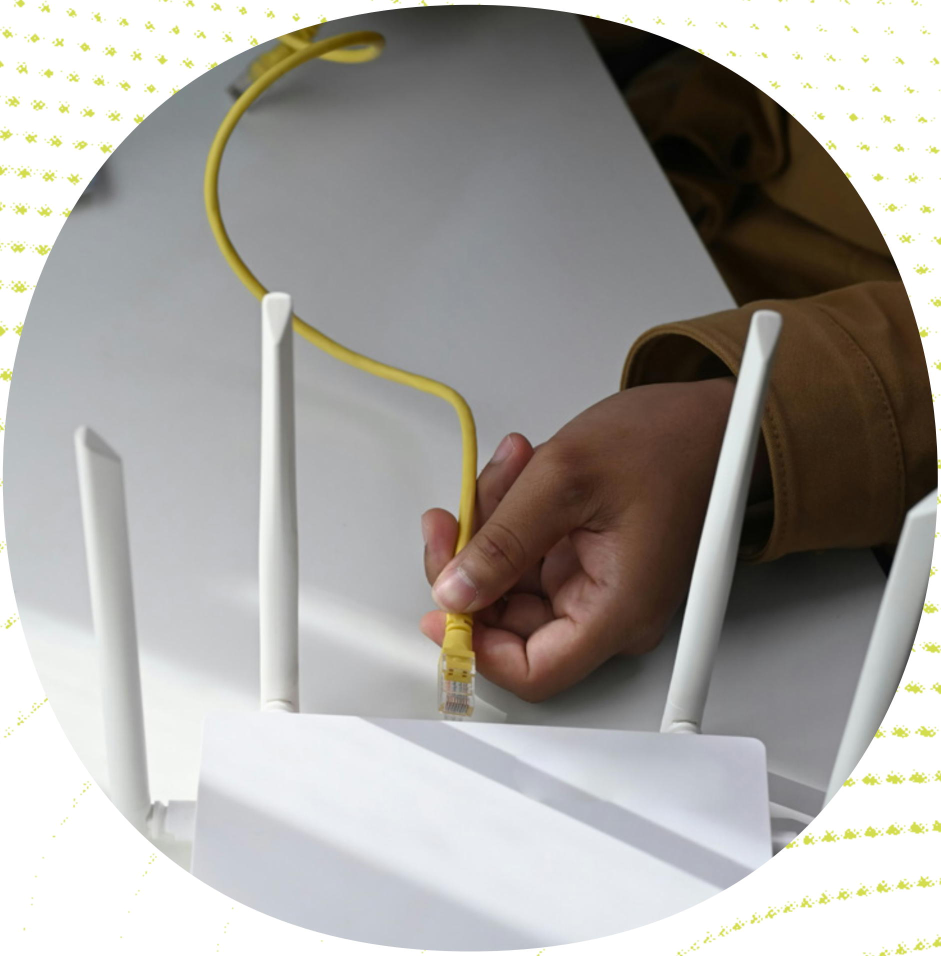
5 Connect, adopt, absorb: digital technology diffusion



Digital technologies such as submarine cables, broadband networks, data-driven platforms and AI have become the backbone of modern economies. Yet, not all economies realize the promise of digital transformation. This chapter traces why connectivity and digital capabilities advance rapidly in some regions while others remain constrained by infrastructure gaps, affordability barriers, skills shortages, and regulatory hurdles. It shows that unlocking inclusive digital diffusion requires more than new technologies—it demands coordinated investments, balanced IP governance, and policies that ensure all countries and communities can participate in the opportunities of the digital age.

Introduction

Digital technologies (DTs) have reshaped the global economy and the way societies innovate. Over the past three decades, they have changed how people communicate, access information and carry out daily transactions.[1] Understanding how these technologies spread, and what this means for economies and societies, is now vital for individuals, businesses and policymakers.[2]

While much of today's digital technology development is concentrated in the United States of America and China, its benefits extend far beyond national borders.[3] Innovation in one region often sparks diffusion in others, enabling countries worldwide to access and adapt new tools and services.[4] This case study explores how digital technologies spread, the forces that drive or hinder their diffusion, and their impact, especially in developing economies.

While many digital technologies matter, this chapter focuses on those that make internet connectivity possible at both national and international levels. These include submarine cables (SMCs) as well as mobile and fixed broadband. Such backbone technologies act as gatekeepers and enablers, providing the foundation for the wider spread of digital innovation. Without them no other DTs have a high chance of widespread diffusion.

Despite the significant potential of digital technologies to drive economic growth and social development, substantial barriers continue to impede their adoption and diffusion, especially in developing economies. This case study examines the primary obstacles to DT diffusion, such as infrastructure constraints, human capital challenges, affordability, regulatory impediments and market structure issues. These barriers vary widely across regions and demographic groups, creating persistent digital divides that threaten to exacerbate existing socioeconomic inequalities.

The chapter also examines how intellectual property shapes diffusion in the digital era. Global technology standards, such as 4G, 5G, and Wi-Fi, play a central role in digital transformation. The patents protecting inventions essential to these standards, known as standard essential patents (SEPs), are central to digital transformation.[5] The growing importance of interoperability in the era of the Internet of Things (IoT), together with the spread of mobile telecommunications standards beyond mobile phones to a wide range of connected products, including smart cars and smart homes, highlights the expanding role of technology standards across sectors. In this context, a balanced approach that ensures access to technology on fair terms while allowing innovators to recover their research and development investments is essential.

By exploring these dynamics, the analysis seeks to inform policies that foster the effective spread of digital technologies while addressing the risks and inequalities that may emerge. The findings aim to serve a broad set of stakeholders, from technology developers and investors to policymakers and development agencies, who are working to harness digital innovation for inclusive and sustainable growth.

Relevance to innovation economics and global development

To begin, we define digital technologies as those innovations that allow information to flow and communication to take place. They include devices such as mobile phones, computers and radios, along with the services and functions that run through them, such as messaging, online transactions and data processing. They also cover the systems that support these functions, from basic text protocols to complex digital platforms. Over the years, successive generations of digital technologies have emerged. They range from intangible tools, such as cloud computing and artificial intelligence (AI) to those with physical manifestations, such as robots and drones.[6] The current generation is characterized by advances in machine learning (ML), the integration of multiple digital technologies, the rise of smart robotics and the growing prominence of generative AI.

DT diffusion refers to the way these technologies spread across people, firms and institutions.[7] It involves adoption of digital knowledge and digital goods, as well as the use of software and digital services. Diffusion can extend both horizontally across regions and industries, and vertically as organizations and individuals integrate digital technologies more deeply into their activities.

Digital technologies reduce many costs. They make it cheaper to search for, copy and transport information. They lower the cost of storing and processing data. They also cut the cost of targeting and tracking, which makes communication and service delivery more efficient. Quantitative evidence shows that digital technologies, compared to traditional technologies such as steam engines, have spread much faster while their usage intensity gap globally has become wider.[8]

For global development, DT diffusion has emerged as both a powerful enabler and a source of new disparities.[9] They give developing economies new ways to access global frontier knowledge, join international markets and, in some cases, leapfrog stages of development. The rise of information technology in East Asia illustrates this potential.[10] So too does the success of mobile financial services in Sub-Saharan Africa (SSA), which has brought financial inclusion to many who previously had no access. However, access does not automatically translate into adoption, particularly in developing economies. Various factors affect adoption. Unequal digital infrastructure, human skills and regulatory impediments have created new layers of inequality. Vulnerable groups, including women, minorities and rural communities, face a heightened risk of being left behind.

On a positive note, while developing countries' constraints often hinder the diffusion of technologies, they can also serve as catalysts for innovation that benefit both developed and developing economies. For instance, Africa's limited grid access has driven the development of off-grid energy solutions, generating technological knowledge that both developed and developing economies can adapt. Empirical evidence supports this dynamic: technological trajectories originating in Africa that have reached the United States and Japan are linked to battery technologies and fuel cells,[11] while those diffusing to China and India relate to wireless and telephonic communications.[12]

Digital technology diffusion follows distinct patterns that differentiate it from the spread of other innovations and has implications for both developed and developing economies. The following section examines the core features that characterize how digital technologies propagate through economies and societies, focusing on network dynamics, infrastructure requirements, local absorptive capacity,[13] and intellectual property considerations that collectively shape adoption trajectories across diverse contexts.

Bandwidth boom: a key feature of digital technology spread

General purpose technology and network effects

From an innovation economics perspective, the spread of digital technologies offers a clear example of how general purpose technologies (GPTs) move through economies.[14] GPTs propagate through economic systems, creating spillover effects and complementary innovations that extend far beyond the initial technological change. Many digital technologies are considered GPTs, the internet being a classic example. Therefore, understanding technologies that enable internet diffusion provides insight into the broader processes of knowledge transfer and technological learning that underpin innovation-driven growth.

