Executive Summary

An ecosystem of interdependent digital technologies is advancing fast, driving major economic and societal changes. Data feed this ecosystem, creating immense value but also risks for privacy and safety on line. Some of these technologies are already an integral part of daily life, while others remain on the horizon. The *OECD Digital Economy Outlook 2024 (Volume 1)* provides new insights on key technologies that underpin digital transformation and their impacts.

Using big data and machine-learning techniques, *Volume 1* provides new estimates of the growth rate of the ecosystem's core – the information and communications technology (ICT) sector. It then looks toward the technology frontier with perspectives on the future of artificial intelligence (AI) and how it can be shaped into a positive force. *Volume 1* also analyses how people, firms and governments are adopting digital technologies, offering insights into the scale and scope of digital divides and how to boost equal opportunity and inclusion. To that end, it looks at the critical need for next generation wireless networks to provide unlimited connectivity everywhere. Moving beyond the hype of immersive technologies, *Volume 1* examines the proven ability of virtual reality (VR) to scale, while identifying its opportunities and risks. Finally, it shines a spotlight on mental health in digital environments, including those most at risk.

Key findings

The ICT sector continues to outperform the total economy

While the "digital economy" is no longer strictly confined to the ICT sector, this sector remains at its heart, underpinning digital innovation. Yet there is a lack of timely data on the performance of this vital sector, which limits the visibility of policy makers. Using a novel nowcasting model that leverages big data and machine-learning techniques, *Volume 1* provides up-to-date and comparable data on the economic growth of the ICT sector. Estimates indicate that in the past decade, the ICT sector grew about three times faster than the total economy in OECD countries. In 2023, the ICT sector reached new heights, growing 7.6% on average in the OECD.

AI actors must collaborate to unleash innovation responsibly and ensure its benefits are widely shared

Technological leaps in AI are prompting people to reconsider the future of work, leisure and society. The future of AI may yield tremendous benefits, including enhanced productivity gains, accelerated scientific progress and solutions for helping to address climate change. However, AI advances also present risks, including those related to trust, fairness, privacy, safety and accountability. Since 2022, media reports of AI-related incidents – i.e. an event involving an AI system that directly or indirectly leads to harm – and hazards grew significantly, led mainly by incidents related to generative AI. Building a shared understanding of the key opportunities and risks will be critical to ensure AI is trustworthy and used to benefit humanity and the planet. Toward this end, countries are developing national AI strategies and other AI policy initiatives at a record pace.

Next generation wireless networks are key to unlimited connectivity everywhere

The proliferation of emerging technologies goes hand-in-hand with the generation of enormous amounts of data, leading to increased demand for higher bandwidth and more data processing. Many new applications also rely on improved broadband performance, including higher speeds and lower network response times (latency). Almost all OECD countries have deployed 5G networks and are starting to shift to "beyond 5G" or "6G" research. They are also harnessing satellites and other aerial technologies, which are expanding worldwide. These technologies are beginning to provide quality connectivity, particularly in rural and underserved areas, helping to reduce connectivity divides. In the future, the integration of terrestrial and non-terrestrial wireless technologies will expand the connectivity ecosystem and make it more resilient.

Digital technology diffusion and the skills to use them effectively are uneven, limiting equal opportunity and inclusion

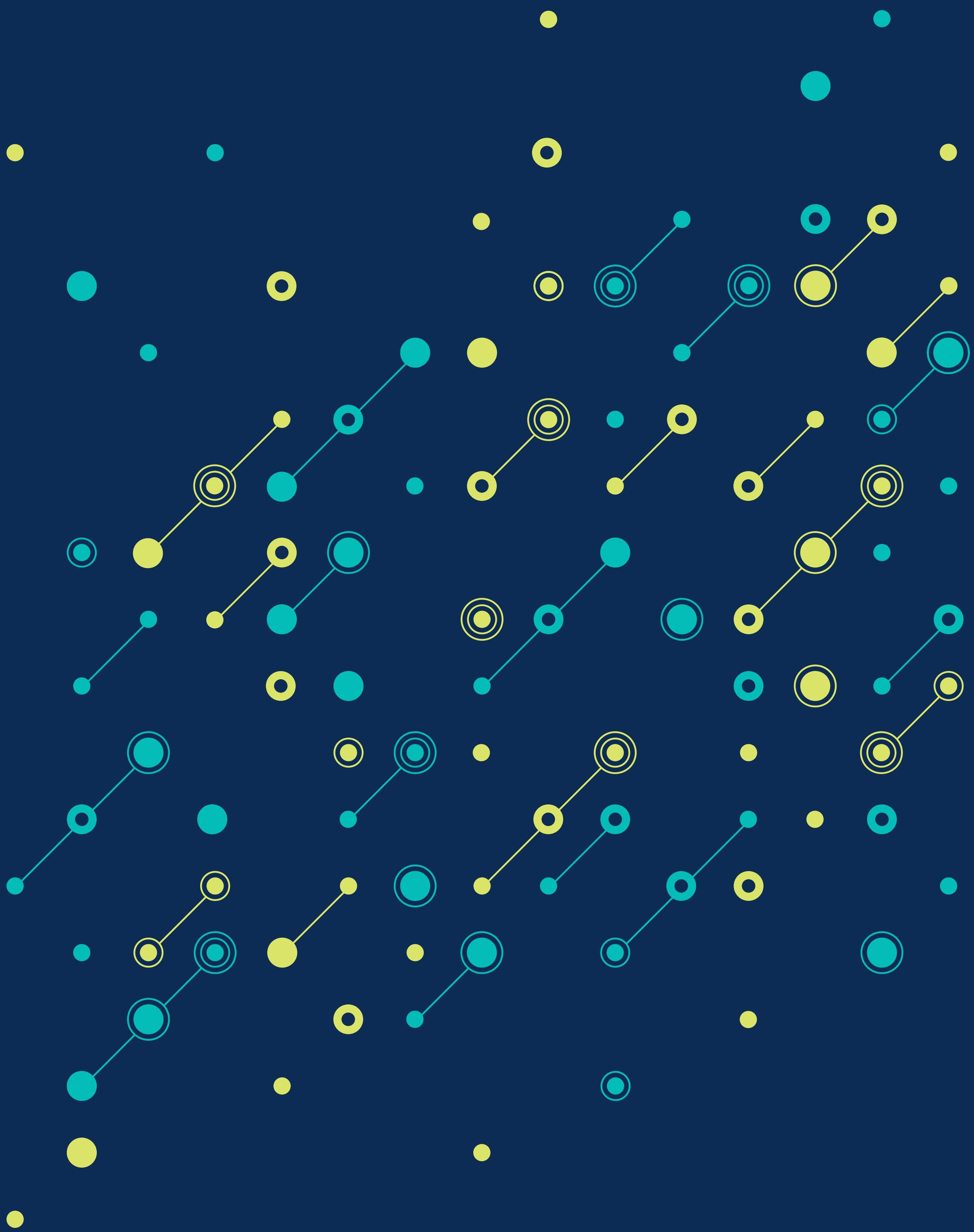
Technologies such as cloud computing and Internet of Things devices have diffused widely. In contrast, adoption of data-dependent technologies like AI remains low and is concentrated in certain sectors. Creating a level playing field among firms in access to key inputs – including data – can accelerate technology diffusion. Stronger technology diffusion and investments in skills can help close divides in Internet use, which are pronounced by age, education and income and put equal opportunity and inclusion at risk. To encourage more people and firms to use online services, governments should provide user-centric, inclusive online services and invest in skills, while supporting those most at risk of being left behind.

Immersive technologies like VR enable extraordinary experiences, but safety on and off line is key

The rise of three-dimensional technologies is accelerating, raising questions about their opportunities and risks. VR is the one immersive medium that has proven its ability to scale in a range of areas. Body tracking facilitates "presence" and sets VR apart from other immersive environments. VR can be self-contained, social or industrial, comprising a cycle of tracking, rendering and display – a continuous process that occurs in real time. VR is best for experiences that are otherwise dangerous, impossible, counterproductive or expensive. Given no one can opt out or go "incognito" in VR, new approaches beyond traditional consent-based models will be needed to protect privacy. Mental and physical safety in VR must be carefully considered, especially for children and in moving vehicles.

Negative behaviours in digital environments are rising and disproportionally affect girls

Anonymity, disembodiment and disinhibition help explain why people communicate and interact differently on line than off line, and they can lead to negative behaviours. Since 2017, the overall rate of young people reporting difficulties in everyday functioning and feeling unhappy because of social media use increased by 49%, with the share of girls increasing more than twice as much as boys. Cyberbullying is also becoming more common among young people, with girls experiencing higher rates than boys on average. Cyberbullying victimisation rose by 26% between 2017 and 2022. While research shows that moderate use of digital technologies tends to be beneficial, "overuse" may be detrimental. Countries and regions with a higher prevalence of problematic social media users have higher percentages of intensive users of instant messaging, social networks, e-mail and other forms of online communication.



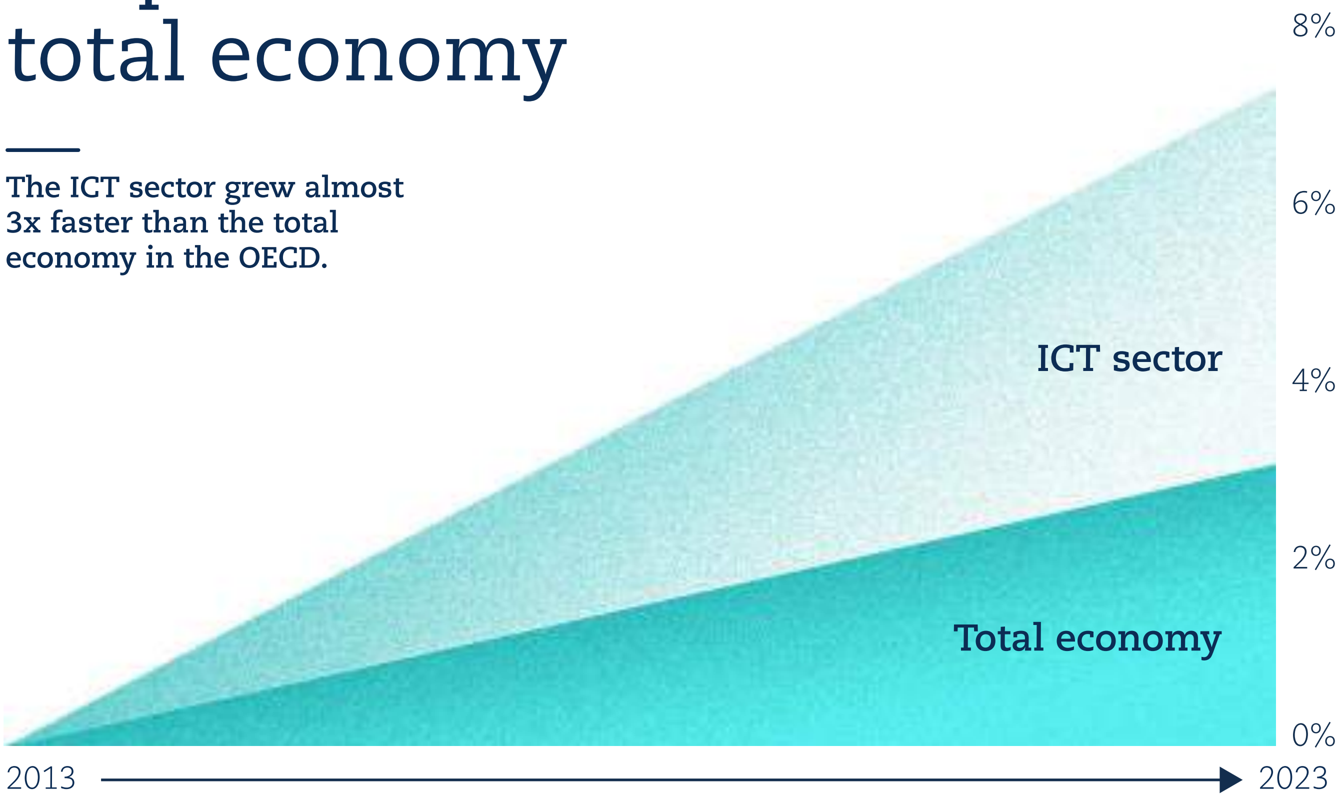
Chapter 1

The growth outlook of the ICT sector

As digital technologies spread and their societal and economic impact deepen, the need for evidence-based policies increases. However, there is a lack of timely and cross-country comparable data on the growth of digital components of the economy. While the "digital economy" is no longer strictly confined to the information and communication technology (ICT) sector, the latter remains at its core and it is essential to supporting further digital innovation. This chapter presents the results of a nowcasting model that leverages online search data and machine-learning techniques to provide policy makers with up-to-date and comparable data on the economic growth of the ICT sector. These estimates can help shed light on how this sector is performing today, which will help inform policy decisions that impact this vital sector of the economy in the future.

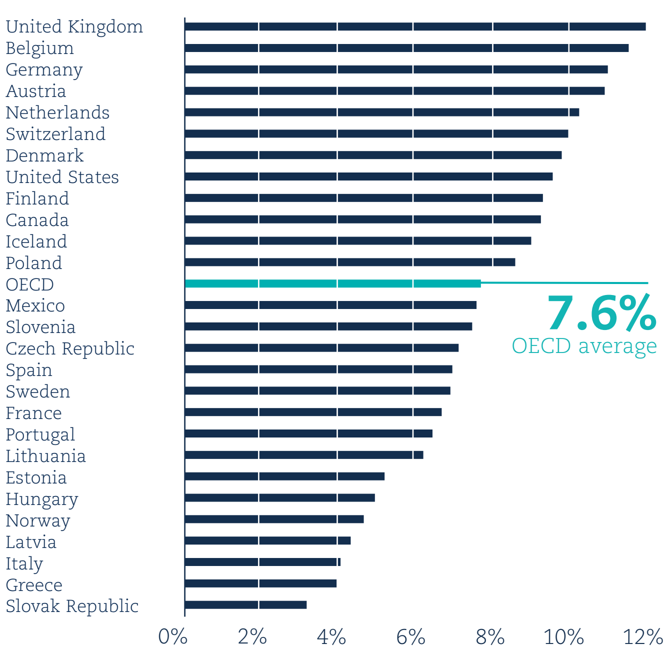
ICT sector growth outperforms the total economy

The ICT sector grew almost 3x faster than the total economy in the OECD.

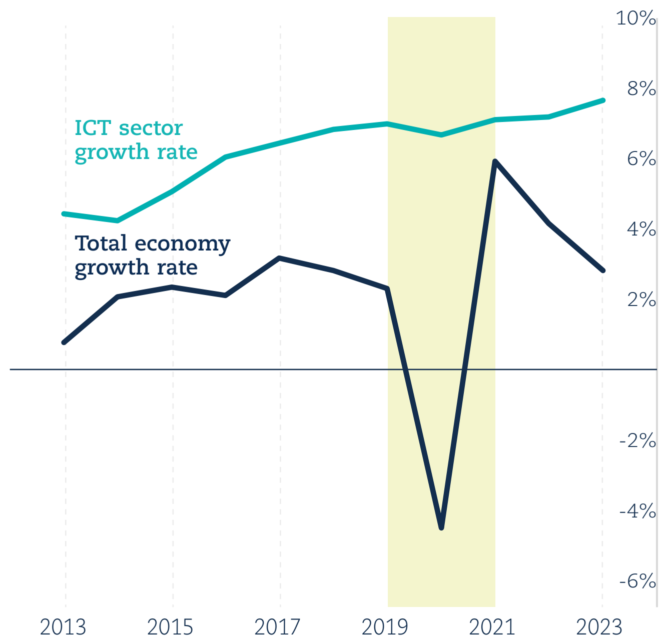


Estimates show strong growth of the ICT sector in 2023.

Predicted ICT sector growth rate, 2023



The ICT sector shrugged off the COVID-19 pandemic, in contrast to the broader economy.



Key findings

Timely estimates of ICT sector growth help inform policy decisions that affect this vital sector

- Non-traditional data and machine-learning techniques can complement official statistics of the digitalisation of the economy. An artificial neural network that leverages Google Trends data provides a measure of ICT sector growth in real time.
- Real-time indicators of economic growth in the ICT sector can help governments understand how the sector performs today, which will help inform future policy decisions.

In the past decade, the ICT sector grew in most OECD countries, but not equally

- Between 2013 and 2023, all OECD countries had positive ICT sector growth rates on average. However, a substantial gap (10 percentage points) separates the economies with top and bottom ICT sector performance.

ICT growth rates in OECD countries are converging

- In 2011, the average growth rate of the fourth quartile (top 25%) of OECD countries was 13 times higher than the average growth of the first quartile (bottom 25%). In 2023, the average growth of the fourth quartile was only twice as high as the average growth of the first quartile. Disparities in ICT sector growth across OECD countries sectors have thus decreased considerably. This is explained both by an increase in the average growth rates in the first quartile and a decrease in the fourth quartile.

The ICT sector performed strongly in all OECD countries in 2023

- Nowcast estimates show that the ICT sector performed strongly in 2023, with an average growth rate of 7.6%. In many OECD countries, 2023 was a record year for ICT sector growth. Ten countries had growth rates above 9%: Austria, Belgium, Canada, Denmark, Finland, Germany, the Netherlands, Switzerland, the United Kingdom and the United States. In Belgium and the United Kingdom, ICT sector growth exceeded 11%. Increased demand for ICT products and services following COVID-19 may partially explain the strong performance in 2023.

While countries measure some aspects of the digitalisation of the economy, they only focus on household and business uptake of digital technologies and activities. Typically, they survey the use of information and communication technologies (ICTs), such as the OECD model surveys on ICT Access and Usage by Businesses, Households and Individuals (OECD, 2015[1]) (OECD, 2015[2]). They may also include additional questions in established business or household surveys.

The uptake and intensity of digital activities in our daily lives are of great interest. However, these metrics do not produce a monetary estimate of the level of production associated with digital transformation or quantify efficiency gains from changing production processes. This lack of a direct link between the value of production associated with digital activity, or productivity gains from using digital technologies, provides only a partial picture of the impact of digital technologies and data on traditional macroeconomic indicators.