Evidence from literature shows that digital GPTs are growing faster than the average patent filings across all technologies.[15] Roughly speaking, many DTs have also directly benefited from Moore's

Law, which predicts an incredibly rapid decline in the cost of computation over time.[16] In turn, this has made the shelf life of many generations of digital technologies relatively shorter than other goods and services.

Network effects stand as another defining characteristic of internet and general DT diffusion, fundamentally altering traditional technology adoption patterns.[17] Unlike conventional goods, whose value remains constant regardless of user base, digital technologies increase in utility as their adoption widens. This creates powerful feedback loops that accelerate diffusion once critical adoption thresholds are crossed.[18]

Two distinct types of network effects drive DT diffusion. Direct network effects occur when a technology's value grows directly with its user base, exemplified by social media platforms, which become more valuable to users as their social contacts join the network.[19] Indirect network effects emerge through complementary innovations and services that develop around widely adopted technologies. The mobile phone operating system illustrates this dynamic: as device adoption expanded, developer participation in the ecosystem surged, creating millions of applications that further enhanced a platform's value.

These network dynamics create distinct adoption patterns, characterized by initial slow uptake followed by rapid acceleration and eventual saturation. The diffusion of smartphones across income groups demonstrates this pattern vividly.

Firewall ahead: barriers to digital adoption and diffusion

While internet use reached 74 percent of the world's population in 2025, this figure masks significant regional disparities, with the African population at only 36 percent connectivity compared to 92 percent in Europe.[20] These disparities extend beyond simple binary measures of access. They exist at infrastructure, technological, usage and financial level. Quantitative evidence shows that, on average, it takes more than 10 years for a new technological trajectory[21] from around the world to arrive in Africa.[22] These gaps can impact how effectively individuals, firms and institutions leverage digital technologies into daily life and economic activity, ultimately shaping who benefits from digital transformation and to what extent.

Infrastructure constraints and capital requirements

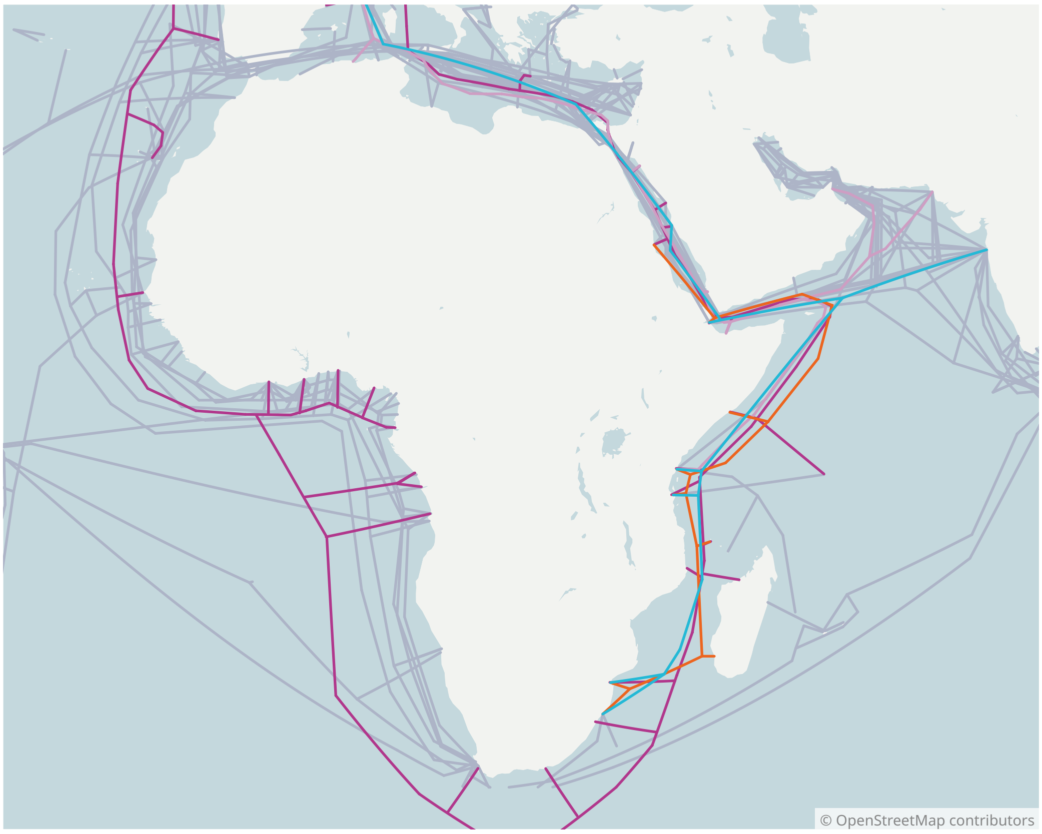
The most fundamental divide is infrastructure and basic connectivity access. This gap stems from physical limitations, such as uneven deployment of broadband networks, energy infrastructure, insufficient carrying or data center capacity, or limited access to appropriate end-user devices. These infrastructures are organized around three interdependent layers that mirror the structure of the internet value chain: network infrastructure, data centers and end-user devices.[23] The internet value chain describes this sequence of interconnected segments through which digital content and services are created, transmitted and consumed.[24] It begins with international connectivity (SMCs and satellites), continues through national backbones and metropolitan networks, and culminates in last-mile access. Along this chain, critical infrastructure nodes, such as data centers, internet exchange points (IXPs) and user terminals, ensure the system's functionality, resilience and efficiency. Weaknesses or bottlenecks in any segment can degrade service quality, increase costs and significantly impede the diffusion of digital technologies, especially in low-connectivity environments.

International infrastructure gap

Backbone connectivity infrastructure, particularly submarine cable deployment and international bandwidth capacity, are critical in facilitating cross-border data flows and ultimately the diffusion of digital technologies.[25] High-capacity SMC connections carry more than 99 percent of international and intercontinental data traffic. They expand internet access and reduce connectivity costs in the most remote parts of the world.[26] Currently, 597 submarine cable systems and 1,712 landing points link countries ranging from small islands to major global economies.[27] Although the greatest advantages are enjoyed by coastal economies, landlocked countries also improve their connectivity through terrestrial fiber networks that interconnect with these cable routes (see Figure 5.1).

Submarine cables connect the smallest economies to the largest global economies

Figure 5.1 Selected global submarine cables and landing points in Africa



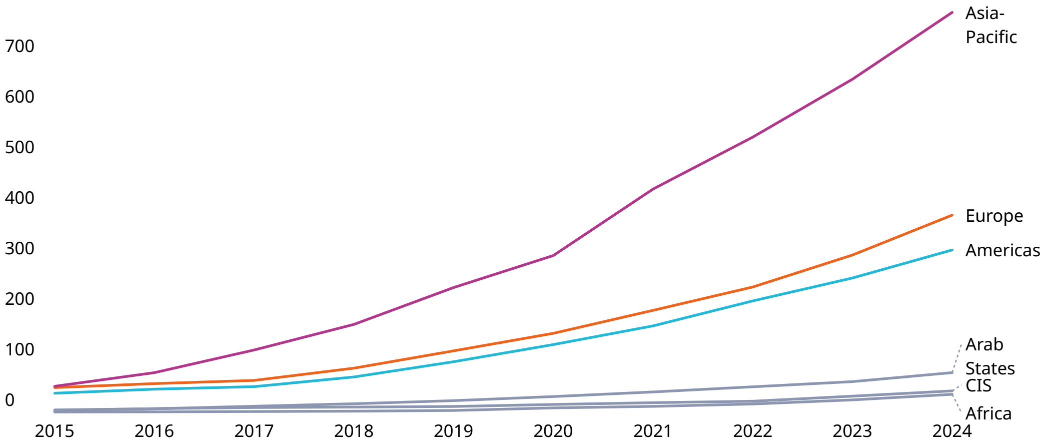
Source: TeleGeography https://submarine-cable-map-2025.telegeography.com.

Access to global bandwidth capacity remains uneven across regions, as illustrated by Figure 5.2. Over the past decade it has expanded significantly in Europe, Asia-Pacific and the Americas, while Africa, the Arab States and Commonwealth of Independent States (CIS) countries continue to lag, despite recent catch-up. These infrastructures are also subject to vulnerability. An SMC cut or fault is probably the most harmful digital hazard. SMC damage is mainly caused by maritime activities, particularly anchoring and fishing nets, and, to a lesser extent, by sabotage or natural hazards, such as earthquakes or typhoons.[28] They were the second most common cause, after government interventions, of internet shutdowns in 2024.[29]

Figure 5.3 illustrates the extent to which regions with a limited number of SMCs, such as Sub-Saharan Africa, are subject to disproportionate level of disruptions in connectivity in cases of SMC damage. In March 2024, for example, 10 African countries, primarily in West and Southern Africa, experienced major internet outages due to failures in four undersea cables.[30] A few months later, countries in East Africa, Europe and Asia also faced service interruptions following cuts to the Eastern Africa Submarine Cable System (EASSy) and the SEACOM cable in the Red Sea.