Lack of comparable indicators across countries of the value of the "digital economy" has led to a proliferation of measurement efforts. From the national perspective, focus has centred on creation of digital supply-use tables (DSUTs) and digital economy satellite accounts in the System of National Accounts (SNA) (OECD, 2020[3]) (Mitchell, 2021[4]). Incorporating the digital dimension of the economy in the SNA is the best long-term solution to this measurement problem. However, it will take many years before such statistics can be implemented and populated in a comparable way across countries.

As digital transformation intensifies, the need for sound and timely measurements of the digital parts of the economy increases. This chapter aims to help advance efforts to measure a core component of the "digital economy" – the ICT sector. This work contributes to the evidence base by producing real-time estimates of the economic growth of the ICT sector using machine-learning and big data. These estimates can provide timely input into the design and development of digital policies complementing official statistics produced by national statistical offices. A technical paper details the methodology used to construct the nowcast estimates (Umana Dajud, forthcoming[5]).

An overview of the efforts to measure the digital transformation

Measuring the extent of the digital economy is complex, partly because digital technologies and data are everywhere to a greater or lesser extent. Foremost, as countries have tried to measure the impact of digitalisation in a way that is consistent with national accounts, they have questioned what economic activity should be considered part of the "digital economy".

DSUTs will improve measurement in the medium term

DSUTs provide a flexible framework to measure the digital parts of the economy that does not rely on or promote any single definition or indicator as being representative of the digital economy (Mitchell, 2021[4]). DSUTs (Box 1.1) not only focus on the various products and actors associated with digital transformation, but also identify the nature of the transactions between these actors. This framework also delineates transactions based on whether they are digitally ordered and/or delivered.

Among other notable changes, the DSUT framework improves the measurement of digital transformation by adding seven supplementary columns to traditional supply-use tables (SUTs). These seven columns correspond to different types of digital industries (e.g. digital intermediary platforms explicitly charging a fee, data and advertising driven platforms, e-tailers). A second important feature is the inclusion of an aggregation of ICT goods and services product rows. This aggregation will provide a simple measure of use-intensity of ICT products of different activities (household consumption, investment, and exports) (Mitchell, 2021[4]). Finally, DSUTs will include additional product rows to explicitly include cloud computing and digital intermediary services.

Box 1.1. The SNA and the digital economy

The SNA offers the most robust framework to measure the digital economy. International statistical standards for National Accounts ensure that measurements are comparable across countries. The framework captures changes in production chains brought on by digitalisation as it already includes any value added. Adopting DSUTs would carve out the contribution of the digital economy. In the absence of one indicator representing all economic aspects of digital transformation, DSUTs can provide estimates to suit a wide range of user needs.

Once implemented, DSUTs will considerably improve the measurement of the digital economy in official statistics. However, there are significant challenges. If these challenges are overcome, DSUTs could be implemented by OECD countries in the medium term.

One obstacle to be overcome is the lack of the required data to populate DSUTs. For traditional SUTs, statistical offices rely on administrative data and business surveys. These sources provide enough data to produce traditional SUTs but not DSUTs (Mitchell, 2021[4]). As a result, implementing DSUTs requires either modifying currently existing or developing new surveys.

Despite these challenges, DSUTs provide a promising avenue to improve the measurement of the digital economy in the medium-term. Practical guidance for how to compile DSUTs, including an illustrative list of statistics that some statistical agencies currently compile, can be found in Mitchell (2021[4]).

Data on the uptake of digital technologies provides complementary information

A second approach to capture the digital transformation is measuring the uptake of digital technologies. Consumer and business use of ICT goods and services has rapidly evolved during the past decades. The development of digital technologies has transformed consumer behaviour and led to the creation of new business models.

Accompanying these changes, the measurement of the uptake of digital technologies has improved considerably. Official household and business statistics often include several measures of the adoption of both mature digital tools (e.g. online platforms or electronic payments) and sophisticated digital technologies (e.g. artificial intelligence, big data analytics). Multiple surveys implemented at the national level have helped build the evidence base in this area.

In this context, in 2002 the OECD introduced two model surveys meant to set international standards to produce indicators of digital transformation in a comparable way. The model survey on the adoption and use of ICTs by households and individuals, as well as the survey on ICT usage by businesses, were designed to improve the measurement of the availability and use of ICT technologies by households, individuals, and businesses, while considering emerging policy needs (OECD, 2015[1]).

The OECD model survey on households and individuals focuses on the core dimensions of digital transformation such as "access to the Internet, the frequency and intensity of use, the uptake of e-commerce, [and] individuals' IT skills" (OECD, 2015[1]). Similarly, the survey on the use of ICTs by businesses is intended to support national statistical offices in collecting core statistics to measure the digital transformation (broadband adoption, computer use, selling online etc.).

This survey also includes supplementary modules that allow for a more in-depth understanding of the use of ICT technologies (i.e. data analytics services; radio-frequency identification; software-as-a-service). On the one hand, using a core survey guarantees that countries prioritise a common set of measures. This set of common measures is essential as it ensures that the most important aspects of digital transformation are measured in all OECD countries in a comparable way. On the other hand, the supplementary modules allow measurement of emerging technologies and trends without foregoing the core part of the survey (OECD, 2015[2]).

Other approaches to measuring digitalisation of the economy

The digital intensity of economic sectors can also provide an indication of the digital parts of the economy. Countries produce their own taxonomies (Statistics Canada, 2019[6]) (US Bureau of Economic Analysis, 2018[7]), and the OECD developed a taxonomy across 12 countries (Calvino et al., 2018[8]). The OECD taxonomy includes a technological component (ICT investment, ICT intermediate consumption and robots), the human capital required to embed technology in production (ICT specialists), and the way technologies influence firm behaviour on the output market (online sales).

The taxonomy is used in a variety of indicators on the OECD Going Digital Toolkit[1] (e.g. digital-intensive sectors' contribution to value added growth).[2] Dashboards like the Toolkit are an important element of this measurement ecosystem. Along with its Data Kitchen, the Toolkit provides policy makers and analysts with key indicators for each dimension of the Going Digital Integrated Policy Framework (OECD, 2019[9]). In this way, it allows for a comprehensive view of available measures about a country's digital performance.

There have also been various efforts to measure different aspects of digital transformation, including digital trade (Mourougane, 2021[10]). Statistics Netherlands has, for example, developed an innovative methodology that combines firms' value-added tax declarations and web-scrapping techniques to estimate cross-border digital trade flows of goods (Meertens et al., 2020[11]). Credit card data have also been used to measure digital trade flows of both goods and services (OECD, 2019[12]; Cavallo, Mishra and Spilimbergo, 2022[13]). The OECD has also strived to measure developments in artificial intelligence including patents (Dernis et al., 2021[14]), trademarks (Nakazato and Squicciarini, 2021[15]) and skills (Samek, Squicciarini and Cammeraat, 2021[16]).

Despite these efforts, there is a lack of timely monetary measures of the digitalisation of the economy comparable across countries

The uptake of digital technologies by households and businesses provides important information about the speed and extent of digital transformation. However, these measurements do not provide information on the evolution of the monetary value of the digital economy. In the medium term, development and implementation of DSUTs will provide part of this information. In the meantime, timely and comparable data across countries are lacking on this front.

As digital transformation progresses, the digital economy moves beyond ICTs to touch all sectors. At the same time, the ICT sector remains at the core of digital transformation, essential to supporting further digital innovation and the economy as a whole. Previous OECD research shows that an increase of multi-factor productivity in the ICT sector can affect overall economic growth (Nicoletti and Scarpetta, 2003[17]).

The contribution of the value added directly generated by the ICT sector in OECD countries increased during the past decade. For countries covered by the OECD Structural Analysis Database (STAN),[3] the ICT sector represented on average 3.9% of total value added in 2010. By 2019, this figure had increased by almost 40%, reaching on average 5.4% of total value added.

Computers, software, and online services, which all form the backbone of digital transformation are changing rapidly. However, the publication lags inherent in official statistics are considerably longer for sectoral growth rates than for consolidated, economy-wide growth rates. Real-time indicators of the economic growth of the ICT sector can help governments understand the sector's current performance, which will help inform future policy decisions.

Methodology for measuring the growth of the ICT sector in real time

Recent advances in statistical techniques have improved the performance of forecasts that use non-traditional data sources. This chapter uses these techniques to measure the economic growth of the ICT sector in OECD countries in real time (i.e. nowcasting), rather than as a forecast. Google Trends data provides valuable information on economic performance.[4,5] The OECD used Google Trends data to nowcast trade in services during the COVID-19 period (Jaax, Gonzales and Mourougane, 2021[18]), as well as to develop weekly estimates of gross domestic product growth rates (Woloszko, 2020[19]). The OECD AI Policy Observatory also regularly leverages non-traditional data to measure the use and diffusion of artificial intelligence technologies in real time.[6]

A nowcasting approach that is parsimonious with data

The model used for this chapter builds on the innovative methodology used to estimate real-time growth rates for the whole economy as developed in OECD (2020[19]). The modified methodology is used to nowcast ICT sector growth rates in OECD countries. For this purpose, the nowcasting procedure follows the OECD (2002[20]) definition of the ICT sector as "a combination of manufacturing and services industries that capture, transmit and display data and information electronically". Following this definition at the two-digit level of the ISIC Rev.4 industry classification (Horvát and Webb, 2020[21]), the ICT sector encompasses three subdivisions: Computer, electronic and optical products (D26), Telecommunications (D61), and IT and other information services (D62-63/D62T63). Values in this paper may sometimes differ from those of national statistical offices, as some countries use other definitions of the ICT sector in their national accounts.

STAN[7] provides data on the value added of the ICT sector for most OECD countries. For a few of them, these data are not available (Australia, Chile, Colombia, Costa Rica, Ireland, Israel, Japan, Korea, Luxembourg, New Zealand and Türkiye). Once STAN also makes data available for these countries, they can be easily included in the nowcasting model.

The nowcasting model uses only two different inputs: ICT sector growth rates in OECD countries and Google Trends data. ICT sector growth rates are computed using data from STAN. More specifically, annual estimates of ICT value-added in volumes[8] from this database are used to compute annual ICT growth rates for 27 OECD countries, from 2010 to 2018 or 2019 depending on the country.

Google Trends provides two different types of data on Internet searches: keywords and predefined categories. Keywords are available for any word that was sufficiently searched on line. Predefined categories regroup different keyword searches into meaningful clusters. These categories have the advantage of being directly comparable across countries, whereas this is not always the case for keywords. Also, some categories are directly related to the ICT sector. Table 1.1 shows nine Google Trends categories directly related to the different components of the ICT sector, although many more are available.

Table 1.1. An indicative matching of Google Trends categories related to the ICT sector

ISIC Rev.4 code	ISIC Rev. 4 division	Google Trends category	Google Trends category ID
D26	Computer, electronic and optical products	Computer Servers	728
		Consumer Electronics	78
		Binoculars, Telescopes, Optical Devices	1384
D61	Telecommunications	Telecom	13
		Mobile Phones	390
		Communications Equipment	385
D62-63/D62T63	IT and other information services	Network Storage	729
		Internet Software	807
		Web Services	302

Note: This table includes a non-exhaustive list of available Google Trends categories related to the ICT sector.

Sources: OECD STAN Database, *http://oe.cd/stan*; Google Trends (accessed on 19 February 2024).

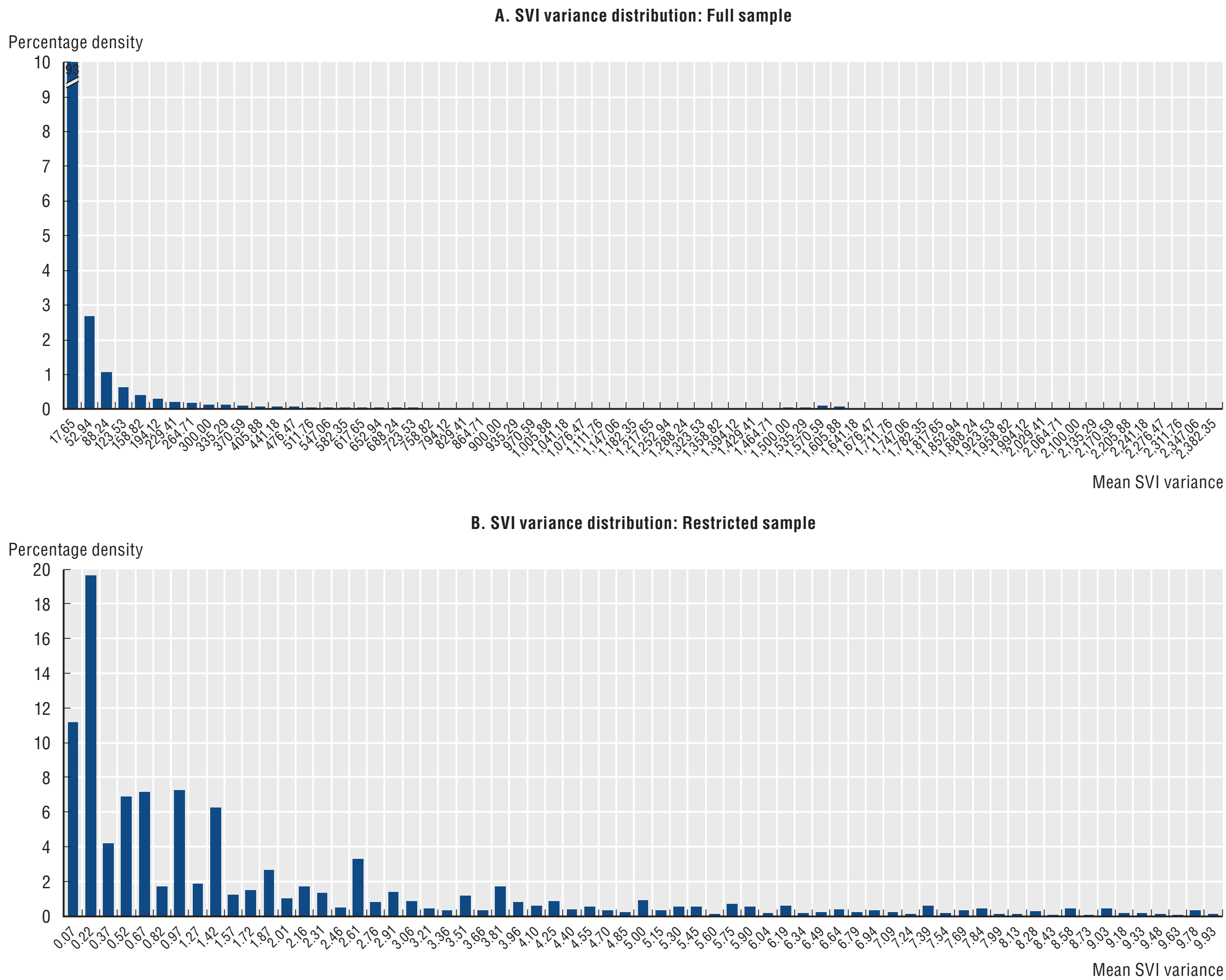
Google Trends provides a time series index of the volume of queries that users enter in Google at a geographic location and at a given time: the Search Volume Index (SVI). The SVI does not represent the actual search volume number; it is an index ranging from 0 to 100 based on the normalised query search volumes in each month and location. The nowcasting estimates in this chapter rely on a monthly panel of SVI queries for 1 131 categories.[9] These cover all OECD countries, from January 2004 to December 2023 (inclusive).

Extracting useful information from Google Trends data

Google Trends data have proven to be valuable in diverse areas (e.g. economics, epidemiology or finance). The data have nonetheless important limitations. First, to preserve the confidentiality of searches, Google provides an SVI based on a random sample of all searches in each category. This is not a problem for popular categories since the sample is large enough to be representative of all searches in those categories. However, for less popular categories, the obtained sample is smaller and therefore might not be representative of the population of searches. Hence, SVIs from categories with few observations in their universe of searches may exhibit a large sampling variance across different draws (Combes and Bortoli, 2016[22]).

One way to identify and fix the sampling noise is to draw multiple samples from Google Trends at different points in time. A threshold is set above which the variance across draws is considered too high. In this chapter, five different Google Trends samples were drawn for every category in every country and the corresponding variance was computed. A threshold of ten[10] was set for the maximum tolerated variance, following an analysis of observed variance in the dataset. Therefore, all the country-category combinations with a variance larger than ten across the five Google Trends samples are dropped.[11] Figure 1.1 shows the distribution of the sampling noise (i.e. SVI variance) before (panel A) and after (panel B), dropping the categories with a variance above ten. As shown in the figure, this threshold eliminates most of the highly volatile categories that could otherwise reduce accuracy of the nowcasting model.[12]

Figure 1.1. Sampling noise distribution before and after correction



Notes: SVI = Search Volume Index. This figure shows the cumulative distribution of the variance across five Google Trends draws (i.e. the "sample noise"). The upper table displays the results for the full sample, while the lower one presents observations whose variance across the five draws is inferior or equal to ten.