Regional disparity indicates persistent global digital divides

Figure 5.2 International bandwidth capacity (Gb/s) in selected regions, 2015–2024

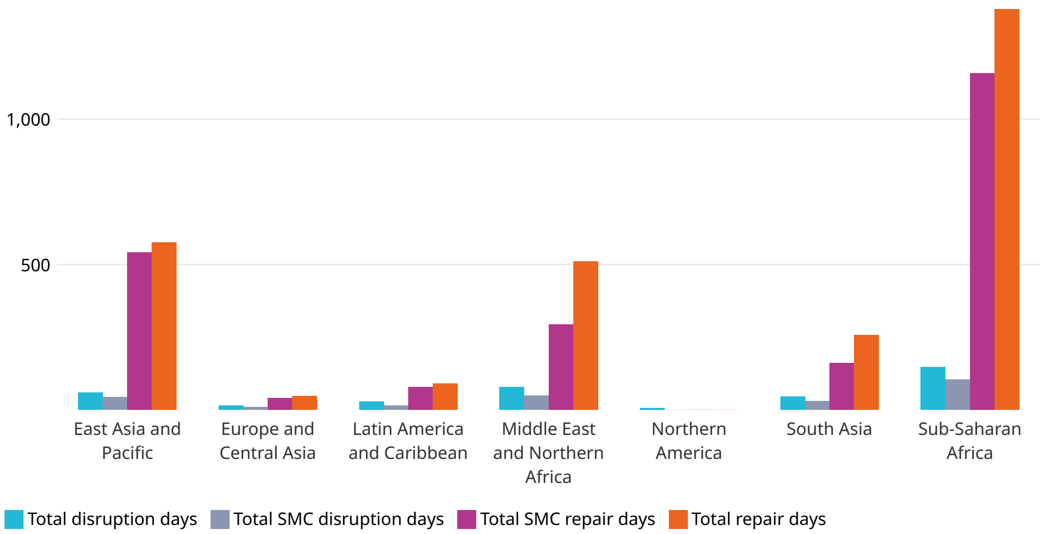


Note: CIS is the Commonwealth of Independent States.

Source: International Telecommunications Union, ITU regional classification https://datahub.itu.int/data/?i=19255.

SMC damage causes a disproportionate level of disruption to connectivity in Sub-Saharan Africa

Figure 5.3 Distribution of internet shutdowns, SMC disruptions and associated repair days, by region, 2008–2020



Note: Raw data drawn from the Subtel forum http://subtelforum.com/category/cable-faults-maintenance, Akamai's reports on the "State of Internet Connectivity" https://www.dropbox.com/t/B7jgPN9if1cZhv5C, and complemented by manual internet searches. The dataset is not exhaustive of all cable faults, but records documented disruptions that effectively impaired internet connectivity. SMC = Submarine cable.

Source: Cariolle, J. (2026). Digital Transformations in Developing Economies: From the First-mile Infrastructure to the End-user Fingertips. *WIPO Economic Research Working Paper Series No. 96*. Geneva: WIPO; data and calculation.

National infrastructure gap

Once SMCs are laid, access to telecommunications and the internet primarily relies on the terrestrial network at the national level. In African countries, this network is mainly the mobile infrastructure network, with cell towers the principal "last-mile" infrastructure (Figure 5.4a). In contrast, European countries extensively rely on fixed broadband networks, including when reaching the last mile, often relegating mobile infrastructure to a supplementary role (Figure 5.4b). This dual deployment pattern profoundly influences internet access devices and the types of digital services accessible to users.

Access to internet infrastructure varies widely between the EU and Africa

Figure 5.4a Access to last-mile infrastructures and internet adoption, Africa, 2005–2025

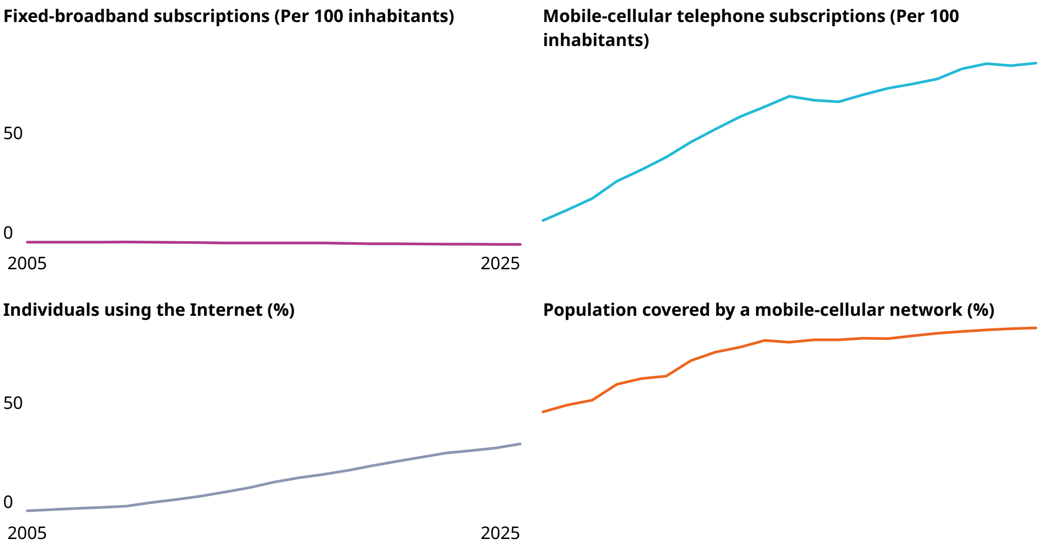
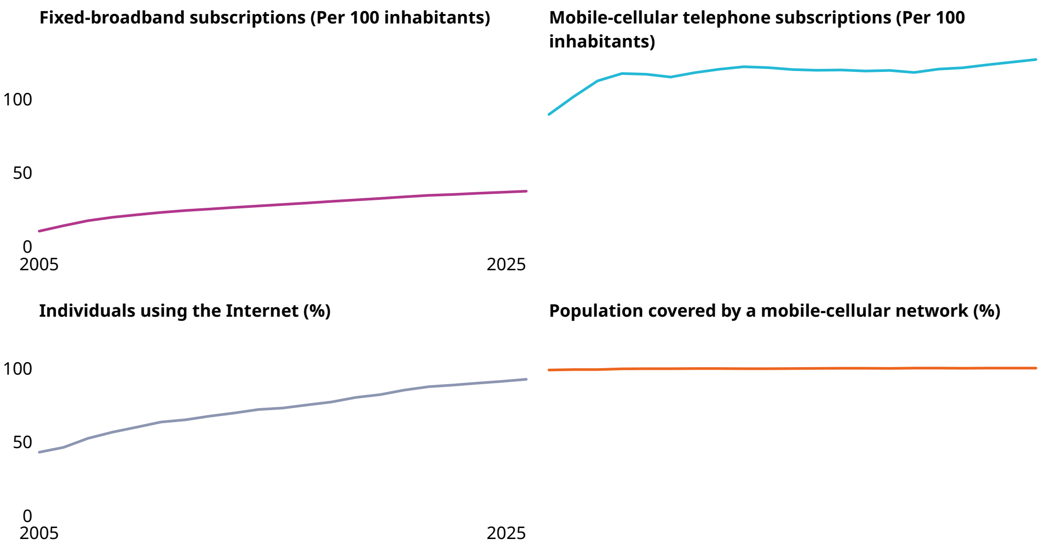


Figure 5.4b Access to last-mile infrastructures and internet adoption, Europe, 2005–2025



Note: Landline internet subscriptions are defined as a fixed access to the public internet with a download speed of at least 256kbit/s. Internet users are people who have accessed the internet from any location in the past three months.

Source: ITU (2025) Measuring digital development: Facts and Figures 2025. International Telecommunication Union https://www.itu.int/en/ITU-D/Statistics/pages/facts/default.aspx.

Technology gap

An often overlooked dimension of digital inequality is the technology gap, which is the difference in the quality and capability of the digital tools available to users. Together with the infrastructure and usage gaps, it shapes how effectively individuals, firms and public institutions can apply digital technologies in daily life and economic activities. Ultimately, these gaps determine the kinds of innovations that emerge, who benefits from digital transformation and to what extent.[31] For instance, while nearly 74 percent of Europe's population had access to 5G networks in 2025, only about 12 percent of Africans did (see Figure 5.5). Even within Africa there are stark disparities in the quality of mobile networks, which varies between urban and rural areas (see Figure 5.6).

Quality of the mobile network available differs drastically between Africa and Europe

Figure 5.5 Population coverage by type of mobile network, Africa and Europe, 2025

Note: The values for 2G and 3G networks show the incremental percentage of the population that is not covered by a more advanced technology network.

Source: ITU (2025). Measuring digital development: Facts and Figures 2025. International Telecommunication Union, https://www.itu.int/en/ITU-D/Statistics/pages/facts/default.aspx.

Quality of the mobile network available differs drastically between rural and urban areas in Africa

Figure 5.6 Population coverage by type of mobile network and area, Africa, 2025

Note: The values for 2G and 3G networks show the incremental percentage of the population that is not covered by a more advanced technology network.

Source: ITU (2025). Measuring digital development: Facts and Figures 2025. International Telecommunication Union, https://www.itu.int/en/ITU-D/Statistics/pages/facts/default.aspx.

In many low-income countries, particularly in Africa, the spread of advanced internet-based technologies remains constrained by low internet penetration and scarce fixed broadband coverage. As a result, much innovation has taken root on mobile platforms. Africa mobile money (MoMo) services, such as Kenya's M-Pesa, show how digital solutions can scale inclusively when they work through basic mobile phones and unstructured supplementary service data (USSD) systems, without needing smartphones or internet access.[32]

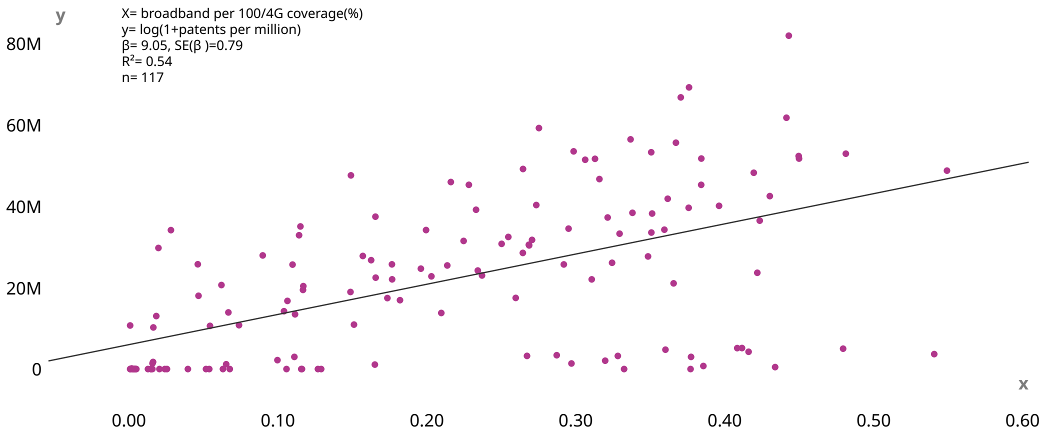
Despite such success stories, the adoption of advanced digital technologies, such as AI, cloud computing, big data analytics and the Internet of Things, remains heavily concentrated in high-income and emerging regions, including Northern America, Western Europe and parts of Asia. These regions benefit from the combined expansion of fixed and mobile broadband networks that support data-intensive applications. Advanced technologies require stable, high-capacity connections, large-scale servers and platforms capable of managing vast data flows – conditions that are still rare in most developing economies.

The result is a dual digital landscape: some countries fully leverage high-value, data-driven innovation, while others depend mainly on simpler, mobile-based solutions. Figure 5.7 illustrates this divide. Countries with both fixed and mobile broadband access show higher innovation outputs, such as patent activity, compared to those with limited infrastructure.

In developing economies, affordability remains the main barrier to accessing high-speed internet, owning smartphones or using mobile internet, underscoring how economic and technological divides continue to reinforce each other.[33]

Better internet infrastructure is correlated with higher innovation outputs

Figure 5.7 Joint access to fixed and mobile broadband technologies and patent creation, 2025



Note: fixed broadband penetration is measured by the number of fixed broadband internet subscriptions per 100 people. Patent creation is the annual number of patents filed per million people.

Sources: World Intellectual Property Organization (WIPO), World Bank (2025); United Nations Population Division, Eurostat, national statistical offices and United Nations Statistics Division.

Usage gap: digital literacy and human capital challenges

The usage gap is shaped by limited digital literacy, skills and the ability to engage in basic and advanced digital activities. At a basic level, digital literacy is often linked to broader affordability issues, as well as language barriers and restrictive social norms, particularly those that disadvantage women and marginalized communities in rural areas. Without these foundational capabilities, potential users cannot effectively utilize available digital technologies.

The gap in intermediate and advanced digital skills has strong ties with education and skilled labor deficits, which combine to shape the absorptive capacity of the population. Many educational systems struggle to cultivate the competencies needed for productive DT adoption, limiting the economic returns from DT investments and hindering the localization and development of contextually relevant digital applications. These challenges are not confined to developing economies. In both developed and developing countries, albeit to varying degrees, disparities persist between urban and rural areas, and between educational and training opportunities available to workers in large firms versus those in small and medium-sized enterprises.

The digital skills gap extends to businesses and governments, hindering organizational adoption of DTs. Similarly, limited technical capabilities within public institutions impede e-government initiatives and digital public services that could otherwise accelerate broader DT diffusion.

Affordability gap: submarine cable deployment and the cost of internet access

As mentioned earlier, the affordability gap continues to present a substantial barrier to DT adoption in low- and middle-income countries. The cost of basic connectivity – “first-mile” access – depends in large part on SMC systems. SMCs require investments of several hundred million dollars and are often financed by consortia of telecom operators. In recent years, large technology companies such as Google, Meta and Microsoft have become leading investors. By 2023, such firms accounted for nearly three-quarters of global bandwidth use.[34]

These international bandwidths lower costs directly by cutting wholesale costs and indirectly by stimulating competition. The size of these effects depends on the structure of domestic markets and the strength of regulation. Empirical evidence from large samples of low-, middle- and high-income countries confirms that the relationship between SMC deployment and broadband prices is not straightforward.[35] In fact, the relationship shows a U-shaped pattern, meaning that low levels of capacity, increases tend to reduce prices, reflecting efficiency gains. Yet beyond a certain point, prices rise again. This may result from the higher costs of maintaining and upgrading infrastructure, or from weaker competitive pressure in large-capacity markets.

Moreover, doubling SMC capacity can cut mobile broadband prices by up to half and fixed broadband prices by about a third, with similar effects across regions.[36] These gains fade over time, especially in fixed broadband markets, where the impact disappears within four years. Over time, prices often return to earlier levels. This may reflect rising network investment costs or weak competitive pressure in fixed broadband markets. In such cases, infrastructure savings are not fully passed on to consumers, slowing internet adoption.

Market concentration also matters. In competitive markets, capacity expansions lead to sustained price reductions. Where markets are more concentrated, the impact of new cables is weaker, especially for fixed broadband. As a result, high costs can keep internet access out of reach in many developing economies, holding back the spread of advanced digital tools and reinforcing global divides. These results are important as they can be factored into policies to alleviate the barriers that disproportionately affect women, rural populations and marginalized communities and reinforce existing patterns of disadvantage.

Institutions, regulations and competition

Regulatory frameworks play a decisive role in determining how quickly and widely digital technologies spread. They shape market entry, competition and innovation, yet restrictive or outdated rules continue to slow DT adoption in many countries.

A country's approach to digital regulation can profoundly affect how technologies take root across its economy. Evidence shows that, in the case of the internet, countries that require internet service providers (ISPs) to obtain formal approval before launching operations tend to have fewer users and hosts. Likewise, government regulation of ISP prices often results in higher end-user costs.[37] These findings highlight how regulatory choices can either promote or hinder digital inclusion.

Data governance frameworks have become another key determinant of diffusion. Clear data protection rules build trust and safeguard privacy, but overly restrictive or ambiguous regulations can deter innovation and raise compliance costs, especially for smaller firms that lack the capacity to navigate complex rules.

Policy predictability is equally critical for investment. Uncertainty or frequent regulatory changes increase risk for telecommunication providers, particularly given the long-term capital commitments required for broadband infrastructure. Stable and transparent regulatory environments are therefore essential to encourage sustained investment, fair competition and the continued spread of digital technologies.

Market structure also shapes DT diffusion by influencing prices, service quality and incentives for innovation. Research consistently shows that competition in telecommunications drives lower prices and better services.[38] However, in many regions, limited competition persists, resulting in market concentration and higher consumer prices.