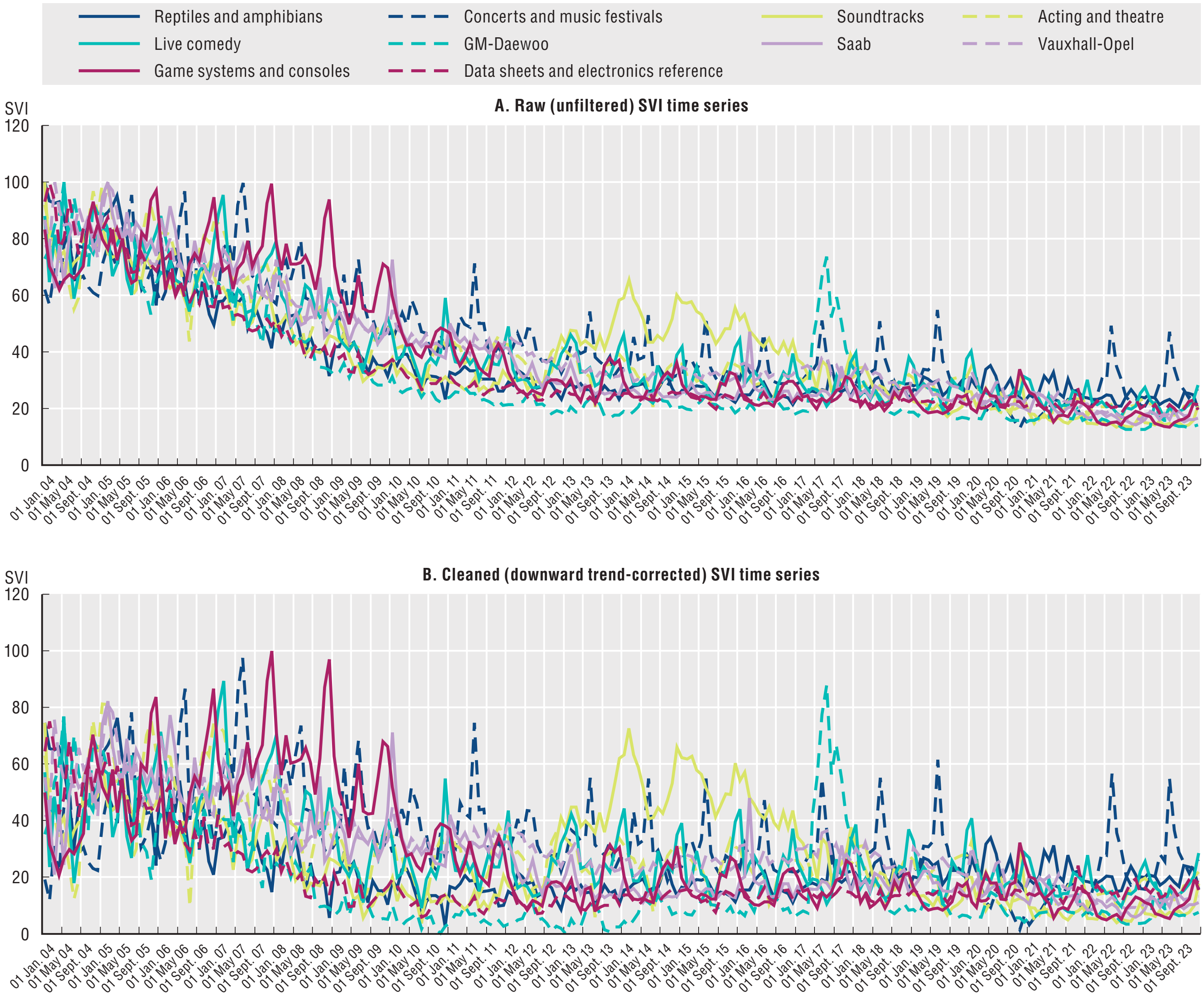
Source: Authors' calculations based on Google Trends data (accessed on 19 February 2024).

StatLink https://stat.link/zuhp79

A second issue with Google Trends is a downward trend for almost all SVIs. An increasing number of Google users since 2004 explains this trend as this number is the denominator for the formula to compute SVIs. This downward bias seems, however, to fade starting in 2010, as the number of Google users increased less rapidly over those years. Panel A of Figure 1.2 plots the SVIs for ten Google Trends categories, chosen randomly in the Netherlands, between 2004 and 2023. The non-linear downward trend, which does not imply these categories became less popular, is clearly visible.

To filter out the downward trend from SVIs, non-parametric locally weighted scatterplot smoothing (LOWESS) is applied to the data. The LOWESS smoother runs a locally weighted regression. The procedure is normally used to filter out the seasonality in Google Trends data (Choi and Varian, 2012[23]). In this chapter, the LOWESS smoother is applied to correct the downward trend of SVIs (Figure 1.2, panel B).

Figure 1.2. Raw and cleaned SVI time series for ten Google Trends categories in the Netherlands, 2004-23



Notes: SVI = Search Volume Index. This figure shows the non-linear bias inherent in all Google Trends series by showing the evolution of the SVIs for ten Google Trends categories (panel A). This downward bias was corrected using a LOWESS smoother on the mean SVI series rescaled from 0 to 100 (panel B).

Source: Authors' calculations using Google Trends data (accessed on 19 February 2024).

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A neural network to measure ICT sector growth in real time

The nowcasting procedure used in this chapter relies on a machine-learning algorithm to fit the relationship between Google Trends data and the ICT sector growth in each country. Given the large quantity of data made available by Google searches, the complex relations between the many features of the data can be modelled using machine-learning. Machine-learning is better suited to detect and model non-linearities than traditional statistical and econometric techniques (Woloszko, 2020[19]).

The model used to nowcast the growth of the ICT sector in OECD countries in this chapter is an artificial neural network.[13] This type of network is based on a simplified probabilistic modelling of organic neurons. More precisely, the machine learning model is a multilayer perceptron. In this type of model, the connection between layers is established only in one direction avoiding any loops in the network.

The model used to compute the nowcasts has two hidden layers of 2 400 and 800 neurons. To train the model, the stochastic gradient-based optimiser developed by Kingma and Ba (2015[24]) is used. The nowcasting procedure in this chapter uses this method due to its computational efficiency. A rectified linear unit function (ReLU) is used to establish connections between the nodes of the model. The function is activated, and thus the connections established, only when a threshold value is exceeded. One of the main advantages of the stochastic gradient-based optimiser is its computational efficiency.

An agnostic modelling approach

The choice of applying machine-learning techniques instead of more traditional statistical and econometrics methods was guided by the ability of neural networks to capture complex, often non-linear, relationships between variables. This principle guides every modelling decision in this chapter. Three of these choices, noted below, are central to the performance of the model.

The first choice is what variables to include in the nowcasting model. Google Trends has 1 131 predefined categories that are comparable across countries. Instead of choosing variables for the model based on intuition, and ultimately arbitrarily, all Google Trends categories are included. The optimisation of the neural network then determines which variables and connections are relevant for measuring the growth of the ICT sector in real time. This modelling decision comes at the cost of not being able to interpret the relation between specific categories and ICT sector growth rates. However, the main goal of the nowcasting model is to measure ICT sector growth in real time as accurately as possible and not to understand how Google searches affect its growth.

The second modelling choice regards network hyperparameters. Hyperparameters are those values set before the model starts learning,[14] while parameters are the estimates learnt by the model. Here again, the methodology is not to be guided by intuition. For this reason, the hyperparameters search was automatised using a grid search function. Root mean squared error (RMSE) was used as the decision parameter for the grid search in the procedure. The number of layers, the learning rate, and the activation function were all chosen through the automatised hyperparameter search.

The third choice concerns the computation of standard errors. Following this agnostic principle, standard errors are computed using a bootstrapping procedure that does not rely on specific assumptions about data distribution. For this purpose, 2 000 random samples with replacement are drawn from the data. The model is then retrained using each new sample. Next, standard errors are ordered to keep 90% confidence intervals.

Evaluating nowcasting performance

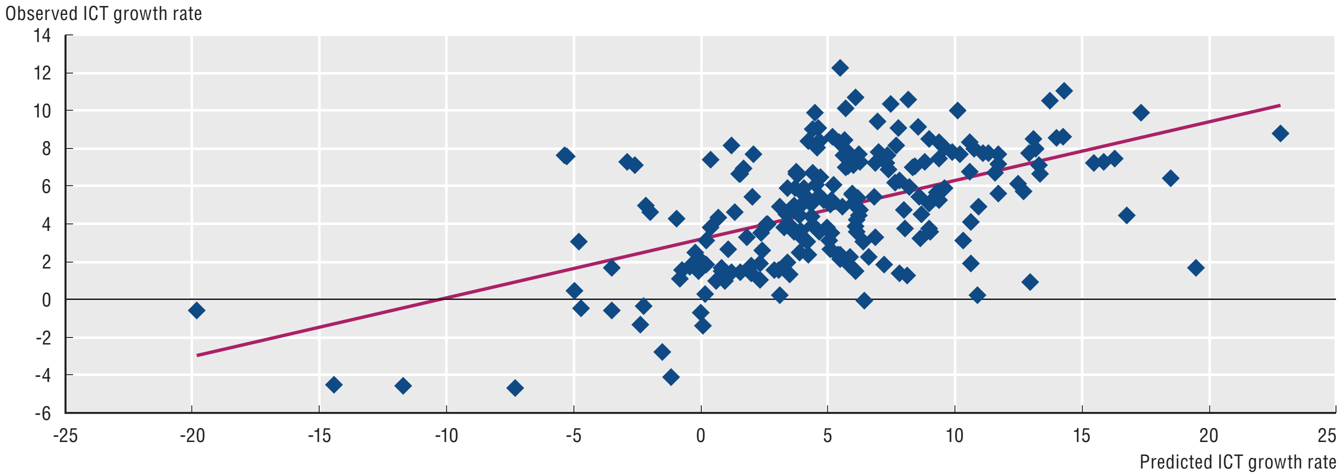
To train and evaluate the artificial neural network, ICT sector growth rates are split into two different samples – training and validation. The training sample comprises data from 2011 to 2018. Data for the last available year in STAN (2019) are chosen for the validation sample.

The performance of the artificial neural network is evaluated using the RMSE of both the training and validation samples. The RMSE can be thought as a measure of the distance separating the values predicted by the neural network and the observed values from the data. For the training sample, the RMSE is 2.9 and for the validation sample it is 2.7. These values can be compared to the very high standard deviation of observed ICT sector growth rates (5.4%).[15]

Figure 1.3 plots ICT sector growth rates predicted by the model against observed growth rates. The figure shows a clear correlation between observed and predicted growth rates of 54% that is statistically significant at the 1% level. This strong positive correlation is in line with obtained RMSE values.

Figure 1.3. The nowcasting model performs strongly

Correlation between the observed and predicted ICT sector growth rates, 2011-19



Notes: ICT = Information and communication technology. The correlation coefficient is 0.54, significant at a 1% level.

Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024). StatLink contains more data.

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In comparison, a standard autoregressive model AR (1) using only historical current account data to predict ICT sector growth in the next period yields an RMSE of 4.82. Thus, the predictions using Google Trends are twice as precise as those using a single lag autoregressive model.

The good performance of the neural network could be based on a common seasonality between Google Trends data and growth rates of the ICT sector. For example, Google Trends could hypothetically be capturing the procyclical economic performance of the ICT sector. The neural network used in this chapter captures, however, a number of more complex non-linear interactions rather than a cyclical component between Google Trends data and the ICT sector growth. Effectively, the correlation between Google Trends data and the ICT sector growth rates is negligible (-2.8%). A common cyclical behaviour of Google searches and growth rates in the ICT sector therefore does not explain the predictions of the neural network.

The growth outlook for the ICT sector across countries

The nowcasting model yields measures of economic performance for all the years for which there are no observed data. For most countries this is 2020 to 2023. In a reduced number of cases, the OECD STAN Database only has data up to 2018. In those cases, the nowcasting model measures the growth of the ICT sector from 2019 to 2023.

More precisely, the nowcasting model yields point estimates of the ICT sector growth rates. This chapter uses these estimates to analyse the economic performance of this sector across OECD countries. Along with point estimates, it presents 90% confidence intervals. These confidence intervals should be considered whenever point estimates are presented.

Timely estimates of ICT sector growth

The data obtained from the model are particularly useful in two respects. First, they allow extending the analysis of the whole period by incorporating the most recent performance. The last available year in STAN is 2018 or 2019 depending on the country. Without nowcasted data, the analysis of the last three or four years would not be possible. Second, nowcasted figures depict the current performance of the ICT sector in OECD countries and allow policy makers to draw timely conclusions about the efficacy of ICT-related policies.

Figure 1.4 presents both observed and nowcasted ICT growth rates for all OECD countries for which all required data are available.[16] The results show that COVID-19 marked an end to an era of sustained increases in growth rates that started shortly after the global financial crisis. However, while growth rates decrease, the growth of the sector nevertheless remains strong: in 2020, the average growth rate of the ICT sector in OECD countries was 6.6%. By 2021, in most OECD countries, the impact of the COVID-19 crisis is not visible anymore with growth rates achieving their historical maxima in 2023. However, these results must be nuanced when looking at point estimates within respective confidence intervals.[17] Still, even considering confidence intervals, the nowcasting results show that the COVID-19 crisis had only a moderate impact on the ICT sector.

Figure 1.4. The ICT sector is resilient in the face of economic headwinds

Observed and predicted ICT sector growth rates, 2011-23

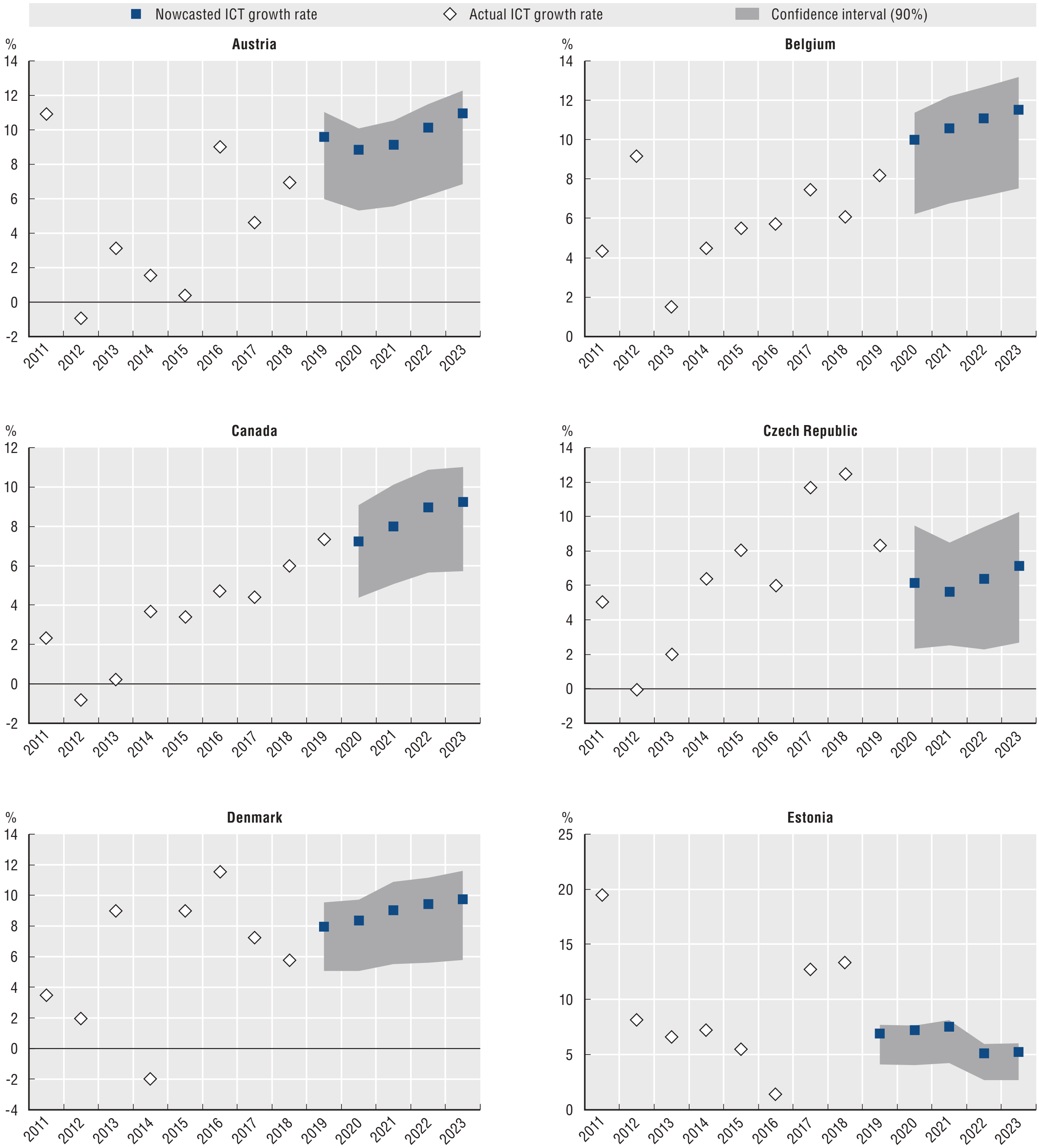


Figure 1.4. The ICT sector is resilient in the face of economic headwinds *(cont.)*

Observed and predicted ICT sector growth rates, 2011-23

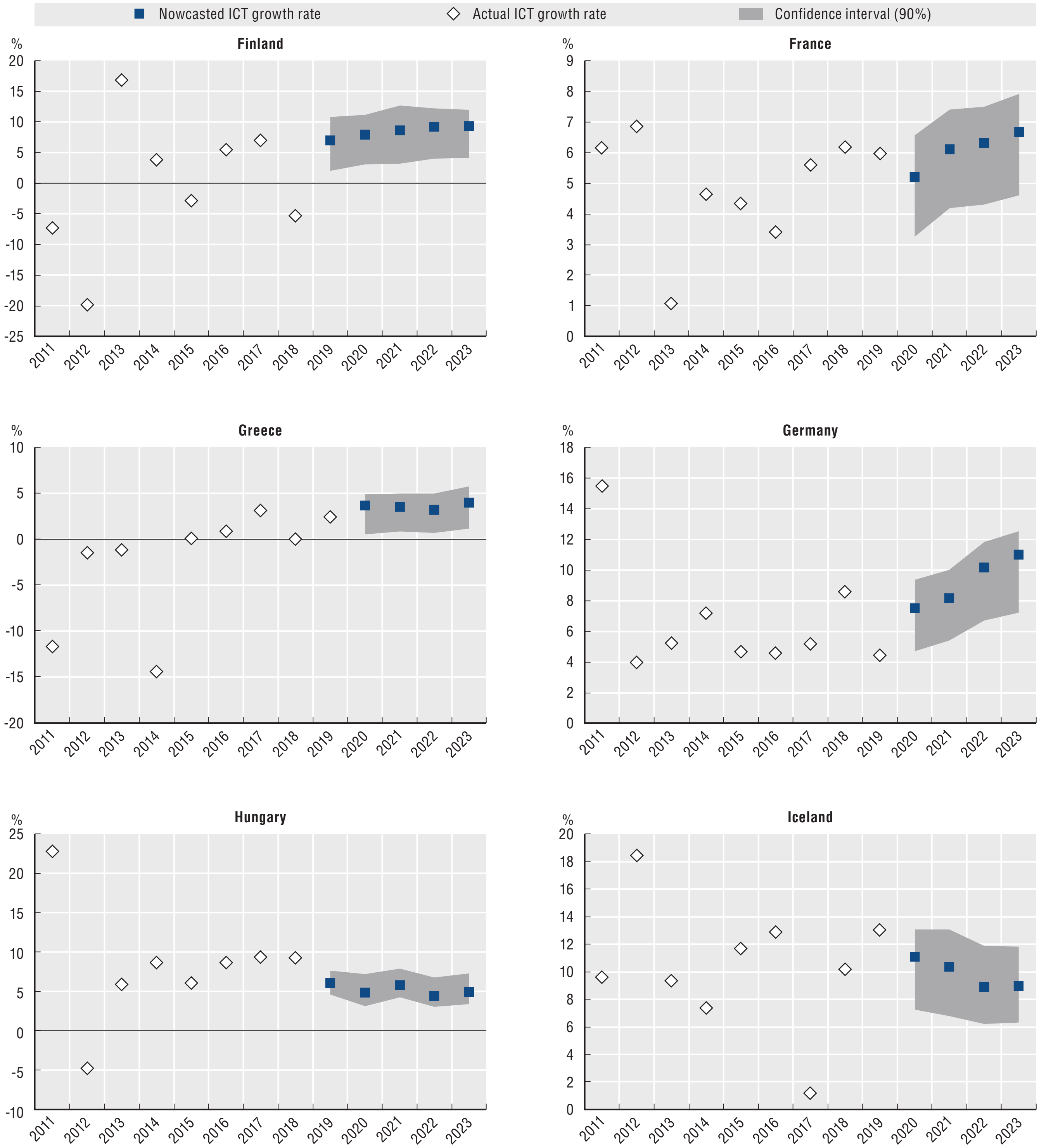


Figure 1.4. The ICT sector is resilient in the face of economic headwinds *(cont.)*

Observed and predicted ICT sector growth rates, 2011-23

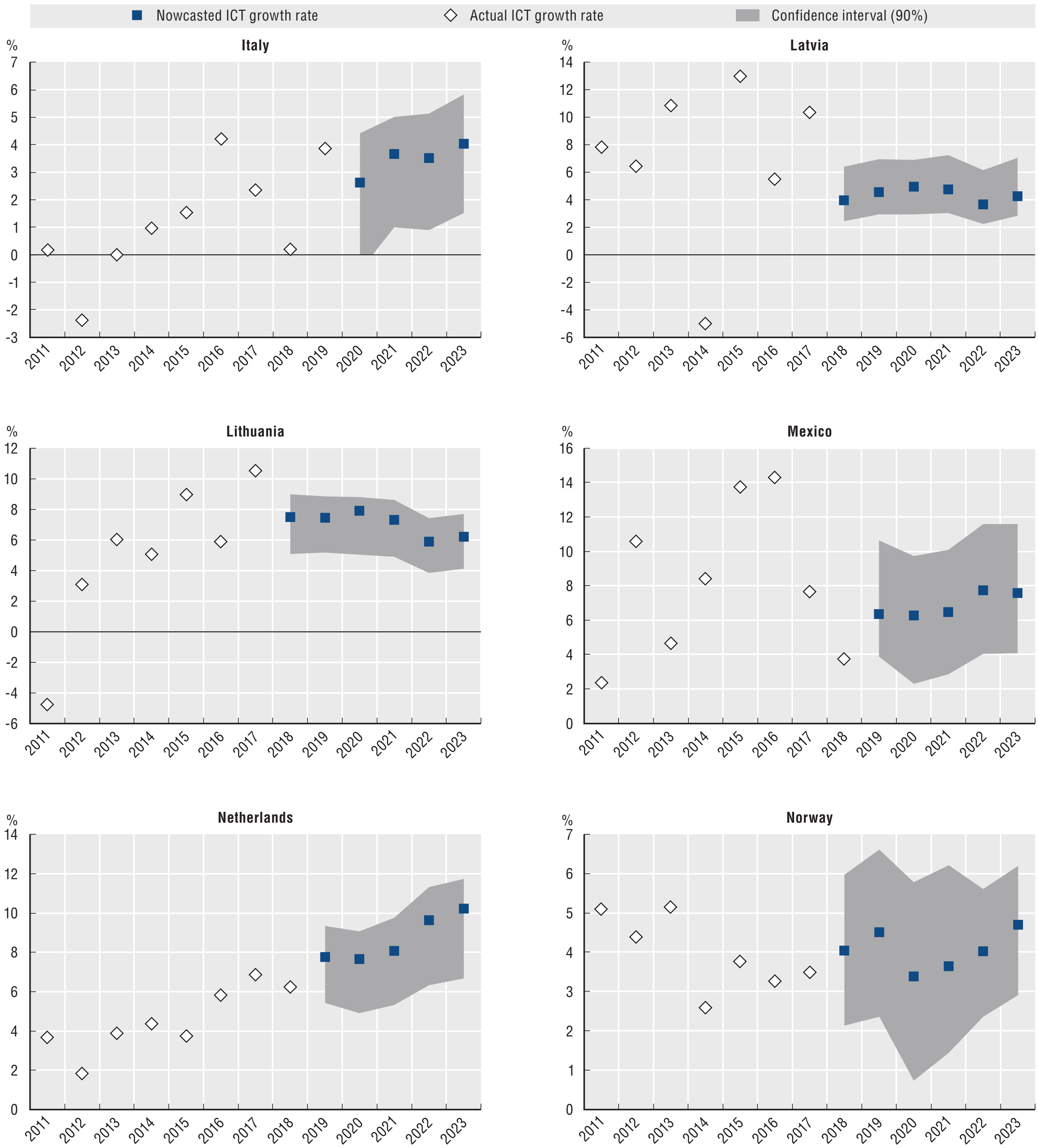


Figure 1.4. The ICT sector is resilient in the face of economic headwinds *(cont.)*

Observed and predicted ICT sector growth rates, 2011-23

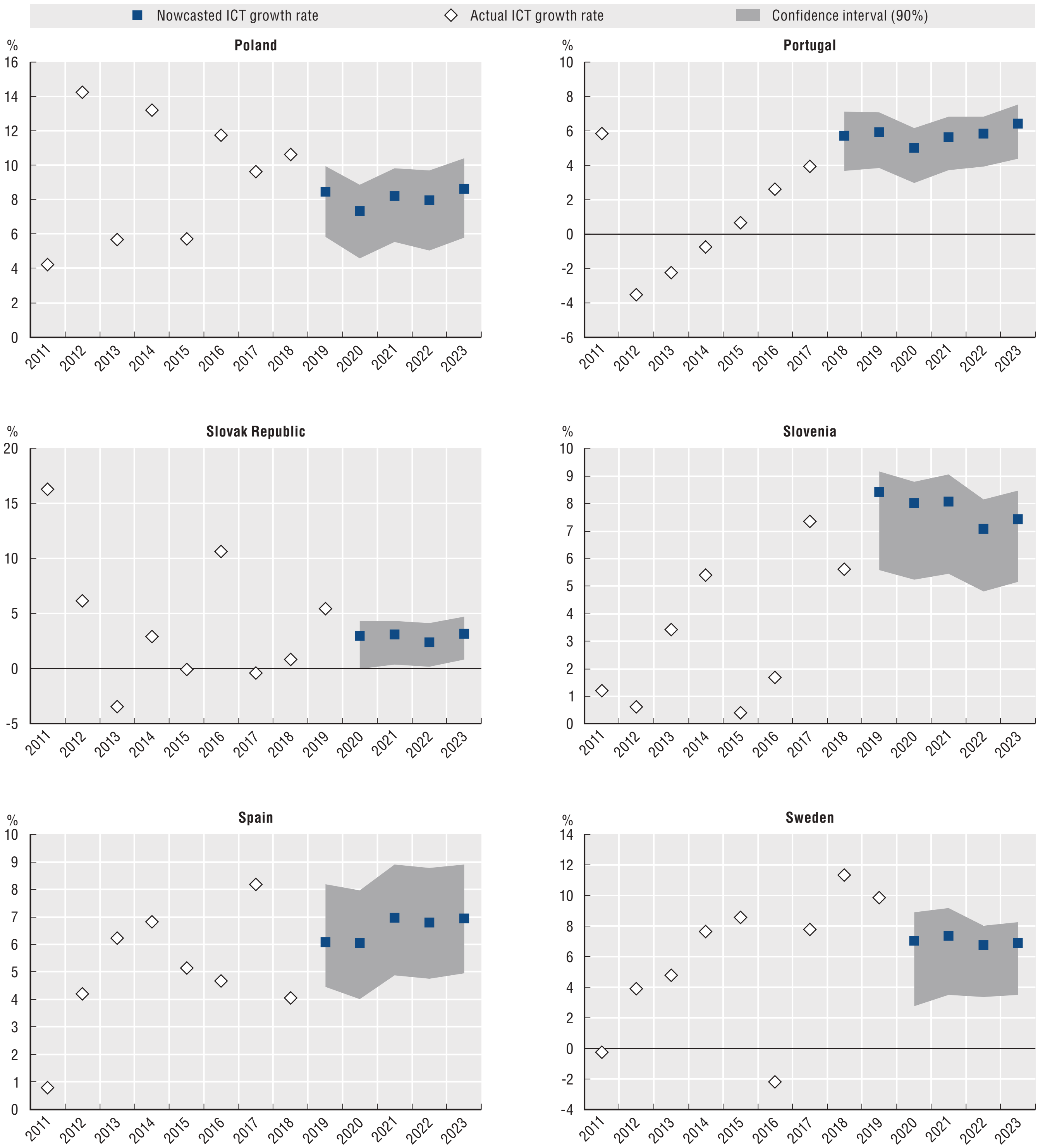
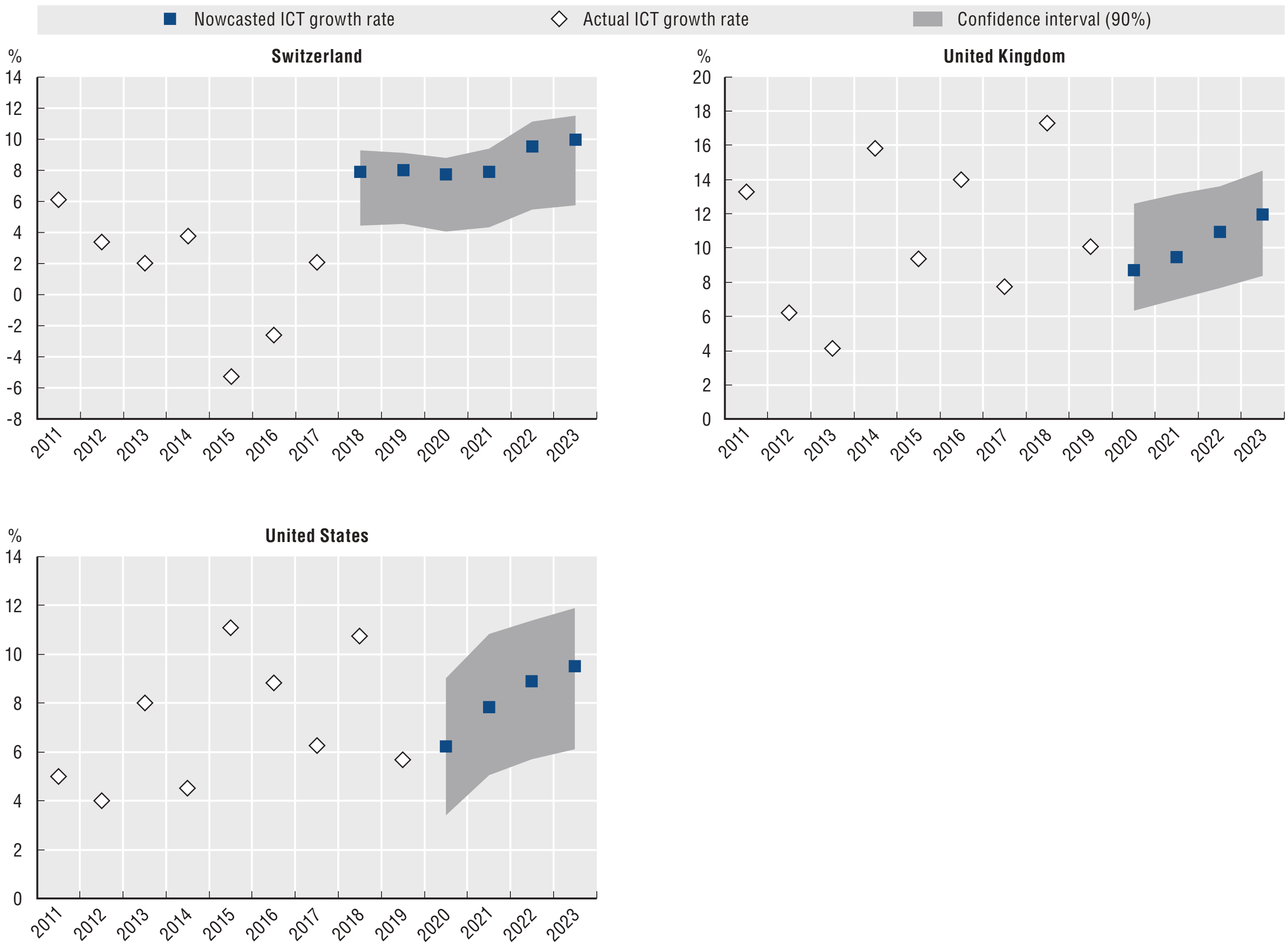


Figure 1.4. The ICT sector is resilient in the face of economic headwinds *(cont.)*

Observed and predicted ICT sector growth rates, 2011-23



Notes: ICT = Information and communication technology. This figure presents observed and nowcast estimates of ICT growth rates in 27 OECD countries from 2011 to 2023 within their 90% confidence interval bands. Depending on the country, nowcast estimates start in 2018 or later. Historical OECD STAN growth rates "Actual ICT growth rate" are represented by white diamonds while nowcast estimates are represented by blue squares.

Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024).

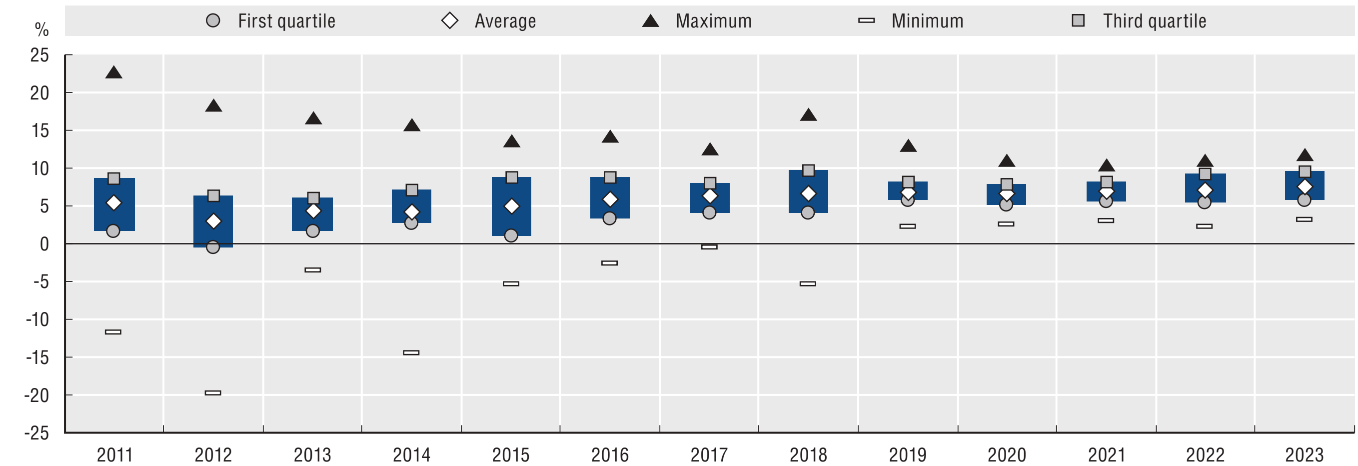
StatLink *https://stat.link/he0zdc*

Average growth rates confirm country-level patterns. Figure 1.5 shows average growth rates of the ICT sector for OECD countries between 2011 and 2023. Average growth rates as of 2011 are computed using observed data provided in STAN. Similarly, average growth rates are computed based on nowcasted growth rates as of 2018 (or later) depending on the country.

Figure 1.5 confirms the remarkable dynamism of the ICT sector.[18] While average growth declined during the global financial crisis, it remained positive throughout the period. After the global financial crisis, the average growth rate increases consistently every year. The sole exception is the emergence of the COVID-19 crisis, where average growth decreased slightly. The ICT sector then continued to grow, reaching its best average growth over the entire period covered in 2023.

Figure 1.5. The ICT sector shows remarkable dynamism

ICT growth rate distribution (observed and predicted), 2011-23



Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024). StatLink contains more data.

StatLink https://stat.link/rcbu6h

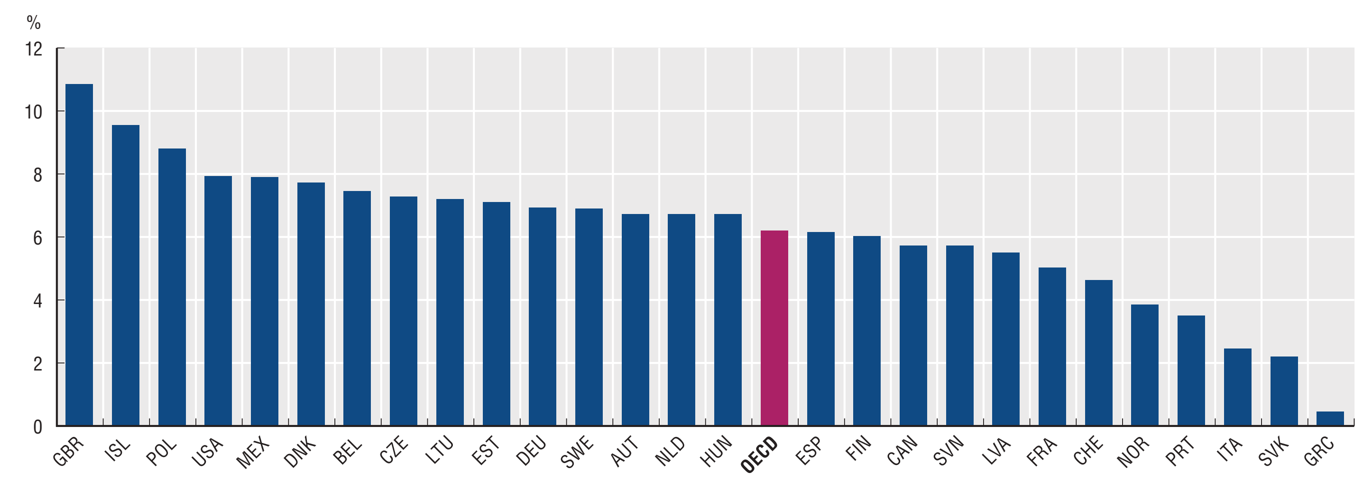
In the past decade, the ICT sector grew in most OECD countries, but not equally

The dynamism of the ICT sector also translated into positive growth rates at the country level. The average growth rate during the period spanning from 2013 to 2023 is positive in every country (Figure 1.6). However, despite the overall positive performance of the ICT sector, a substantial gap separates the top performing economies from those with the lowest ICT sector growth rates. This gap is of more than 10 percentage points between the highest and lowest growth rates.