Recent findings demonstrate that international bandwidth, delivered through SMCs, can reduce broadband costs through two main channels.[39] First, it directly lowers wholesale prices by enabling economies of scale. Second, it indirectly reduces consumer prices when competition ensures that savings are passed on. Where competition remains weak, providers often capture most of these benefits, keeping prices elevated.

The strength of these effects depends on domestic market structure and regulatory oversight. Strong, independent regulators are therefore vital to ensure that infrastructure investments translate into affordable, high-quality connectivity and support broader digital inclusion.

Economic and social impact

The dual nature of digital diffusion and trade

Digital technology diffusion has a dual nature. It acts as a catalyst for export growth and productivity, yet it can also deepen global trade disparities. On the positive side, digital tools improve efficiency, reduce transaction costs and enable innovation. Firms benefit from better inventory management, customer engagement and data-driven decision-making. High-speed connectivity infrastructure has particularly strong effects. The arrival of the SEACOM and EASSy submarine cables in Eastern and Southern Africa, for example, led to higher exports in logistics-intensive sectors, such as minerals and vegetables.[40]

Yet the benefits of connectivity are uneven. Studies show that, while new SMC links encourage export participation among firms in advanced economies, they can lead to exit among exporters in developing economies with limited capacity to absorb digital technologies.[41] Connectivity tends to benefit large, resource-rich firms more than smaller ones. As a result, bilateral submarine cable connections increase the number of exporters by almost 10 percent in developed economies but reduce it by about 8 percent in developing ones.[42]

Recent work highlights the importance of *digital connectedness*.[43] Stronger digital ties expand access to information, technologies and regulations, encouraging export diversification and upgrading. The quality of these connections matters as much as their number. The study shows a positive correlation between international bandwidth capacity and resident patent applications, controlling for GDP per capita, suggesting that connectivity supports innovation beyond income effects. It also indicates that resident patenting is positively associated with high-tech exports. Finally, using digital connectedness instead of bandwidth capacity, it confirms that who a country is connected to is critical for the innovation process: controlling for both GDP per capita and bandwidth capacity, stronger ties to major economic hubs are associated with greater patent activity.

A study conducted on 60 developing countries, including 23 from Sub-Saharan Africa, shows a positive and significant effect of digital connectedness on export complexity, with especially strong impacts in SSA.[44] A notable finding is a *new distance puzzle*: in most regions, the effect of digital connectedness declines with greater distance from major markets except in SSA, where it increases.[45] The study finds that a 3,000 km increase in sea distance reduces the effect on the economic complexity index (ECI)[46] by 47 percent in non-SSA countries but increases it by 75 percent in SSA, suggesting that geographically remote SSA countries, facing high traditional trade barriers, gain disproportionately from improved digital connectivity.

Human capital also shapes outcomes. Broader primary education coverage strengthens the gains from connectivity, while limited internet penetration continues to hold back progress in many African economies.

Overall, the evidence shows that digital connectivity is multidimensional. It links directly to the four divides discussed earlier: the *infrastructure gap*, which reflects whether bandwidth connects to key global and local nodes; the *technology gap*, which captures the quality of digital technologies available to users; the *usage gap*, how effectively firms and individuals engage in basic and advanced digital activities; and the affordability gap, which concerns the cost of connectivity. Addressing all four is essential for digital diffusion to drive inclusive global growth.

Social inclusion and equity considerations

Beyond economic impacts, digital technology diffusion profoundly shapes social inclusion. Digital technologies can either reduce or deepen existing inequalities. This dual potential underscores the importance of inclusive approaches to digital development.

In rural areas, low population density, limited purchasing power and weaker digital skills often slow adoption, even where coverage exists. Yet, once adopted, the effects can be transformative. Mobile telecommunications can reduce isolation, and digital financial services can expand access to payments, credit and savings. The spread of mobile coverage and mobile phones has had a particularly strong impact on agricultural markets, lowering price dispersion and improving producers' access to market information.[47]

By reducing the cost of obtaining and transmitting information, mobile phones can allow farmers and traders to monitor prices across distant markets more frequently and at lower cost. This helps them to identify better trading opportunities and avoid less favorable markets. Studies on India's fisheries[48] and Niger's grain markets[49] show that these information gains lead to narrower price gaps, higher and more stable producer prices, and less waste. Later work confirms that mobile coverage increases the number of markets that traders engage with and strengthens farmers' bargaining power.[50] However, the benefits are not uniform. Early adopters (often larger or better-connected traders) gain first, while late adopters may lag, creating new layers of inequality even as overall efficiency improves.

Evidence from the eight West African Economic and Monetary Union (WAEMU) countries shows that mobile connectivity has the strongest equalizing effect in agricultural tasks where labor markets are segmented by gender, helping to reduce wage disparities within these segments.[51] Mobile access to information also enables farmers to use hired labor more effectively and strengthens workers' bargaining position.

For women, these benefits can be particularly significant. Mobile technologies can help them monetize previously unpaid tasks and negotiate higher wages.[52] Studies find a consistent positive relationship between proximity to 2G+ networks and female wages across multiple agricultural activities, while the link for men is weaker and more varied. This suggests that mobile connectivity delivers disproportionate gains for women, with gender wage gaps widening as distance from network coverage increases.[53] Mobile phone owners also consume more market-purchased food and rely less on self-production, with the shift toward market-based consumption particularly strong in rural areas.[54]

Employment and labor market transformations

The diffusion of digital technologies is reshaping labor markets around the world, transforming the demand for skills, the structure of employment and the geography of work.[55] Digitalization creates new opportunities for job growth, entrepreneurship and productivity gains. DTs can complement labor, enable new forms of work and expand market access, particularly through e-commerce, remote work and online services. Evidence from literature indicates that regions with higher digital adoption tend to experience faster employment growth in technology-intensive and service-oriented sectors, as well as positive spillover effects across local economies.[56]

However, these gains are unevenly distributed.[57] Automation and AI are increasingly replacing routine and manual tasks, displacing workers in certain occupations while creating demand for new, often higher-skilled, roles. This shift has widened wage inequalities and regional divides, especially between workers with advanced digital skills and those without. The platform economy has also generated both opportunities and vulnerabilities. While digital platforms enable flexible and cross-border work, they often depend on precarious, low-paid or invisible labor. Recent research highlights the hidden human effort behind the AI economy, where large-scale data annotation, content moderation and training tasks are outsourced to low-wage workers in developing countries.[58]

These contrasting dynamics illustrate the dual nature of digital diffusion in the labor market. On the one hand, digital technologies can foster inclusive growth, stimulate innovation and create new pathways for youth and women's participation. On the other, they risk reinforcing structural inequalities if benefits are concentrated among highly skilled, well-connected workers in urban areas.

Intellectual property role in diffusion of digital technologies

Intellectual property (IP) systems play a central role in shaping how digital technologies spread. Patent protection, licensing models and trademark regimes all influence who innovates, who gains access and how fast technologies move across markets.

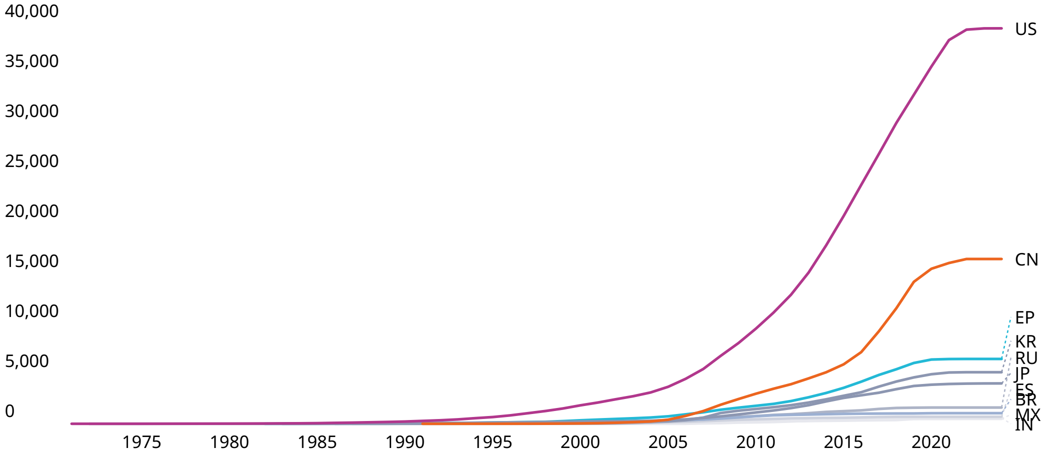
The patent landscape for digital technologies is highly concentrated. Most DT patent applications come from five major jurisdictions; namely, China, the United States, Japan, the

Republic of Korea and the European Patent Office (see Figure 5.8). Together, they account for most global filings. This concentration creates uneven diffusion patterns, as technology often follows the investment and licensing channels controlled by leading patent holders.[59]