STAN data, nowcast estimates calculated in this chapter, and nowcast estimates of the total economy from the OECD Weekly Tracker (OECD, 2023[26]) indicate substantial growth in the ICT sector. In the past decade (January 2013 – April 2023), the ICT sector grew nearly three times faster than the entire economy in OECD countries. Over the past decade, the ICT sector had an average growth exceeding 8% in three countries: Iceland, Poland and the United Kingdom. The two countries with the highest ICT sector growth – Iceland and the United Kingdom – had average growth rates during the analysed period above 9%. In turn, Greece, Italy and the Slovak Republic experienced the lowest ICT sector growth, with average growth rates below 3%.

Figure 1.6. ICT growth rates vary markedly across countries

Average ICT sector growth rates (observed and predicted), 2013-23



Note: This figure presents the mean observed and predicted ICT growth rates by country.

Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024). StatLink contains more data.

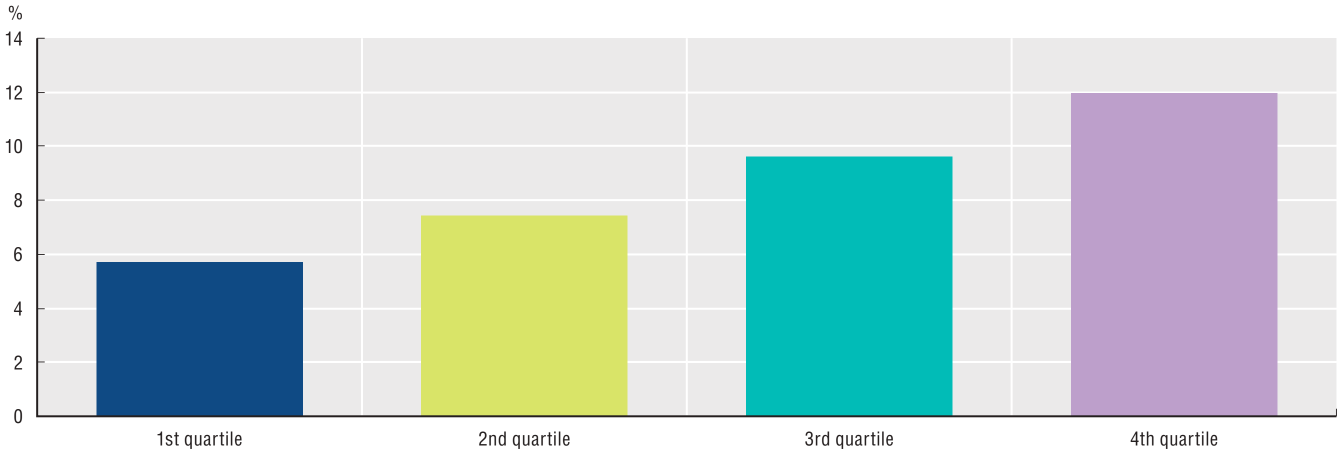
StatLink https://stat.link/q3rcbp

ICT sector growth rates in OECD countries are nevertheless converging

In 2023, countries with the highest ICT sector growth rates (top 25%, or fourth quartile), had an average ICT sector growth rate of 11.9%. That same year, countries with the lowest ICT sector growth rates (bottom 25%, or first quartile), had average ICT sector growth rate of 5.7% (Figure 1.7).

Figure 1.7. Six percentage points separate the top and bottom ICT sector performers

Predicted ICT sector growth rates by quartile, 2023



Note: This figure presents the distribution of predicted ICT growth rates in 2023 by quartile.

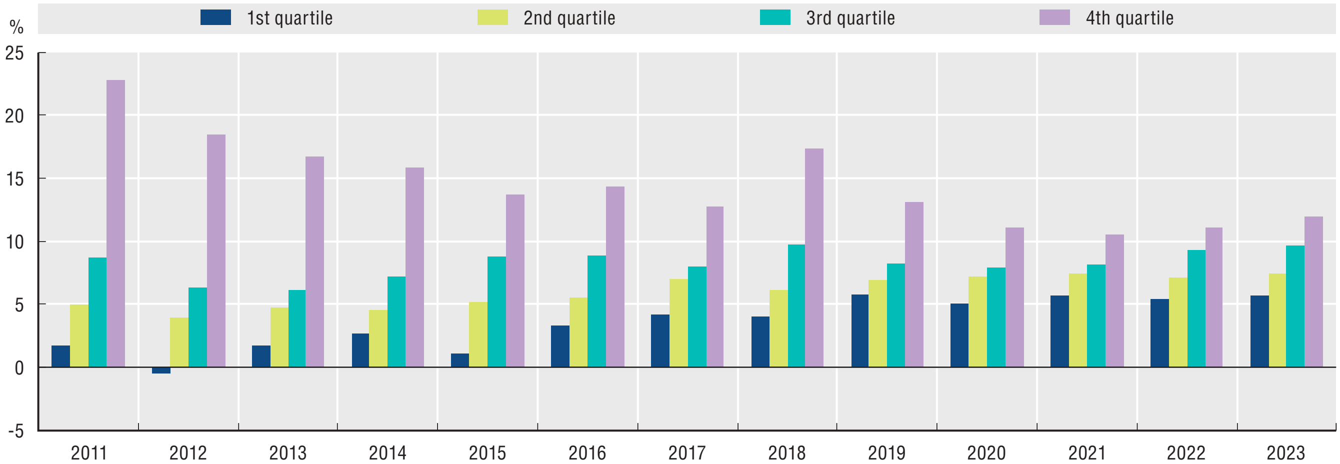
Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024). StatLink contains more data.

StatLink https://stat.link/9d7u1a

Figure 1.8 shows that the large difference between countries in the first and fourth quartiles has nonetheless decreased over time. In 2011, the average growth in the fourth quartile was thirteen times higher than in the first quartile. By 2016, average growth in the fourth quartile was only four times higher than in the first quartile. In 2023, average growth in the fourth quartile was only twice as high as in the first quartile. The disparity in ICT sector growth rates across OECD countries has thus continued to narrow.

Figure 1.8. ICT sector growth rates are converging across countries

Average ICT sector growth rates (observed and predicted) by quartile, 2011-23



Notes: This figure presents the distribution of observed and predicted ICT growth rates from 2011 to 2023 by quartile. Values from 2011 to 2018 (earliest) originate from the STAN Database depending on the country, while those from 2019 (or 2020) to 2023 are nowcast estimates.

Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024). StatLink contains more data.

StatLink https://stat.link/tdpoly

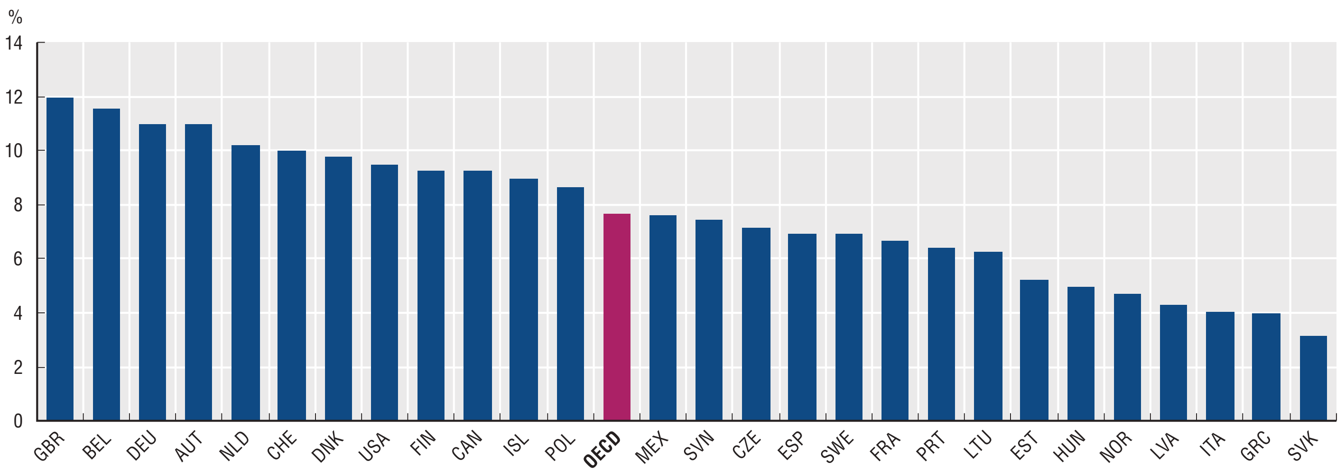
The ICT sector performed strongly in all OECD countries in 2023

Nowcasted figures allow for an up-to-date analysis of the economic growth of the ICT sector in OECD countries. The first key insight from the nowcast predictions is that the ICT sector is performing strongly. While average the growth between 2011 and 2022 was 5.7%, it reached 7.6% in 2023.

In many OECD countries, 2023 marked a significant milestone for the growth of the ICT sector. Ten countries had growth rates above 9%: Austria, Belgium, Canada, Denmark, Finland, Germany, the Netherlands, Switzerland, the United Kingdom and the United States. In Belgium and the United Kingdom, ICT sector growth exceeded 11%. Even countries with the lowest ICT sector growth rates, like Greece and the Slovak Republic, had growth above 3%.

Figure 1.9. ICT sector growth is strong across countries

Predicted ICT sector growth rates, 2023



Source: Authors' calculations using OECD STAN Database and Google Trends data (accessed on 19 February 2024).

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Measuring the ICT sector is key to evaluating its performance and designing sound policies

The need for evidence-based policies increases as digital transformation intensifies and its societal and economic impact widens. It is crucial to improve the timely measurement of the digitalisation of the economy to design public policies that support an innovative and inclusive digital economy and society, and to evaluate their efficacy. Available statistics on the uptake of digital technologies by businesses and households provide important insights. However, they cannot measure the evolution of the monetary value of the digital economy. DSUTs will provide robust information on this front in the medium term. In the meantime, there is a lack of timely data comparable across countries on the economic evolution of the digital economy.

The "digital economy" touches all sectors. However, the ICT sector remains at the core of digital transformation, and is essential to supporting further digital innovation. When designing digital policy frameworks, governments often focus on rules, regulation, policies, and strategies related to the ICT sector. This can include the computer, electronic, telecommunication, and information technology industries, among others. Timely data on ICT sector performance are essential to evaluate the efficacy of these frameworks. For this reason, the ICT sector estimates complement official statistics in this chapter. By developing a nowcasting model that leverages Google Trends data and machine-learning techniques, it provides governments and policy makers with timely and comparable data on the economic growth of the ICT sector in OECD countries.

The nowcasting model could also be used to measure growth rates of other important sectors beyond the "core" of ICT in real time. For example, real-time estimated growth rates of all digital-intensive sectors would provide a more complete picture of the growth of digital components of the economy. Further, nowcast estimates of growth rates of all sectors would enable policy makers to see in real time how highly digital sectors perform compared to those relatively less digitalised.

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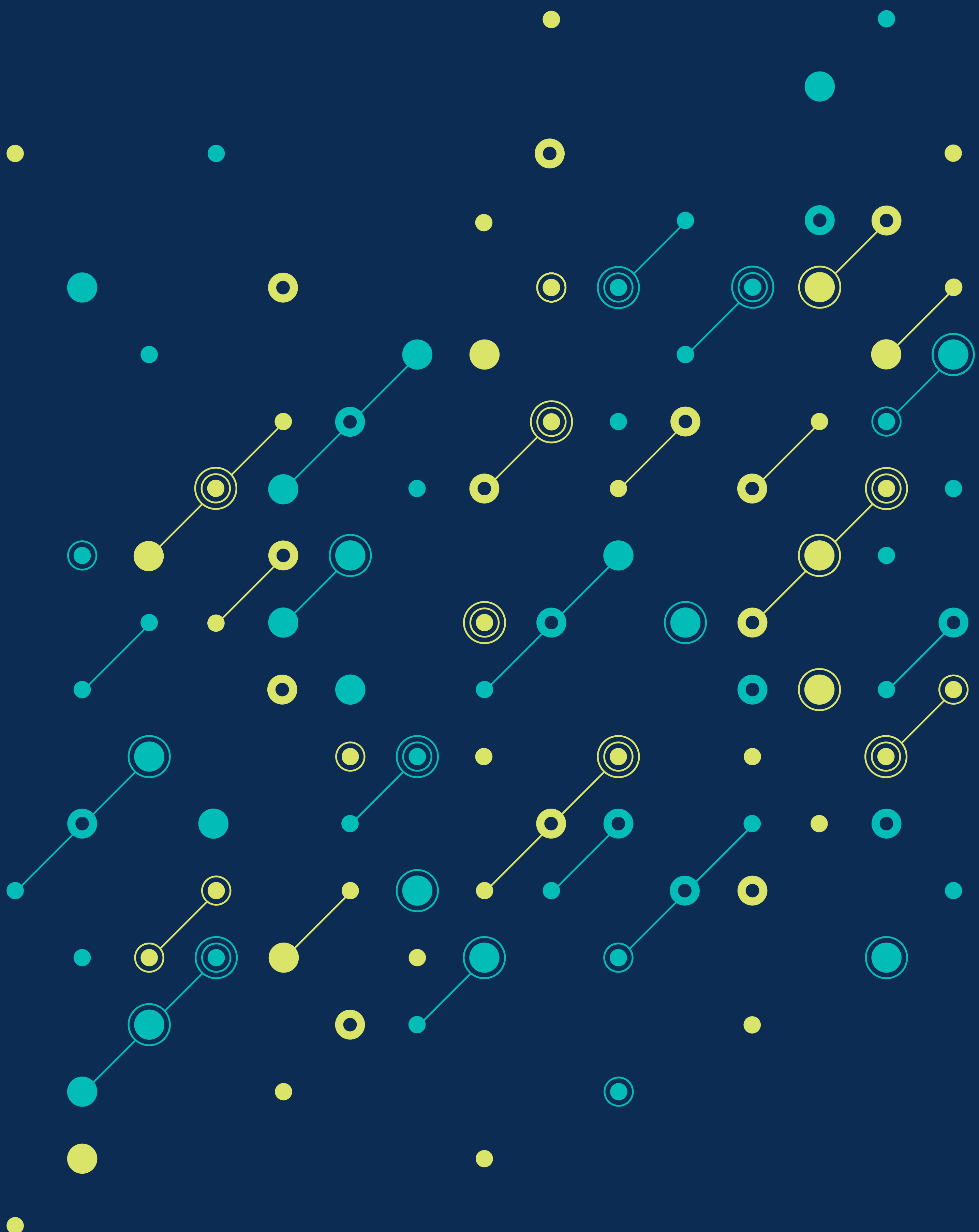
Notes

1. *https://goingdigital.oecd.org*.
2. *https://goingdigital.oecd.org/indicator/08*.
3. More information on STAN is available at: *http://oe.cd/stan*.
4. Recent work suggests that Google Trends data are less useful to measure aggregate gross domestic product (GDP) growth when official data are available (Ferrara, 2022[25]). For aggregate GDP, this lag varies in most countries between one to three months. However, at the sectoral level, this lag is considerably longer, routinely exceeding 12 months. As a result, non-traditional data sources remain a relevant source for information on economic growth at the sectoral level (as opposed to the aggregate level).
5. An alternative model using aggregate GDP growth rates as an input was also tested. However, the model using Google Trends data outperformed it. The results can be found in the accompanying technical paper (Umana Dajud, forthcoming[5]).
6. *https://oecd.ai*.
7. More information on STAN can be found at: *http://oe.cd/stan*.
8. Gross value-added volumes (VALK) from the STAN Database are computed using price deflators. They are presented in terms of the current price value in reference year 2015. More information about how the VALK series is calculated can be found in the STAN Database documentation: *http://oe.cd/stan*.
9. The list of all categories can be found at: *https://serpapi.com/google-trends-categories* (accessed on 19 February 2024).
10. Setting this threshold for the analysis helps reduce excessive variance in the dataset.
11. Dropping observations with a variance larger than ten reduces the sample size from 7 328 880 to 6 186 710 observations (i.e. 1 142 170 observations deleted). Nevertheless, each of the 1 131 categories is still present in the restricted sample.
12. Despite the higher variance of country-categories that were dropped, they exhibit similar statistical properties to the full sample. The mean and standard deviation of the full sample are 35.97 and 25.60, respectively. For the dropped observations, these same figures are 35.52 and 24.78. For the observations used in the nowcasting exercise, the mean is 36.06 and the standard deviation is 24.78.
13. The model is trained using the Scikit-learn 1.2.1 package in Python.
14. Google's definition of hyperparameters can be found at: *https://developers.google.com/machine-learning/guides/text-classification/step-5*. The learning rate and the number of hidden layers are examples of these hyperparameters.
15. The precision of the RSME diminishes the farther one moves from the last observed value used to train the model.

16. STAN does not include VALK for the ICT sector for Australia, Chile, Colombia, Costa Rica, Ireland, Israel, Japan, Korea, Luxembourg, New Zealand and Türkiye.
17. Sectoral growth rates display a considerably larger variance than total GDP growth rates. This feature of sectoral data largely explains the magnitude of the nowcasting model confidence intervals (90%) compared to those using a similar methodology for total GDP growth rates (95%) (Woloszko, 2020[19]).
18. See for example *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=ICT_sector_-_value_added,_employment_and_R%26D* and *www.cbs.nl/en-gb/news/2020/42/ict-sector-growing-faster-than-the-economy*.