Digital technologies typically integrate multiple layers of innovation, many of which rely on technology standards. Technology standards are developed and established in standardization organizations (SOs), also referred to as standards development organizations (SDOs) or standard-setting organizations (SSOs). SOs bring together a range of stakeholders, including industry representatives, researchers, and policymakers, to collaborate in identifying the most effective technical solutions for a given standard. When participants in SOs contribute protected technical solutions to a standard, they commit to licensing their relevant patents to implementers in accordance with the SO's intellectual property rights (IPR) policy. These IPR policies vary, but they generally seek to strike a balance between the interests of SEP owners in recouping research and development investments, on the one hand, and implementers' access to standardized technologies, on the other. For example, the 3rd Generation Partnership Project (3GPP) brings together, so-called Organizational Partners, seven regional and national SDOs.[60] These SDOs have agreed that their IPR policies should be compatible and respected by their respective members, who are encouraged to declare "their willingness to grant licenses on fair, reasonable, and non-discriminatory (FRAND)" terms.[61] Members are also expected to declare, at the earliest opportunity, any IPR they believe to be essential or potentially essential to ongoing work within 3GPP.[62] This call for the declaration of potential SEPs, together with the undertaking to license on FRAND terms, plays a key role in facilitating the diffusion of technologies by helping to create equitable market conditions for both SEP owners and implementers, and by promoting competition and innovation in industries that rely on standardized technologies. However, FRAND negotiations can be complex and may pose a particular burden for smaller companies and firms from developing economies.[63]

Digital technology patenting, especially SEPs, is highly concentrated

Figure 5.8 Cumulative SEPs filings by the top 10 countries, 1970–2022



Note: BR is Brazil, CN is China, EP is the European Patent Office, ES is Spain, IN is India, JP is Japan, KR is the Republic of Korea, MX is Mexico, RU is the Russian Federation, US is the United States.

Source: SEP Standard Patent Application Database (Cumulative) https://www.wipo.int/en/web/patents/topics/sep.

The economic importance of SEPs has grown in recent decades.[64] SEPs often command a higher value since they are integral to industry standards. Firms use them both as strategic assets in cross-licensing negotiations and as sources of direct revenue. Researchers measure this value through indicators such as patent transfers, citations, litigation and firm performance.

Beyond patents, other forms of IP strongly affect digital diffusion. Evidence shows that firms with greater DT capital tend to file new trademarks more frequently and retire existing ones more rapidly, resulting in shorter trademark life cycles. This reflects the faster pace of innovation and product turnover in digital industries, where business value is often realized through greater product variety, as captured by the number of trademarks held.[65] In recent years, the aesthetic appeal of digital products, protected by industrial designs, has also become increasingly important in influencing consumer preferences and adoption. Copyright shapes software adoption, and the rise of open-source licensing has transformed how technologies cross borders and industries. Data protection frameworks also matter.

At the same time, the growing market concentration of major digital platforms raises new policy challenges. A small number of global technology firms increasingly control key digital infrastructures, data resources and IP portfolios, shaping the direction and speed of diffusion. Ensuring dynamic competition therefore requires regulatory frameworks that prevent excessive market dominance, encourage interoperability and promote open innovation. Balancing the legitimate protection of IP rights with measures that safeguard competition and facilitate entry for smaller and local innovators remains a central policy priority for inclusive digital transformation.

Conclusions and policy implications

Several key findings emerge from this analysis of global digital technology diffusion patterns. First, while digital technologies have spread more rapidly than earlier waves of innovation, the depth and quality of adoption differ widely both across and within countries. The classic S-shaped adoption curve remains a useful model, yet its steepness and timing depend heavily on enabling conditions, particularly infrastructure availability, local absorptive capacity, affordability and institutional and regulatory support.

Second, key features of digital technologies, such as their nature as GPTs, and the presence of strong network effects and their adherence to Moore’s Law, make their diffusion fundamentally different from that of other types of technology.

Third, DTs tend to amplify existing strengths and weaknesses rather than generate development automatically. Barriers to diffusion often interact, creating overlapping constraints that single-issue or siloed policy approaches struggle to overcome. Evidence shows that comprehensive digital economy strategies, which integrate infrastructure, skills and regulatory measures, achieve greater and more sustainable impact than fragmented initiatives.

Fourth, the dual nature of digital diffusion in trade and productivity further highlights the importance of complementary policies. While digital connectivity can boost exports, innovation and diversification, gains often accrue disproportionately to large firms and advanced economies. Evidence from Africa shows that investments in submarine cables, mobile infrastructure and digital connectedness yield the strongest benefits when supported by human capital development, digital skills training and inclusive policies that enable smaller firms and marginalized groups to participate in global markets.

Fifth, regulatory and market conditions are central to digital technology diffusion. Outdated rules, weak competition and policy uncertainty raise costs, deter investment and limit inclusion. Transparent, stable regulation and strong competition oversight are essential to ensure that infrastructure investments translate into affordable, high-quality and inclusive digital connectivity.

Sixth, IP systems are pivotal in determining how digital technologies diffuse across economies. While IP protection supports innovation and interoperability through the participation of innovative companies in technology standardization, supra-FRAND licensing rates, complex licensing negotiations, and fragmented data governance can slow diffusion, especially in developing economies. Knowledge sharing, education and balanced IP governance are critical for inclusive digital transformation.

In sum, accelerating and broadening the diffusion of digital technologies requires a holistic policy approach. Expanding infrastructure must go hand in hand with strengthening competition, reforming regulatory frameworks, investing in human capital and promoting equitable IP governance. These combined actions will help to ensure that digital transformation becomes a driver of inclusive and sustainable growth, enabling all economies, and all people, to participate fully in the opportunities of the digital age.

Notes

1 See Goldfarb, A. and Tucker, C. (2019). Digital economics. *Journal of Economic Literature*, 57(1), 3–43.

2 This case study draws on Cariolle J. (2026). Digital Transformations in Developing Economies: From the First-mile Infrastructure to the End-user Fingertips. *WIPO Economic Research Working Paper Series No. 96*. Geneva: World Intellectual Property Organization.

3 See Krugmann, P. (2025). Tech and the Wealth of Nations: Does every country need to have a Silicon Valley?

4 See WIPO (2019). *World Intellectual Property Report 2019: The Geography of Innovation: Local Hotspots, Global Networks* https://www.wipo.int/wipr/en/2019/.

5 A SEP is a patent that protects an invention essential to the implementation of a particular technology standard. See https://www.wipo.int/en/web/patents/topics/sep.

6 See Ciarli, T., Kenney, M., Massini, S. *et al*. (2021). Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy*, 50(7), 104289.

7 See Chapters 1 and 2 for a broad definition of diffusion of technologies and knowledge and the channels through which technological knowledge diffuses.

8 See Chapter 1 of this report. See Comin, D. and Mestieri, M. (2018). If technology has arrived everywhere, why has income diverged? *American Economic Journal: Macroeconomics*, 10(3), 137–78.

9 Covid-19 and the polarized impact of remote working is an example of this dual effect. See Braesemann, F., Stephany, F., Teutloff, O. *et al*. (2022). The global polarisation of remote work. *PloS one*, 17(10), e0274630.

10 See the section on "Rise of IT in East Asian countries" in WIPO (2022). *World Intellectual Property Report 2022: The Direction of Innovation* https://www.wipo.int/en/web/world-ip-report/2022/index.

11 IPC code H01M is the most frequent class originating from Africa that has reached the United States. See Table 4 in Miguelez E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

12 IPC codes H04L is the most frequent class originating from Africa that has reached China and India. See Table 4 in Miguelez E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

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15 See Figure 3.7 in WIPO (2022). *World Intellectual Property Report 2022: The Direction of Innovation*. Geneva: WIPO. https://www.wipo.int/en/web/world-ip-report/2022/index.

16 Intel co-founder, Gordon Moore's observation that the speed and capability of computers can be expected to double every two years, as a result of increases in the number of transistors a microchip can contain.

17 See Björkegren, D. (2019). The adoption of network goods: Evidence from the spread of mobile phones in Rwanda. *The Review of Economic Studies*, 86(3), 1033–60; and see Björkegren, D. and Karaca, B.C. (2022). Network adoption subsidies: A digital evaluation of a rural mobile phone program in Rwanda. *Journal of Development Economics*, 154, 102762.

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20 See ITU (2025). Measuring Digital Development Facts and Figures. International Telecommunications Union, https://www.itu.int/en/ITU-D/Statistics/Pages/facts/default.aspx?utm_source.

21 See the definition of "trajectory" in Chapter 2 and in Miguelez E., Pezzoni, M., Visentin, F. *et al*. (2025). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

22 See Figure 13 in Miguelez E., Pezzoni, M., Visentin, F. *et al*. (2026). The Changing Geography of International Knowledge Diffusion. *WIPO Economic Research Working Paper Series No. 92*. Geneva: WIPO.