Chapter 2

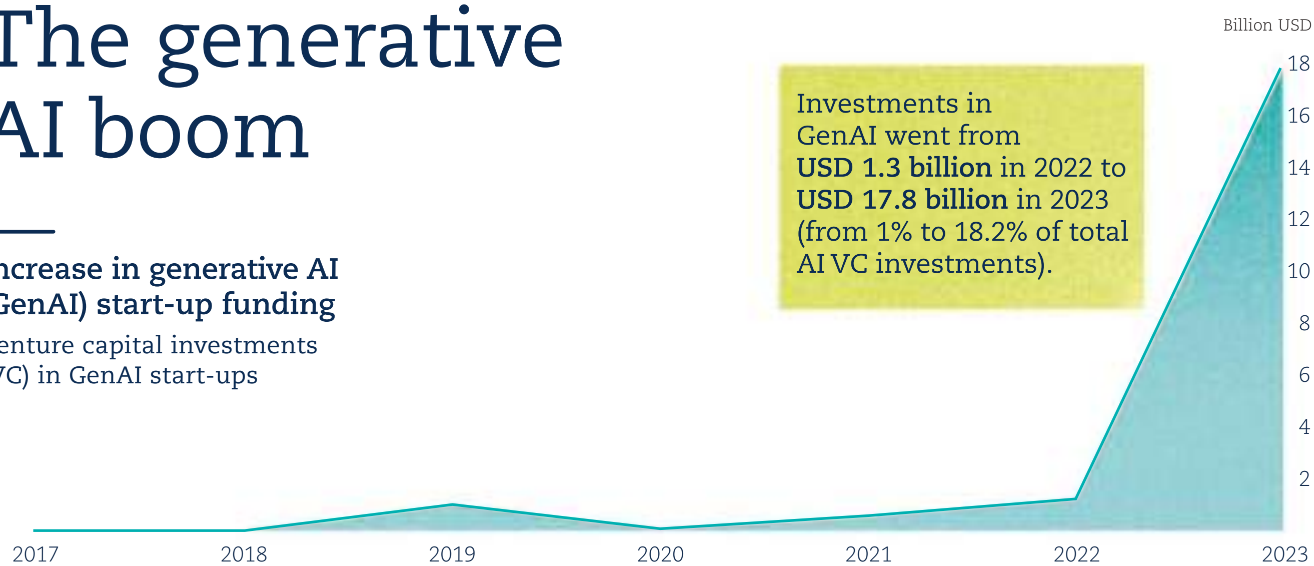
The future of artificial intelligence

The artificial intelligence (AI) landscape has evolved significantly since 1950 when Alan Turing first posed the question of whether machines can think. Today, AI is transforming societies and economies. It promises to generate productivity gains, improve well-being and help address global challenges, such as climate change, resource scarcity and health crises. Yet, the global adoption of AI raises questions related to trust, fairness, privacy, safety and accountability, among others. Advanced AI is prompting reflection on the future of work, leisure and society. This chapter examines current and expected AI technological developments, reflects on the opportunities and risks foresight experts anticipate, and provides a snapshot of how countries are implementing the OECD AI Principles. In so doing, it helps build a shared understanding of key opportunities and risks to ensure AI is trustworthy and used to benefit humanity and the planet.

The generative AI boom

Increase in generative AI (GenAI) start-up funding

Venture capital investments (VC) in GenAI start-ups



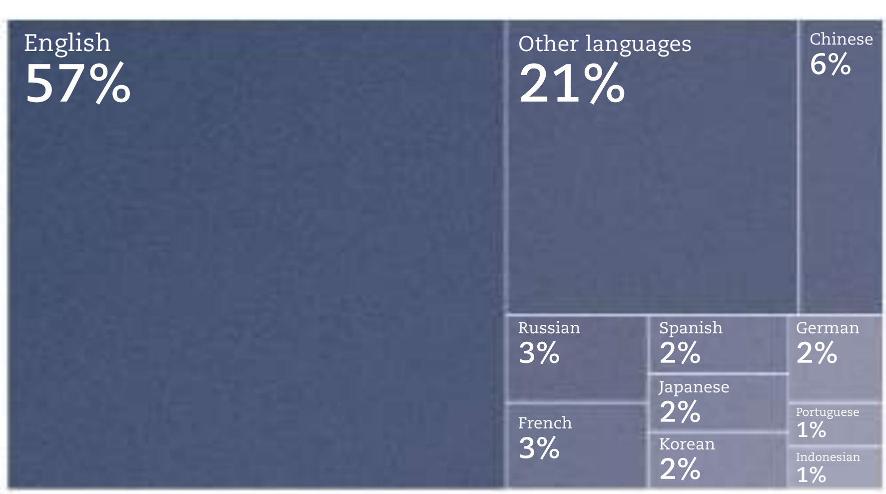
Surge in GenAI incidents and hazards

Reported GenAI-related incidents and hazards in reputable news outlets globally (three-month moving average)

Language divides in AI datasets

Breakdown of open-source AI training datasets on Hugging Face, by language, 2024

Training language models poses a challenge for countries where English is not the primary language.



Source: OECD.AI (accessed on 10 March 2024).

Key findings

Technical breakthroughs have enabled generative AI that is so advanced users may be unable to distinguish between human and AI-generated content

- In late 2022, generative AI advances took many by surprise, despite some researchers anticipating such developments. Collaboration and interdisciplinarity between policy makers, AI developers and researchers are key to helping keep pace with AI progress and close knowledge gaps.

Research and expert opinions suggest that future impacts of AI could vary widely, promising considerable socio-economic benefits but also presenting substantial risks that need addressing

- The future of AI may yield tremendous benefits, including enhanced productivity gains, accelerating scientific progress and helping address climate change. However, AI advances also present critical risks, including spreading mis- and dis-information, and threats to human rights.

The long-term trajectories and risks of AI are often discussed and widely debated

- Most AI today can be considered "narrow" (designed to perform a specific task), but some experts argue that foundation models are an early form of more "general" AI. This includes progress towards artificial general intelligence (AGI) – a controversial concept that can be described as machines with human-level or greater intelligence across a broad spectrum of contexts.
- Some experts argue that challenges in ensuring alignment of machine outputs with human preferences could result in humans losing control of AGI. However, the plausibility and potential nature of AGI are disputed. Many future risks do not require AGI, leading others to argue that focusing on hypothetical AGI distracts from near-term risks.

AI research and development and venture capital (VC) investments are poised to increase

- Since mid-2019, the People's Republic of China (hereafter "China") published more AI research than the United States or the European Union. India is also making strides, more than doubling its AI research publications since 2015.
- Between 2015 and 2023, global VC investments in AI start-ups tripled (from USD 31 billion to USD 98 billion), with investments in generative AI specifically growing from 1% of total AI VC investments in 2022 (USD 1.3 billion) to 18.2% (USD 17.8 billion) in 2023, despite cooling capital markets.

AI development and use is expected to continue to depend on access to computing infrastructure

- Compute divides may worsen between and within countries. Increasingly, within countries, public sector entities lack the computing resources to train advanced AI.

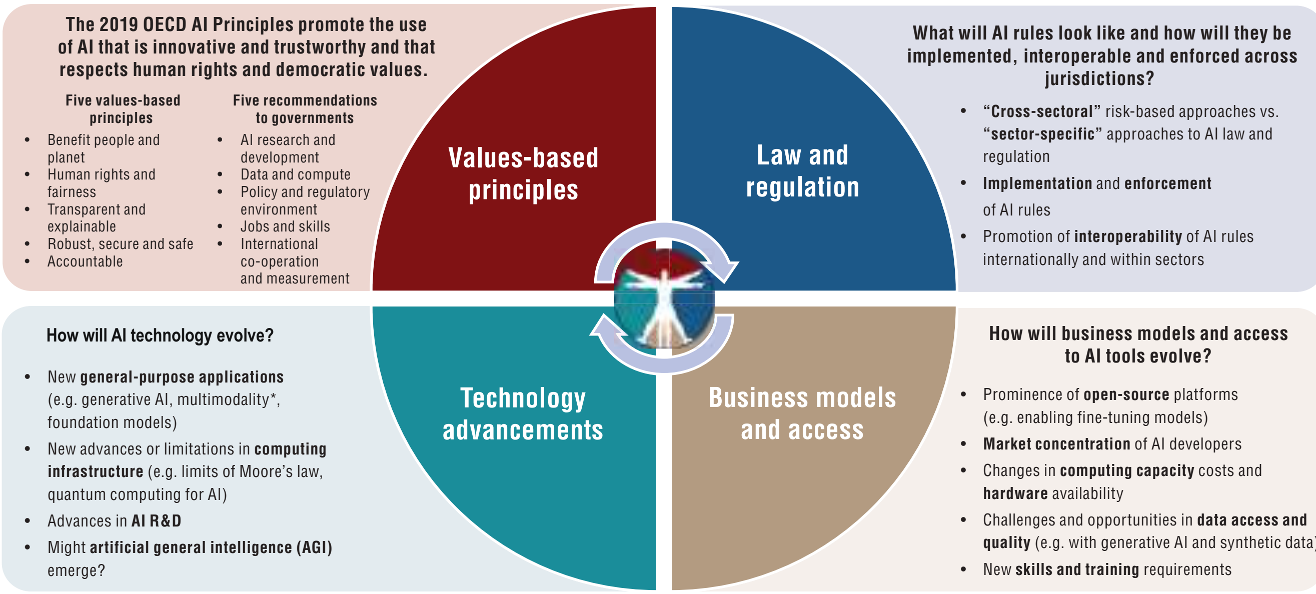
AI benefits and risks have global reach, making international co-operation critical to ensure AI policies and laws are complementary, effective and interoperable

- AI systems around the world can use the same underlying AI inputs and tools, such as AI algorithms, models and training datasets. This makes countries and organisations vulnerable to similar risks like bias, human rights infringements, and security vulnerabilities or failures.

Artificial intelligence (AI) is transforming economies and societies, but is the world ready? AI promises to generate productivity gains, improve well-being and help address global challenges, such as climate change, resource scarcity and health crises. Yet, as AI is adopted around the world, its use raises questions and challenges. AI has advanced significantly, prompting reflection on the future of work, education, leisure and society. This chapter looks to potential futures to help build an understanding of key opportunities and risks in ensuring AI is trustworthy and used for good.

This chapter examines current and expected AI technological developments, reflects on the opportunities and risks foresight experts anticipate may lie ahead, and provides a snapshot of how countries are implementing the OECD AI Principles. It examines the interrelated factors that will likely shape AI governance in the decades to come (Figure 2.1), to help build a shared understanding of key opportunities and risks to ensure AI is trustworthy and used to benefit humanity and the planet.

Figure 2.1. Examples of interrelated factors that will likely shape AI governance in future decades



Note: *Multimodal AI combines multiple types of data – such as data from text, image or audio – via machine-learning models and algorithms. It is key for AI research and applications such as in manufacturing and robotics (The Alan Turing Institute, 2023[1]).

Source: Adapted from Figure 1.S.2. of the Spotlight "Next generation wireless networks and the connectivity ecosystem" in this volume.

The AI technological landscape today and tomorrow

The AI technological landscape has evolved significantly from the 1950s when British mathematician Alan Turing first posed the question of whether machines can think (Turing, 2007[2]). Coined as a term in 1956, AI has evolved from symbolic AI where humans built logic-based systems, through the AI "winter" of the 1970s, to the chess-playing computer Deep Blue in the 1990s. The 21st century saw breakthroughs in the branch of AI called machine learning that improved the ability of machines to make predictions from historical data (OECD, 2019[3]). Recent years have witnessed the emergence of generative AI, including large language models, that can generate novel content and enable consumer-facing applications like advanced chatbots at people's fingertips (OECD, 2023[4]). For many, AI became "real" in 2022 – the year that OpenAI's ChatGPT became the fastest-growing consumer application in history (Hu, 2023[5]). To understand the evolution of AI technological developments to date, and how they might develop in future years, policy makers need a shared understanding of key AI terms (Box 2.1), as well as of the basic AI production function, described by three enablers: algorithms, data and computing resources ("compute").

Advances in neural networks and deep learning are resulting in larger, more advanced and more compute-intensive AI models and systems

The application of machine-learning techniques, the availability of large datasets, and faster and more powerful computing hardware have converged. Together, they are dramatically increasing the capabilities, impact and availability of AI models and systems, moving from academic discussions into remarkable real-world applications. Inspired by the human brain, neural networks are made up of layers of "neurons", known as "nodes", that process inputs with weights and biases to give specific outputs (Russell and Norvig, 2016[11]). A subset of algorithms in the area of neural networks – called deep neural networks (in the field of study and set of techniques called deep learning) – allows machine-based systems to "learn" from examples to make predictions or "inferences", based on the large amount of data processed during their training phase. Deep neural networks are distinct mostly in that they are general and require little adaptation (or "cleaning") of input data to make accurate predictions.

In 2017, a group of researchers introduced a type of neural network architecture called "transformers". It became a key conceptual breakthrough, unleashing major progress in AI language models. Transformers learn to detect how data elements – such as the words in this sentence – influence and depend on each other (Vaswani et al., 2023[12]). Unlike previous neural networks, transformers can process inputs from a sequence, such as words of text, in parallel. This enabled AI developers to design larger-scale language models with significantly more parameters – the numerical weights that define the model – and greater efficiency (OECD, 2023[4]; Vaswani et al., 2023[12]). Transformers have unlocked significant advances across language recognition (such as chatbots) and science (such as protein folding). Vision transformers are also becoming popular for various computer vision tasks (Islam, 2022[13]). Notable transformer models include AlphaFold2 (DeepMind), GPT-4 (OpenAI), LaMDA (Google) and BLOOM (Hugging Face) (Collins and Ghahramani, 2021[14]; Hugging Face, 2022[15]; Merritt, 2022[16]).

Box 2.1. "A" is for artificial intelligence

AI has received notable attention in the media and in policy circles. Amid the flurry of headlines and analysis, policy makers require a shared understanding of key AI terms to help keep up with rapid AI advancements, and to respond with AI policies that can stand the test of time. This chapter uses the following terms:

- **Artificial intelligence**: "An AI system is a machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations or decisions that can influence physical or virtual environments. Different AI systems vary in their levels of autonomy and adaptiveness after deployment" (OECD, 2024[6]).
- **Algorithm**: "[A] set of step-by-step instructions to solve a problem (e.g. not including data). [It] can be abstract and implemented in different programming languages and software libraries" (EU-US Trade and Technology Council, 2023[7]).
- **AI compute**: "AI computing resources ('AI compute') include one or more stacks of hardware and software used to support specialised AI workloads and applications in an efficient manner" (OECD, 2023[8]).
- **Foundation model**: A model that is trained on large amounts of data – generally using self-supervision at scale – that can be adapted (e.g. fine-tuned) to a wide range of downstream tasks. Examples include BERT (Google) and GPT-3 (OpenAI) (Bommasani et al., 2021[9]).
- **Generative AI**: AI systems capable of creating new content – including text, image, audio and video – based on their training data, and usually in response to prompts. The recent growth and media coverage of generative AI, notably in the areas of text and image generation, has spotlighted AI's capabilities, leading to significant public, academic and political discussion (Lorenz, Perset and Berryhill, 2023[10]).
- **AI language model**: A model that can process, analyse or generate natural language text trained on vast amounts of data, using techniques ranging from rule-based approaches to statistical models and deep learning. Chatbots, machine translation and virtual assistants that recognise speech are all applications of language models. Not all language models are generative in nature, and they can be large or small (OECD, 2023[4]).
- **Machine learning**: "[A] branch of artificial intelligence (AI) and computer science which focuses on development of systems that are able to learn and adapt without following explicit instructions imitating the way that humans learn, gradually improving its accuracy, by using algorithms and statistical models to analyse and draw inferences from patterns in data" (EU-US Trade and Technology Council, 2023[7]). The "learning" process using machine-learning techniques is known as "training". A machine-learning technique called "neural networks", and its further subset technique called "deep learning", has enabled leaps in technological AI developments (OECD, 2019[3]).
- **Multimodal AI**: AI that combines multiple types of data – such as data from text, image or audio – such as through machine-learning models and algorithms. Multimodal AI is key for AI research and applications such as in manufacturing and robotics (The Alan Turing Institute, 2023[1]).

Notes: This is an inexhaustive list of terms selected for this chapter. The EU-US Trade and Technology Council released a second edition of Terminology and Taxonomy for Artificial Intelligence in April 2024. For further information, please visit: *https://digital-strategy.ec.europa.eu/en/library/eu-us-terminology-and-taxonomy-artificial-intelligence-second-edition*.

Researchers are exploring whether transformers can create "generalist" and "multimodal" AI systems that can perform multiple of different tasks across robotics, computer vision, simulated environments, natural language and more. For example, Google DeepMind's Gato (2022) can perform tasks such as stacking blocks with a robot arm, playing video games, captioning images and chatting with users. Unlike previous AI models that could only learn one task at a time, some new transformer models can learn multiple different tasks simultaneously, enabling them to switch between tasks and learn new skills without forgetting previous skills (Heikkilä, 2022[17]; Reed et al., 2022[18]). However, AI models and systems today still exhibit factual inaccuracy; "hallucinations" (making up facts in a credible way, often when a correct answer is not found in the training data); inconsistency; and misunderstanding when used in new contexts, often requiring human assistance and oversight for correct functioning. Some experts argue that advanced AI systems and models represent a step towards more capable and general forms of AI. Some even claim progress towards the hypothetical advent of artificial general intelligence (AGI) that would usher in significant benefits and risks. Such discussions are actively debated in the AI expert community (Box 2.2).

Box 2.2. Increasingly general AI systems

Some experts believe the latest large language and other generative AI models can apply outputs in a general way across many contexts. However, the extent to which these models can generalise versus simply mimicking information from their datasets is actively debated.

Since their origin in the 1950s, AI systems have been "narrow" and context-specific. However, due to recent advances, some experts argue that state-of-the-art "foundation models" are moving to capabilities that are more general in nature.

Foundation models are trained on large amounts of data and can be adapted and built upon for a wide range of downstream tasks. Some experts argue that such models represent a significant step towards the hypothetical advent of artificial general intelligence (AGI), the timeline, definition and premise of which is intensely debated. AGI is a controversial concept that can be described as machines with human-level or greater intelligence across a broad spectrum of domains and contexts.

Many experts argue that a focus on speculative notions of AGI obfuscates potentially significant benefits and risks posed by existing and near- to medium-term AI systems. To move away from this debate, some AI experts have begun using the phrase artificial capable intelligence (ACI). This is meant to describe potentially transformative AI systems that require minimal human supervision but that may not achieve the hypothesised state of AGI.

Researchers at DeepMind (Google) have proposed a framework for classifying progress in capabilities based on AI systems' levels of performance, generality and autonomy. They aim to provide a common language for comparing AI models, assessing risks and measuring progress in AI advancements.

AGI is the focus of active debates and media reporting. While an increasing number of experts from a wide array of disciplines are engaging in the debate around achieving more general AI systems, their views, forecasts and understanding of key related terms vary greatly.

Source: Based on Russell and Norvig (2016[11]); OECD (2019[3], 2023[4]); Elangovan, He and Verspoor (2021[19]); Bubeck et al., (2023[20]); Morris et al., (2023[21]); Suleyman (2023[22]).

Foundation models are enabling increasing AI generality across application domains, industries and tasks

Recent AI breakthroughs have shifted capabilities from task-specific models and systems to those that are more flexible and applicable across domains, industries and tasks. These advances centre on "foundation models" – models trained on large amounts of data that can be adapted to a wide range of downstream tasks such as OpenAI's Generative Pretrained Transformers (GPT) series (Bommasani et al., 2021[9]; Jones, 2023[23]; Lorenz, Perset and Berryhill, 2023[10]). Foundation models can be further trained or "fine-tuned", for example, with specific data to gain insights relevant to a specific sector or adapted to a wide range of distinct tasks (Bommasani et al., 2021[9]).

Today's foundation models share several common characteristics. First, they often include billions of parameters, making them very large in size. Second, their outputs can be difficult to explain due to their complex computational processes. This has resulted in impressive performance and outputs, even beyond their developers' expectations. However, the model's steps or process to arrive at an output often cannot be explained. Third, training today's foundation models requires massive amounts of AI compute, data and specialised AI talent, making them expensive to develop (Dunlop, Moës and Küspert, 2023[24]). However, as the technology, hardware/software and training methods advance, it is unclear whether future foundation models will require similarly large datasets and compute, and retain such large numbers of parameters.

Many have called the recent emergence of foundation models a major "paradigm shift" and technological advancement. Enabled by foundation models, some AI models can transfer capabilities from one domain to another. For example, they can combine multiple types of data across domains (e.g. image, text, audio). Foundation models, especially those available as open-source, can also allow AI developers and researchers with limited resources to fine-tune and deploy AI in their specific domains. Using foundation models, developers do not necessarily require access to advanced compute hardware and large datasets, or need to incur significant training costs to train the foundation model to begin with.

Foundation models will likely continue to drive advancement of AI capabilities, unlocking promising opportunities for innovation and productivity gains across domains and sectors. However, they also raise several challenges. A reliance on foundation models – for example by smaller and less well-capitalised downstream users like start-ups – could create dependency dynamics between the users and producers of such models. The cost and complexity of foundation models have limited their development to well-capitalised firms, such as models like GPT-4 (OpenAI/Microsoft), BERT (Google) or LlaMA 2 (Meta), or to organisations and governments that can afford to fund their training.

It is often difficult and expensive to understand what foundation model training datasets contain, and verifying the validity of outcomes sometimes requires specialised expertise. Moreover, foundation model developers may not disclose key information about such models, for a variety of business or technical reasons. Distribution mechanisms by developers – such as application programming interfaces (APIs) – can mask certain model properties. This makes it difficult to assess how models align with certain principles, or to use models in downstream contexts in ways that promote transparency, explainability and accountability (Dunlop, Moës and Küspert, 2023[24]).

Such issues illustrate the possible increasing imbalance between those who can perform the most resource-intensive first steps of building such models and those who rely on pretrained models (i.e. foundation models). Access to the most advanced AI models could be limited by those who own them. This would pose challenges for policy makers and governments as they seek to create a level playing field that allows smaller and less-resourced groups to innovate (OECD, 2023[25]). Policy challenges could include questions around access to tools for innovation and market dynamics concerning competition.

AI development and use is expected to continue to depend on access to computing infrastructure

Computing infrastructure ("AI compute") is a key component needed for AI development and expected to be a continued driver of AI's improved capabilities over time. Unlike other AI inputs like data or algorithms, AI compute is grounded in "stacks" (layers) of physical infrastructure and hardware, along with software specialised for AI (OECD, 2023[8]). Advancements in AI compute have enabled a transition from general-purpose processors, such as Central Processing Units (CPUs), to specialised hardware requiring less energy for more computations per unit of time. Today, advanced AI is predominantly trained on specialised hardware optimised for certain types of operations, such as Graphics Processing Units (GPUs), Tensor Processing Units, Neural Processing Units and others. Training AI on general-purpose hardware is less efficient (OECD, 2023[8]). The high volume of AI-focused computing infrastructure has also enabled AI advances, in addition to technological advances in AI hardware itself.

The demand for AI compute has grown dramatically, especially for deep learning neural networks (OECD, 2023[8]). Securing specialised hardware purpose-built for AI can be challenging due to complex supply chains, as illustrated by bottlenecks in the semiconductor industry (Khan, Mann and Peterson, 2021[26]). Integrated circuits or computer chips made of semiconductors are a critical input for AI compute. They are called the "brains of modern electronic equipment, storing information and performing the logic operations that enable devices such as smartphones, computers and servers to operate" (OECD, 2019[27]). Any electronic device can have multiple integrated circuits fulfilling specific functions, such as CPUs or chips designed for power management, memory, graphics (e.g. GPUs used for AI). Demands on semiconductor supply chains have grown in recent years, especially as digital and AI-enabled technologies become more commonplace, such as Internet of Things devices, smart energy grids and autonomous vehicles. The semiconductor supply chain is also highly concentrated, making it more vulnerable to shocks (OECD, 2019[27]).

Training and inference related to advanced AI requires significant compute resources, leading to environmental impacts: energy and water use, carbon emissions, e-waste and natural resource extraction like rare mineral mining. Experts have raised concerns around the direct environmental impacts of AI (i.e. those created from training or inference). This is especially relevant as generative AI becomes more accessible, with applications like chatbots increasing demand for server time and AI inference. Some compute providers have given AI-specific estimates, but such standardised measures remain underreported and scarce (OECD, 2022[28]).

AI has advanced significantly thanks to increases in computer speeds and to Moore's Law (i.e. computer speed and capability are expected to double every two years). However, experts have warned of potentially reaching the limits of such scaling, posing challenges for future leaps in computer performance (OpenAI, 2018[29]; Sevilla et al., 2022[30]). Researchers are looking at new ways to enable continued improvements. These include more powerful processors; faster data transmission; larger memory and storage; next-generation networks like 6G; and expanded and faster edge and distributed computing devices and quantum computing capabilities. Experts are also researching neuromorphic computing modelled after human cognition. This aims to make processors more efficient using orders of magnitude less power than traditional computing systems (Schuman et al., 2022[31]). Computing methods like optical computing – technology harnessing the unique properties of photons – are also being explored for AI applications (Wu et al., 2023[32]).

The availability of vast amounts of data for training AI has greatly enhanced systems' capabilities, including their ability to generate realistic content

Access to data is crucial for AI, including for training, testing and validation. The demand for data to train AI ("AI input data") has increased significantly, particularly with the rise of generative AI and large language models. Today, data used to train AI are aggregated from a variety of sources, such as through curated datasets, data-sharing agreements, collecting user data, using existing stored data and "data scraping" of publicly available data from the Internet.

The availability and collection of data raise policy questions. This is especially true when data contain personally identifiable information (i.e. personal data) or protected material, such as that under licence or copyright (e.g. software, text, images, audio or video). The limited availability of digitally readable text for non-English languages could also limit the benefits of AI for linguistic groups, including those using minority languages. Based on open-source AI training datasets available on Hugging Face, English represents more than half of all languages. This points to a potential diversity gap in terms of training dataset languages for AI (OECD.AI, 2024[33]) (Figure 2.2).

Figure 2.2. More than half of open-source AI training datasets are in English

Percentage breakdown of languages for open-source AI training datasets on Hugging Face from a list of 225 languages, 2024

Notes: This chart represents the language distribution of all datasets. Multilingual and translation datasets on Hugging Face contain more than one language and are thus double counted. More methodological information available at: *https://oecd.ai/huggingface* (accessed on 10 March 2024).

Source: OECD.AI (2024[33]), using data from Hugging Face. For more information, please see: *https://oecd.ai/en/data?selectedArea=ai-models-and-datasets*.

StatLink *https://stat.link/ku47rj*

Privacy-enhancing technologies are emerging, including confidential computing methods and federated learning

The use of vast amounts of personal data in some AI training data raises policy questions around the protection of privacy rights. Several techniques are emerging to help preserve privacy when using large datasets (e.g. for machine learning) (OECD, 2023[34]). These "privacy-enhancing technologies" (PETs) can help implement privacy principles such as data minimisation, use limitation and security safeguards. For example, "confidential computing" methods help ensure that companies hosting or accessing data in the cloud or through edge devices cannot view the underlying data without unlocking it with controlled encryption methods (O'Brien, 2020[35]; Mulligan et al., 2021[36]). Another example is "federated learning", where users can each train a model using data on their own device. The data are then transferred to a central server and combined into an improved model that is shared back with all the users (Zewe, 2022[37]). Researchers are also developing methods of training machine-learning models over encrypted data. For example, in homomorphic encryption, the underlying data remains undisclosed during the entire training process. This strengthens privacy protections, while allowing for data to be used effectively (OECD, 2019[3]).

The potential of PETs to protect confidentiality of personal and non-personal data is recognised and applications are maturing. However, many PETs are still at the research stage and not yet scaled-up and used in production for major consumer-facing AI systems. It is also generally recognised that use of PETs can still be associated with privacy breaches and thus should not be regarded as a "silver bullet" solution.

The use of synthetic data has attracted significant interest as a PET approach. Synthetic data are generated via computer simulations, machine-learning algorithms, and statistical or rules-based methods, while preserving the statistical properties of the original dataset.[1] Synthetic data have been used to train AI when data are scarce or contain confidential or personally identifiable information. These can include datasets on minority languages; training computer vision models to recognise objects that are rarely found in training datasets; or data on different types of possible accidents in autonomous driving systems (OECD, 2023[25]). However, challenges remain. For example, "[r]e-identification is still possible if records in the source data appear in the synthetic data" (OPC, 2022[38]). Furthermore, similar to anonymisation and pseudonymisation, synthetic data can also be susceptible to re-identification attacks (Stadler, Oprisanu and Troncoso, 2020[39]).

Generative AI could lead to more representative datasets but also raises concerns about manipulation

Some types of AI, like generative AI, can also produce new data, creative works and inferences or predictions about individuals or a topic that could serve as AI input data (i.e. "AI output data" for training) (Staab et al., 2023[40]). Such AI-generated data may not preserve the statistical properties of the original data and therefore should not be conflated with synthetic data. Nevertheless, the ability of AI to generate new data and content has been highlighted as an opportunity for generating larger and eventually more representative datasets that could be used for training. However, emerging research finds that using AI-generated content can degrade AI models over time. This leads to "model collapse" where the use of model-generated content in training causes "irreversible defects" in the model's results, causing models to "forget" (Shumailov et al., 2023[41]). This is particularly worrisome if training data are collected by "scraping" the Internet without the ability to verify whether a given data sample was AI-generated.

AI-generated content can also be manipulated for various harms, such as for mis- and dis-information campaigns and influencing public opinion (OECD, 2023[25]). Current research suggests there is no reliable way to detect AI-generated content, even by using watermarking schemes or neural network-based detectors. This could allow for AI-generated content to be spread widely without detection, enabling sophisticated spamming methods, mis- and dis-information like manipulative fake news, inaccurate document summaries and plagiarism (Sadasivan et al., 2023[42]). Bad actors could engage in large-scale and low-cost "data poisoning". In these cases, training datasets are "poisoned" by inaccurate or false data, changing a model's behaviour or reducing its accuracy. For example, datasets could be poisoned to deliver false results in all or specific situations.

Regulation around generative AI is emerging in response to such tools becoming widely available at the end of 2022. However, the lag in policy, implementation, and enforcement of such responses around the world, may result in damage to the quality of public discourse online and the quality of information itself on the Internet. This damage may be difficult, if not impossible, to rectify in the years ahead (OECD, 2023[43]).

Open-source resources can make progress more broadly accessible but introduce other challenges

Many resources and tools for AI development are available as open-source resources. This facilitates their widespread adoption and allows for crowdsourcing answers to questions. Tools include TensorFlow (Google) and PyTorch (Meta) (open-source libraries for the programming language Python). Such tools can be used to train neural networks in computer vision and object detection applications. Some companies and researchers also publicly share curated training datasets and tools to promote AI diffusion (OECD, 2019[3]). Open-source developers have adapted and built on notable AI models with impressive speed in recent years (Benaich et al., 2022[44]).

The open-source AI community uses platforms like GitHub and Hugging Face to access open-source datasets, code and AI model repositories, and to exchange information on AI developments. Between 2012 and 2022, the number of open-source AI projects worldwide (measured by AI-related GitHub "repositories" or "projects"), grew by over 100 times, showcasing the increasing popularity of open-source software platforms (OECD.AI, 2023[45]). Training AI has become more accessible through low or no-code paradigms, where user-friendly interfaces substantially lower the barrier to entry for training and using AI (Marr, 2022[46]).

Although several AI firms operate proprietary AI models and systems and commercialise their access, some – such as Meta's language model LLaMA 2 (Meta, 2023[47]) – make them available as open-source. The emergence of several open-source AI models contributes to more rapid innovation and development. This could mitigate "winner-take-all dynamics" that lead a few firms to seize significant market share (Dickson, 2023[48]). Yet open-sourcing entails other potentially significant risks, including non-existent or weak safeguards against use by bad actors.

Computer vision capabilities continue to develop, but applications like facial recognition raise concerns

Since its emergence in the 1960s, computer vision has been key to developing AI that can perceive and react to the world (Russell and Norvig, 2016[11]). Advances in face detection and recognition or image classification underpin significant technological progress in areas like image captioning and image translation (the process of recognising characters in an image to extract text contained in the image). Some computer vision technologies are mature, like face detection and recognition, or image classification.

Facial recognition, a key application enabled by computer vision, has received significant attention in public debate and in policy circles as countries move to create laws to govern AI. In many jurisdictions, facial recognition has been central to discussions on "high-risk" applications of AI, including the question of its use by law enforcement. Risks of algorithmic bias and data privacy concerns have resulted in various calls and actions to limit certain uses of facial recognition technology, such as in public spheres (OECD, 2021[49]). Previous analysis of commercial AI-enabled facial-recognition technologies revealed their greater accuracy when identifying light-skinned and male faces compared to darker-skinned and female faces (Buolamwini and Gebru, 2018[50]; Anderson, 2023[51]). In many cases, this bias is caused by using large training datasets that lack representative population samples from diverse groups. This highlights the important role that synthetic data can play in generating more representative datasets for training. Facial recognition technology has also been involved in mistaken identifications and wrongful arrests, predominantly in communities of colour (Benedict, 2022[52]). For example, a facial recognition system in China mistook a face on a bus for someone illegally crossing the street ("jaywalking") (Shen, 2018[53]). These examples point to the potential for this powerful technology to be misused to harm specific population groups. Jurisdictions are considering stronger regulation, including prohibiting public authorities to use AI for biometric recognition.

Experts have identified key considerations for policy makers in ensuring trustworthy computer vision technology. First, policy makers should consider the data used for training the model, which have recently led to privacy, bias or copyright issues. Second, AI models themselves often require large computational architectures that consume significant amounts of energy and are complex. This raises issues like explainability because they are too complex for people to understand. Some researchers are attempting to improve explainability through methods such as "mechanistic interpretability" by "reverse-engineering" model elements to be understandable to humans (Conmy et al., 2023[54]). Third, policy makers should consider the impact of deploying AI in the real world, particularly around societal and economic impacts like fairness (OECD, 2023[25]).

Robots are getting better and smarter thanks to AI

Robots can be defined as "physical agents that perform tasks by manipulating the physical world" where mechanical components such as arms, joints, wheels and sensors, such as cameras and lasers, allow perception of an environment (Russell and Norvig, 2016[11]). AI can be "embodied" into robots to perform a wide range of tasks, including manufacturing and assembly, transportation and warehousing. It can also be used for various applications where human interaction might be dangerous or physically impossible, for example in emergency rescue contexts. Robotics can also be combined with image, audio and video generation models to produce advanced systems with multimodal capabilities combining these functions (Lorenz, Perset and Berryhill, 2023[10]).

Pending more advanced technology, the market for robotics may grow rapidly. Further technological developments are still needed for robotics to reach wide commercial markets. Some estimated the market for autonomous mobile robots at USD 2.7 billion in 2020. Projections put the market as high as USD 12.4 billion by 2030 (Allied Market Research, 2022[55]).

Researchers are also advancing with "neuro-morphic" robots, machines controlled by human brain waves rather than a voice command, for example. This could include brain chip implants and wearable robotic "exoskeletons" that use machine learning and sensors to gather and process data in real time (Lim, 2019[56]). AI-enabled digital twins, copies of systems or networks for modelling purposes, have also been explored in remote surgery applications alongside robots and virtual reality. Such environments need low network latency (i.e. fast networks) and high levels of security and reliability (Laaki, Miche and Tammi, 2019[57]). These developments could significantly advance the strength and reliability of prosthetic limbs, bring precision to remote surgery applications and even to robot-assisted surgery in space and remote areas, and other cutting-edge health care applications (Bryant, 2019[58]; Newton, 2023[59]).

Will scaling-up current AI models continue to drive advancements in AI capabilities?