23 See UNCTAD (2024). *Digital Economy Report 2024: Shaping an Environmentally Sustainable and Inclusive Digital Future*. UN Trade and Development, based on Pohl, J. and Hinterholzer, S. (2023). Environmental effects along the life cycle of digital technologies. *Einstein Centre Digital Future Working Paper No. 6*. Berlin: ECDF.

24 See Schumann, R. and Kende, M. (2013). Lifting barriers to Internet development in Africa: Suggestions for improving connectivity. *Analysys Mason Report for the Internet Society, London*, 9, 30–5.

25 See Hjort, J. and Poulsen, J. (2019). The arrival of fast Internet and employment in Africa. *American Economic Review*, 109(3), 1032–79; Cariolle, J. (2021). International connectivity and the digital divide in Sub-Saharan Africa. *Information Economics & Policy*, 55, 100901; Simione, F.F. and Li, Y. (2021). The macroeconomic impacts of digitalization in Sub-Saharan Africa: Evidence from submarine cables. *IMF Working Paper WP/21/110.*, International Monetary Fund.

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27 See TeleGeography https://submarine-cable-map-2025.telegeography.com/.

28 See https://www.iscpc.org/publications/icpc-viewpoints/damage-to-submarine-cables-from-dragged-anchors/.

29 See https://radar.cloudflare.com/year-in-review/2024#internet-outages.

30 See https://carnegieendowment.org/research/2025/03/beneath-the-waves-addressing-vulnerabilities-in-africas-undersea-digital-infrastructure?lang=en.

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32 See Aker, J.C. and Cariolle, J. (2023). *Mobile Phones and Development in Africa*. Springer International Publishing AG.

33 See Global Findex (2025). The Global Findex Database: Connectivity and Financial Inclusion in the Digital Economy. World Bank Group.

34 See TeleGeography (2025). Transport Networks, formerly Global Bandwidth Research Service, https://submarine-cable-map-2025.telegeography.com.

35 See Cariolle, J., Houngbonon, G.V., Silue, T. *et al*. (2025). Submarine Cables, Internet Access Price and the Role of Competition and Regulation. *Ferdi Working Paper No. 357*. Updated version of the *World Bank Policy Research Paper Series No. 10840*. World Bank Group.

36 See Cariolle, J., Houngbonon, G.V., Silue, T. *et al*. (2025). Submarine Cables, Internet Access Price and the Role of Competition and Regulation. *Ferdi Working Paper No. 357*. Updated version of the *World Bank Policy Research Paper Series No. 10840*. World Bank Group.

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40 See Cariolle, J. and Da Piedade, C. (Forthcoming). Submarine Cable Infrastructure and Trade in Africa.

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42 See Imbruno, M., Cariolle, J. and de Melo, J. (2022). Digital connectivity and firm participation in foreign markets: An exporter-based bilateral analysis, *Journal of Development Economics*, 177,103551.

43 The concept of digital connectedness measures how closely a country is linked to world markets through its share of global gross domestic product (GDP) directly connected by submarine cables. See Cariolle, J. and Da Piedade, C. (2023). Digital connectedness and exports upgrading: Is Sub-Saharan Africa catching up? *The World Economy*, 46(11), 3325–44.

44 See Cariolle, J. and Da Piedade, C. (2023). Digital connectedness and exports upgrading: Is Sub-Saharan Africa catching up? *The World Economy*, 46(11), 3325–44.

45 See Imbruno, M., Cariolle, J. and de Melo, J. (2022). Digital connectivity and firm participation in foreign markets: An exporter-based bilateral analysis, *Journal of Development Economics*, in press.

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47 See Jensen, R. (2007). The digital provide: Information (technology), market performance, and welfare in the South Indian fisheries sector. *The Quarterly Journal of Economics*, 122(3), 879–924; Aker, J.C. (2010). Information from markets near and far: Mobile phones and agricultural markets in Niger. *American Economic Journal: Applied Economics*, 2(3), 46–59; Suri, T., Aker, J., Batista, C. *et al*. (2023). Mobile money. *VoxDevLit*, 2(2), 3.

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52 See Ngoa, G.B.N. and Song, J.S. (2021). Female participation in African labor markets: The role of information and communication technologies. *Telecommunications Policy*, 45(9), 102174; Cariolle, J. and Dsouza, A. (Forthcoming), Rural Youth Employment in the West African Economic and Monetary Untion. Ferdi report, 96 pages.

53 See Cariolle, J. and Da Piedade, C. (Forthcoming). Submarine Cable Infrastructure and Trade in Africa.

54 See Cariolle, J. and Carroll, D. (2025). From Phone Access to Food Markets: How Mobile Connectivity is Transforming Rural Livelihoods in West Africa. *Ferdi Working Paper No. 341*.

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57 See Hjort, J. and Poulsen, J. (2019). The arrival of fast Internet and employment in Africa. *American Economic Review*, 109(3), 1032–79.

58 See Cant, C., Muldoon, J. and Graham, M. (2024). *Feeding the Machine: The Hidden Human Labor Powering AI*. Bloomsbury Publishing USA.

59 See WIPO (2022). *World Intellectual Property Report 2022: The Direction of Innovation*.Geneva: WIPO.https://www.wipo.int/en/web/world-ip-report/2022/index

60 See https://www.3gpp.org/about-us/partners.

61 See Article 3.1 3GPP agreement: https://www.3gpp.org/ftp/Inbox/2008_web_files/3gppagre.pdf; https://www.3gpp.org/about-us/3gpp-faqs.

62 See Article 55 of the 3GPP Working Procedures: https://www.3gpp.org/ftp/Information/Working_Procedures/3GPP_WP.htm#Article_55, https://www.3gpp.org/about-us/3gpp-faqs.

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64 See Contreras, J.L. (2019). *Technical Standards, Standards-setting Organizations, and Intellectual Property: A Survey of the Literature (with an emphasis on empirical approaches)*. Edward Elgar Publishing, 185–235.

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Acronyms

AGC
Apollo guidance computer

AI
artificial intelligence

AMC
advance market commitment

CalTech
California Institute of Technology

CCD
charged-coupled device

CCS
carbon capture and storage

CEPI
Coalition for Epidemic Preparedness Innovation

CFRP
carbon fiber and carbon fiber reinforced plastics

CMR
Committee on Medical Research

CO_2
carbon dioxide

COVID
coronavirus disease, also COVID-19

DARPA
US Defense Advanced Research Projects Agency

DoD
US Department of Defense

DoE
Department of Energy

D-RAM
dynamic random-access memory

DT
digital technology

FDA
US Food and Drug Administration

FDI
foreign direct investment

FRAND
fair, reasonable and non-discriminatory

GE
Genetically engineered

GenAI
generative artificial intelligence

GHG
greenhouse gas

GM
genetically modified

GPS
global positioning system

GPT
general purpose technology

GRI
government research institutes

ICAO
International Civil Aviation Organization

HT
Herbicide tolerant

ICT
information and communication technology

IEA
International Energy Agency

IoT
Internet of Things

IP
intellectual property

IPC
International Patent Classification

IPR
intellectual property rights

IRENA
International Renewable Energy Agency

ISO
International Organization for Standardization

ISP
internet service provider

IT
information technology

ITU
International Telecommunication Union

JPL
Jet Propulsion Laboratory

LAC
Latin America and the Caribbean

LCOE
levelized cost of energy

LLM
large language model

LNP
lipid nanoparticle

LiDAR
Light detection and ranging

MIT
Massachusetts Institute of Technology

ML
machine learning

MoMo
mobile money

mRNA
messenger ribonucleic acid

NARS
national agriculture research system

NASA
National Aeronautics and Space Administration

NGO
non-governmental organization

NIH
National Institutes of Health

NRC
National Research Council

NRRL
Northern Regional Research Laboratory

NSF
National Science Foundation

OBM
original brand manufacturer

ODM
original design manufacturer

OEM
original equipment manufacturer

ORSD
Office of Scientific Research and Development

OWS
Operation Warp Speed (renamed the Countermeasures Acceleration Group (CAG) in 2021)

PAT
precision agriculture technology

PNT
position, navigation and timing data

PV
photovoltaic

R&D
research and development

RPS
radioisotope power system

RR
RoundUp Ready™

RTK-GNSS
Real-time kinematic global navigation satellite system

SARS-CoV-2
Severe Acute Respiratory Syndrome Coronavirus 2

SDO
standards development organization

SEP
standard essential patent

SMC
submarine cable

SME
small and medium-sized enterprise

SMS
short messaging service

SO
standardization organization

SSA
Sub-Saharan Africa

SSO
standard-setting organization

TFP
total factor productivity

3GPP
3rd Generation Partnership Project

TRIPS
Trade-related Aspects of Intellectual Property Rights

TRL
technology readiness level

UAV
Unmanned aerial vehicle

UNFCCC
United Nations Framework Convention on Climate Change

US
United States of America

USPTO
United States Patent and Trademark Office

VTF
vaccine taskforce

VTR
variable rate technology

V2G
vehicle-to-grid

WAEMU
West African Economic and Monetary Union

WIPO
World Intellectual Property Organization

WPB
War Production Board

ZEV
zero emission vehicle

Glossary

Adoption intensity: a measure based on the number of capital units embodying a new technology within a country or output volume generated using innovative technology.

Adoption lag: number of years between the first invention of a technology anywhere in the world and its first recorded adoption within a particular country.

Agro-ecological condition: refers to a zone that has a combination of soil, landform and climactic conditions characteristic of a given region.

Blue hydrogen: hydrogen produced from natural gas with emissions trapped using carbon capture and storage (CCS). Sometimes called "low-carbon hydrogen" because CO_2 is created, but not released into the environment.

Breakthrough technologies: technologies that emerge through a novel combination of existing technical knowledge.

Deep tech innovations: includes transformative technologies like artificial intelligence, quantum technologies, advanced biotechnology, and clean energy solutions.

General purpose technology (GPT): a foundational technology that can be used across many different industries and activities, spurring widespread innovation and long-term gains in productivity and economic change. Rather than serving a single function, GPT enables numerous new applications and improvements throughout the economy. The steam engine and the internet are examples of a GPT.

Generative AI (GenAI): based on machine learning, generative AI tools are trained using enormous amounts of data, often including billions of pages of text or images. Training data sets may consist of freely available, unencumbered information (pure data), protected data (such as copyright protected works) or a mixture of both. The trained AI tool is then prompted by human input which triggers a complex series of often billions of calculations that determine the output. It is generally not possible to predict the output or determine whether and to what extent certain parts of the training data influence the output produced.

Green hydrogen: hydrogen created through electrolysis using clean electricity from renewable sources to split water into hydrogen and oxygen. The process emits no carbon.

Grey hydrogen: hydrogen produced from natural gas using steam methane reformation without capturing the resultant greenhouse gas emissions.

Knowledge spillovers: spillovers occur when ideas, expertise, or skills spread from one economic actor to others without there being a deliberate transfer or payment. They may further adopt outside a formal technology transfer framework. Spillovers happen unintentionally as others benefit from knowledge flows the originator did not plan or control.

Patent thicket: a dense web of overlapping patent rights requiring innovators to secure multiple licenses in order to commercialize a new technology.

Reuse (of technological knowledge): the replication of an existing combination of technological components in subsequent inventions. Consistent with a evolutionary view of innovation, reuse captures the continuation of a technological trajectory through later patents that employ the same combination of patent classification codes first introduced by an initial invention.

Standard essential patent (SEP): a patent that protects an invention essential to the implementation of a particular technology standard. Such standards are critical for ensuring the safety, interoperability, and compatibility of different products and services made available by various companies.

Technology adoption: describes how individuals and organizations start using a new technology and integrate it into their activities.

Technology diffusion: refers to the broader spread of new technology across firms, industries or economies as more users adopt it over time.

Technology readiness level (TRL): technologies are classified using the (TRL) framework, originally developed by NASA in the 1970s and subsequently adapted by the International Energy Agency (IEA) for energy technologies. The classification employed in this analysis draws from the IEA Clean Energy Technology Guide.

Technology transfer: a particular form of adoption. It involves the deliberate sharing of knowledge, skills, methods or technologies between parties.

Technological trajectory: the path of incremental improvements and problem-solving activities that a technology follows over time, guided by a shared set of principles and technical solutions.

Total factor productivity (TFP): a measure of productivity across firms, industries and sectors. In agriculture, TFP is calculated as the ratio of output farmers produce with the amount of land, labor, machinery and other inputs used.

Technical notes

Country income groups

This report uses the World Bank income classification to refer to particular country groups. The classification is based on gross national income per capita in 2018 and establishes the following four groups: low-income economies (USD 1,135 or less); lower middle-income economies (USD 1,136 to USD 4,465); upper middle-income economies (USD 4,466 to USD 13,845); and high-income economies (USD 13,846 or more).

More information on this classification is available at: http://data.worldbank.org/about/country-classifications.

Country region groups

The country regions used in this report are closely based on the geographic regions from the Standard Country or Area Codes for Statistics Use, 1999 (Revision 4) known as M49 and published by the Statistics Division (UNDS) of the Department of Economic and Social Affairs, United Nations (UN). The full methodology can be found at unstats.un.org. To simplify the analysis, some changes are introduced to this methodology. These are the following: Western Europe includes Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, and United Kingdom. Central and Eastern Europe includes all countries in the M49's Northern and Southern Europe regions not included in Western Europe. The geographical subregions Southern Asia, Central Asia and Southeastern Asia are grouped in one category, which also includes Mongolia.

Scientific publication data

The scientific publication data used in this report comes from Open Alex. Open Alex is a catalog of 474 million scholarly works, which links to authors, institutions, funders and other related information.

More information on Open Alex is available at:https://openalex.org/.

Patent data

The patent data used in this report are from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT, autumn 2025 edition).

The main unit of analysis is the first filing for a set of patent applications filed in one or more countries and claiming the same invention. Each set containing one first and, potentially, several subsequent filings that refer to the same identical priority is defined as a patent family.

The analysis focuses only on foreign-oriented patent families. Foreign-oriented patent families concern those inventions for which the applicant has sought patent protection beyond its home patent office.

Mapping strategies

The mapping strategy for each of the case studies – agricultural technologies and clean technologies – is based on prior studies and expert suggestions. Each strategy was compared to existing alternative sources whenever possible.

The patent mapping strategies are based on a combination of patent classifications – namely, the International Patent Classification (IPC) and/or the Cooperative Patent Classification (CPC) – and keywords searched for in PATSTAT data. The production mapping strategies are based on the categories from the Standard International Trade Classification (SITC) version 3.

A brief description of the two strategies follows:

Agricultural technologies

The agricultural technologies patent mapping is based on the combination of CPC and IPC symbol of "A01".

Clean technologies

The clean technologies mapping cover technologies related to combustion and engine control, exhaust gas treatment, waste and wastewater management, materials processing and recycling, chemical and biological treatment processes, energy conversion and storage, environmental monitoring, and supporting mechanical, hydraulic, and infrastructure systems.

The relevant IPC class symbols include F02D/41, F02D/43, F02M/23, F02M/25, F02M/27, F23J/15, F23B/80, F23C/09, F23C/10, F02D/45, F02P/05, B01D/46, B01D/47, B01D/49, B01D/50, B01D/51, B03C/03, F01N/03, F01N/05, F01N/07, F01N/09, F01N/11, F01N/13, B63J/04, C05F/01, C05F/05, C05F/07, C05F/09, C05F/17, E01H/15, B22F/08, B29B/07, B29B/17, B30B/09, B62D/67, B65H/73, B65D/65, C02F, C03B/01, C03C/06, C04B/07, C04B/11, C04B/18, C04B/33, C05F, C08J/11, C09K/03, C09K/11, C10G/01, C10L/05, C10L/10, C10M/175, C12N/15, C21B/07, C21C/05, C22B/07, C22B/19, C22B/25, D01G/11, D21B/01, D21C/05, D21H/17, E01H, E02B/15, E03B/01, E03B/03, E03B/05, E03B/09, E03B/11, E03C/01, E03D/01, E03D/03, E03D/05, E03D/13, E03F, F01D/11, F01K/23, F01M/13, F02B/47, F02D/21, F02M/03, F02M/31, F16K/21, F16L/55, F23G/05, F23G/07, F27B/01, G01M/15, G08B/21, H01B/15, H01J/09, H01M/06, H01M/10, A01G/25, A23K/01, A43B/01, A43B/21, A47K/11, A61L/11, B01J/23, B03B/09, B09B, B09C, B63B/35, and B65F.

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The *World Intellectual Property Report 2026: Technology on the Move* sheds light on how technologies diffuse and what drives successful diffusion outcomes. It examines the role of intellectual property (IP) and how IP systems influence the pace and direction of diffusion.

The report highlights two major insights: technologies are spreading faster than ever, and the usage gap between advanced and other economies is narrowing. However, meaningful adoption still depends on local capabilities, infrastructure, and regulatory conditions, as shown in the case studies on agricultural, clean, and digital technologies. Finally, four key factors are identified that shape diffusion: technology characteristics, information flows, absorptive capacity, and supportive policy and IP frameworks.

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INTELLECTUAL PROPERTY
ORGANIZATION