In deep learning, research around "scaling laws" offers insights into predictable patterns for "scaling up" AI (i.e. advancing AI by training models with more parameters, compute and data, often bringing significant training costs). These approximate laws describe the relationship between an AI model's performance and the scale of key inputs. For example, some researchers have observed an increase in the performance of language models with increases in compute, dataset size and parameter numbers (Kaplan et al., 2020[60]). Typically, larger language models perform better, pointing to a relationship between performance and scale.

However, models may not be able to scale in perpetuity if AI developers become limited by access to compute and data. As AI models scale with an increasing number of parameters, trade-offs may emerge, such as the cost of compute and increasing memory requirements. Some also argue that large language models based on probabilistic inference cannot reason and thus might never achieve completely accurate outputs (LeCun, 2022[61]). Consequently, some hypothesise that current model architectures may never allow for complete accuracy and generalisation.

Some experts also question whether AI chat-based search models – such as ChatGPT – will benefit from scaling laws, given the significant cost required to retrain their underlying models to keep them up to date so users can search for the most recent information (Marcus, 2023[62]). In addition, some research shows the scaling of models may outpace data availability in the next few years (Villalobos et al., 2022[63]).

Experts offer varying predictions for the future trajectories and implications of AI

AI research and policy discussions often cover existing AI challenges. Yet the long-term implications of rapidly advancing AI systems remain largely uncertain and fiercely debated. Experts raise a range of potential future risks from AI, some of which are already manifesting in various ways. At the same time, experts and others expect AI to deliver significant or even revolutionary benefits. Future-focused activities are critical to better understand AI's possible long-term impacts and to begin shaping them in the present to seize benefits while mitigating risks (OECD, forthcoming[64]).

Strategic foresight and other future-oriented activities can support policy makers to anticipate possible futures and begin to actively shape them in the present. Strategic foresight is a structured and systematic approach to using ideas about the future to anticipate and prepare for change. It involves exploring different plausible futures, and associated opportunities and risks. It reveals implicit assumptions, challenges dominant perspectives and considers possible outcomes that might otherwise be ignored. Strategic foresight uses a range of methodologies, such as horizon scanning to identify emerging changes, analysing "megatrends" to reveal and discuss directions and scenario exploration to help engage with alternative futures (OECD, forthcoming[64]).

In November 2023, recognising that future AI developments could present both enormous global opportunities and significant risks, 28 governments and the European Union signed the Bletchley Declaration. In so doing, they committed to co-operation on AI, ensuring it is designed, developed, deployed and used in a manner that is safe, human-centric, trustworthy and responsible (AI Safety Summit, 2023[65]). The Declaration also committed signatories to convene a series of future AI Safety Summits. This gave further impetus to ensuring that potential future AI benefits and risks remain a topic of international importance and dialogue.

AI is expected to yield significant future benefits

While many headlines focus on AI risk, tremendous benefits are also expected to accrue. Through the G7 Hiroshima Process on Generative AI, G7 members unanimously saw productivity gains, promoting innovation and entrepreneurship, and unlocking solutions to global challenges as some of the greatest opportunities of AI technologies worldwide, including for emerging and developing economies. G7 members also emphasised the potential role of generative AI to help address pressing societal challenges. These include improving health care, helping solve the climate crisis and supporting progress towards achieving the United Nations Sustainable Development Goals (SDGs) (OECD, 2023[66]). The benefits AI may generate include:

- **Enhancing productivity and economic growth.** Projections vary for how much AI may contribute to gross domestic product (GDP) growth. Some market research estimates the global AI market, including hardware, software and services, will have a compound annual growth rate of 18.6% between 2022 and 2026, resulting in a USD 900 billion market for AI by 2026 (IDC, 2022[67]). Others estimate the AI market could grow to more than USD 1.5 trillion by 2030 (Thormundsson, 2022[68]). For generative AI specifically, estimates include raising global GDP by 7% over a ten-year period (Goldman Sachs, 2023[69]).

- **Accelerating scientific progress.** AI could spur scientific breakthroughs and speed up the rate of scientific progress (OECD, 2023[70]). AI can increase the productivity of scientists and overcome previously intractable resource bottlenecks, saving time and increasing resource efficiency (Ghosh, 2023[71]). Impacts in this area can already be seen, with AI driving progress in areas like nuclear fusion and generating new life-saving antibodies to disease (Stanford, 2023[72]; Yang, 2023[73]).
- **Strengthening education.** AI may be able to provide personalised tutoring and other individualised learning opportunities that are currently only available to those who can afford them, increasing access to quality education for all (Molenaar, 2021[74]). On the teaching side, AI can potentially help teachers create materials and lesson plans tailored to students' needs (Fariani, Junus and Santoso, 2023[75]).
- **Improving health care.** Advances in AI technologies could transform many aspects of health care service and delivery. These include interventions at the individual level to provide people with information about their personal health, as well as those that improve diagnoses and alleviate workload for health care providers (Anderson and Rainie, 2018[76]; Davenport and Kalakota, 2019[77]).

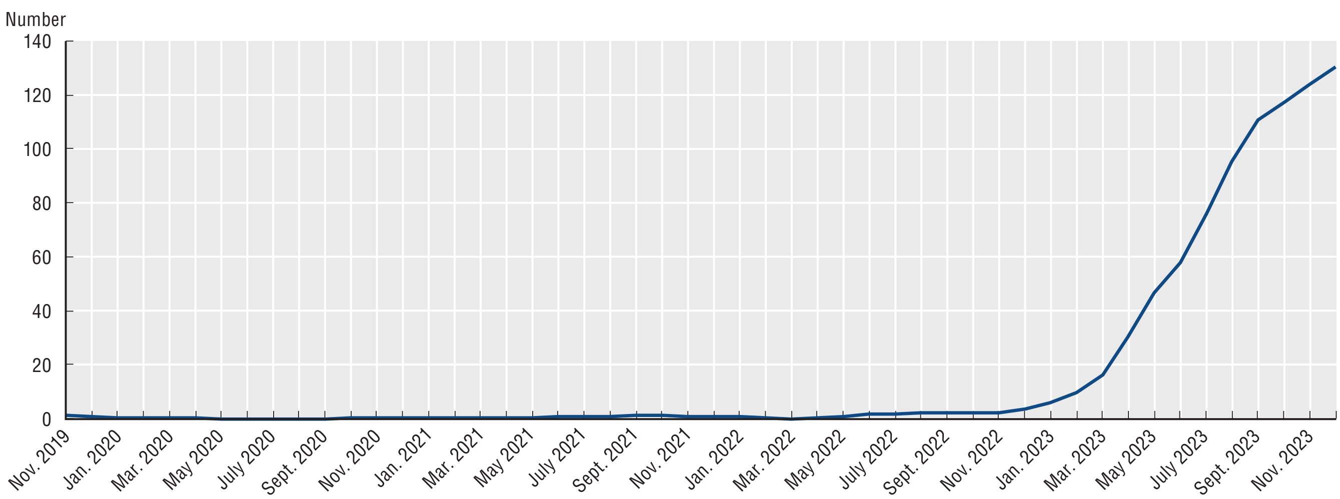
Potential benefits of AI come with risks and uncertain future trajectories

Experts, civil society and governments have all identified many potential risks from AI. The Bletchley Declaration, for example, notes the potential for unforeseen risks, such as those stemming from dis-information and manipulated content. It also points to potential safety risks from highly capable narrow and general-purpose AI models. These could result in substantial or even "catastrophic harm" stemming from the most significant capabilities of leading-edge models.

Although attention has been placed on preventing negative outcomes from advanced AI systems in the medium- to long-term, some risks are already apparent. Early efforts to track AI incidents found that generative AI-related incidents and hazards reported in the press have increased steeply since 2022 (Figure 2.3) (OECD, 2023[66]). G7 members see risks of mis- and dis-information, intellectual property rights infringement, and privacy breaches as major threats stemming from generative AI in the near term (OECD, 2023[66]).

Figure 2.3. Generative AI-related incidents and hazards reported by reputable news outlets have increased steeply since 2022

Number of generative AI-related incidents and hazards, three-month moving average 2019-23



Notes: This chart shows the three-month moving average of real count of incidents and hazards reported. Results might differ from previous analysis due to modifications in the methodology of clustering articles into incidents.

Source: OECD.AI (2024[78]), AI Incidents Monitor (AIM), using data from Event Registry. Please see: *www.oecd.ai/incidents* for more information.

StatLink *https://stat.link/svuo83*

AI could amplify mis- and dis-information on a considerable scale. Generative AI can produce novel images or video from text prompts or produce audio in various tones and pitches with relatively limited input (such as a short recording of a human voice). Already today, generative AI outputs can be challenging to distinguish from human creation (Kreps, Mccain and Brundage, 2022[79]), raising policy implications about the ease of using AI to produce mis- and dis-information – fake news, deep fakes and other convincing manipulated content (Sessa, 2022[80]). Challenges may be particularly acute on issues related to science, such as vaccine effectiveness and climate change, and in polarised political contexts.

Mitigation measures are emerging, such as watermarking and AI-enabled deep fake detection, but current approaches have limitations and may be insufficient to address future challenges (Lorenz, Perset and Berryhill, 2023[10]). Over time, some experts argue that increasingly advanced AI systems could fuel mass persuasion and manipulation of humans (Anderson and Rainie, 2018[76]). This, in turn, could cause material harm at the individual and societal levels, eroding societal trust and the fact-based exchange of information that underpins science, evidence-based decision making and democracy (OECD, 2022[81]).

AI hallucinations, information pollution and data poisoning harm data quality and erode public trust. AI outputs may decrease the quality of data online, as they exhibit hallucinations (making up facts in a credible way, often when a correct answer is not found in the training data). This can contribute to information pollution, allowing AI-produced data to harm the online "commons" and produce a vicious cycle whereby AI is trained on lower quality data produced by AI (Lorenz, Perset and Berryhill, 2023[10]). Bad actors could also use AI to sabotage or ruin robust data (i.e. data poisoning) (OECD, 2023[43]).

AI could significantly disrupt labour markets. Advanced AI could help people find jobs but also displace highly skilled professionals, or at the very least, change the nature of some jobs. Advanced AI can be designed to assist humans in the labour market, including with "collaborative robots" or "cobots". However, some research and experts have raised concerns that increasingly capable AI, such as AI that can act as autonomous agents, could in some cases replace high-skilled and high-wage tasks (e.g. programmers, lawyers or doctors), leading to economic and social disruption (Russell, 2021[82]; Clarke and Whittlestone, 2022[83]; Metz, 2023[84]). Even if AI does not result in net job losses the task composition of jobs is likely to evolve significantly, changing skills needs (OECD, 2023[85]; 2023[86]).

Significant risks could emerge by embedding AI in critical infrastructure. AI is increasingly embedded in critical infrastructure because it can improve timeliness and efficiency, safety and/or reliability, or reduce costs (Laplante et al., 2020[87]). However, some argue this could enable bad actors using AI to cause physical or virtual harm (Zwetsloot and Dafoe, 2019[88]; OECD, 2022[89]). AI deployed in critical infrastructure, like in chemical or nuclear plants, could pose serious risks to safety and security if AI models and systems prove unreliable or unsafe.

AI models and systems can exacerbate bias and inequality. AI can echo, automate and perpetuate social prejudices, stereotypes and discrimination by replicating biases, including those contained in training data, in their outputs. This could further marginalise or exclude specific groups (Bender et al., 2021[90]; NIST, 2022[91]). For example, generative AI tools have been shown to produce sexualised digital avatars or images of women, while portraying men as more professional and career oriented (Heikkilä, 2022[92]). Biases involving specific religions have also been found (Abid, Farooqi and Zou, 2021[93]). As AI becomes more complex, it could also exacerbate divides between advanced and emerging economies, creating inequalities in access to opportunities and resources. "Automation bias" – the propensity for people to trust AI outputs because they appear rational and neutral – can contribute to this risk when people accept AI results with little or no scrutiny (Alon-Barkat and Busuioc, 2022[94]; Horowitz, 2023[95]). At the same time, AI tools can help human operators interpret and question complex AI decisions, discouraging overreliance. More generally, inequal access to AI resources risks creating and deepening inequality both within and between countries (e.g. between developed and emerging economies).

Generative AI raises data protection and privacy concerns. The vast amounts of data used to train AI, especially generative AI, raise data protection and privacy concerns. The processing of personal data for training purposes or its use for automated decision making may conflict with data protection regulations. For example, where data are used for automated decision-making, the European Union General Data Protection Regulation requires the operator to provide "meaningful information about the logic involved". This may pose challenges with AI trained by processing information in "black box" neural networks that humans cannot understand or replicate.

Intellectual property rights represent another area of challenges and unknowns. Generative AI in particular raises issues around intellectual property rights. This could include unlicensed content in training data; potential copyright, patent and trademark infringement of AI creations; and ownership questions around AI-generated works. Generative AI is trained on massive amounts of data from the Internet that include copyrighted data, often without authorisation of the rights-owners. Whether this is permissible is being discussed across jurisdictions, with numerous court cases under way (Zirpoli, 2023[96]). Legal decisions will set precedents and affect the ability of the generative AI industry to train models. Because legal systems around the world differ in their treatment of intellectual property rights, the treatment of AI-generated works also varies internationally (Murray, 2023[97]). Although most jurisdictions agree that works generated by AI are not copyrightable (Craig, 2021[98]), views could shift as AI becomes ubiquitous.

Many solutions are being proposed to help yield AI's benefits and mitigate its challenges

Actions are needed to answer unknowns and shape potential AI futures. AI researchers, experts and philosophers have proposed many potential solutions to enable future benefits, while mitigating risks. The OECD, through its Expert Group on AI Futures, has identified nearly 70 potential solutions being explored and analysed.[2] Surveyed expert group members agreed on the most important potential solutions listed below:

- Liability rules for AI-caused harms;
- Requirements that AI discloses that it is an AI when interacting with humans;
- Research and development (R&D) on approaches to evaluating the capabilities and limitations of AI systems and preventing accidents, misuse or other harmful consequences;
- AI red-lines, such as regulation prohibiting certain AI use cases or outputs; and
- Controlled training and deployment of high-risk AI models and systems.

Other solutions include moratoriums or bans on advanced AI, and international statements or declarations on managing potential risks from AGI. These proposals have gathered less widespread agreement among expert group members.

Demystifying debates on maintaining human control of AI systems and on the alignment of AI systems and human values

The risk that humans lose control of AI systems received significant attention in 2023 both in news media and at the AI Safety Summit hosted by the United Kingdom. However, the topic is controversial. In a 2023 survey of the OECD Expert Group on AI Futures, respondents rated loss of control as both one of the most important and least important risks of AI.

As AI systems become more capable and are assigned more responsibility over important tasks, some experts believe that a lack or misalignment of shared values and goals between humans and machines could lead AI systems to act against the interests of humans. This concern has spawned "AI alignment" work to ensure the behaviour of AI systems aligns consistently with human preferences, values and intent (Dietterich and Horvitz, 2015[99]; Russell, 2019[100]; Bekenova et al., 2022[101]; Dung, 2023[102]).

It can be difficult to discern whether an AI system is pursuing objectives that align with its creators' intent and goals. For example, such issues have begun to emerge through "reward hacking". In these cases, a model finds unforeseen and potentially harmful ways of achieving its objective while exploiting reward signals (Cohen, Hutter and Osborne, 2022[103]; Skalse et al., 2022[104]). In trying to increase user engagement, for example, AI systems managing content on social media could promote articles that spread extreme views and keep users engaged. However, humans may benefit most from balanced and non-polarised content, and real human preferences may reflect this belief (Grallet and Pons, 2023[105]).

A number of experts believe that sufficiently robust methods are not available today to ensure that AI systems align with human values (OECD, 2022[89]). They consider this perceived gap to be one of the top "unsolved problems" in AI governance (Hendrycks et al., 2022[106]). In the 2023 survey of members of the OECD Expert Group on AI Futures, respondents ranked the absence of robust methods to ensure alignment between AI systems' outputs and human values as one of the most important potential future risks. In connecting the concepts of alignment and control, some AI experts believe the negative consequences already witnessed in relatively basic AI systems could be taken to extremes. They argue this could happen if highly capable AI systems were developed in ways that unfold so quickly that humans cannot maintain control, for example if machines gained the ability to improve themselves independently (Cotton-Barratt and Ord, 2014[107]).

As another underlying issue, AI systems can be highly efficient at pursuing human-defined objectives but in ways their developers did not always anticipate. To achieve these aims, AI systems could develop subgoals (i.e. means to an end) that differ dramatically from the values and intent that underpin human-defined objectives. Some argue this could even lead to machines resisting being switched off since this could be considered counter-productive to the achievement of objectives (Russell, 2019[100]). However, as mentioned in Box 2.2, achieving AGI – the level of advancement hypothesised as needed for such scenarios – is hypothetical and highly controversial. Some experts argue that achieving AGI itself might be an exceedingly complex and challenging task. This would make the notion of misalignment a premature concern lacking agreed-upon definitions and clear boundaries (LeCun, 2022[109]). Research on such topics can be challenging, including a limited number of peer-reviewed articles, lack of appropriate modelling techniques and lack of specific definitions and standardised terminology (McLean et al., 2021[110]).

Policy considerations for a trustworthy AI future

The rapid progress in AI capabilities has not yet been matched by assurances that AI is trustworthy and safe. AI is advancing rapidly and could produce unsafe outputs, especially as AI-enabled products are transferred from research contexts to consumer use before the full consequences and risks of their deployment are understood. Advanced AI techniques such as deep learning pose specific safety and assurance challenges: technologists and policy makers alike do not fully understand their functioning and therefore cannot use traditional guardrails to ensure reliability. Lack of explainability inhibits understanding of how AI generates outputs in the form of predictions, content, recommendations or decisions. This, in turn, creates issues related to transparency, robustness and accountability. "Narrow" AI focuses on optimising outcomes for well-defined contexts. However, the increasingly generality of AI applications makes it difficult to train advanced models and systems to produce an appropriate response for every relevant scenario.

There is little understanding or agreement on how significant future AI risks may be. Experts should build awareness and understanding of AI risks, particularly among policy makers, and identify key sources of these risks. To help mitigate some AI risks, improved methods to interpret and assure AI are needed. In addition, policy makers need to ensure that developers can deploy models and systems that operate reliably as intended, even in novel contexts.

Where are countries in the race to implement trustworthy AI?

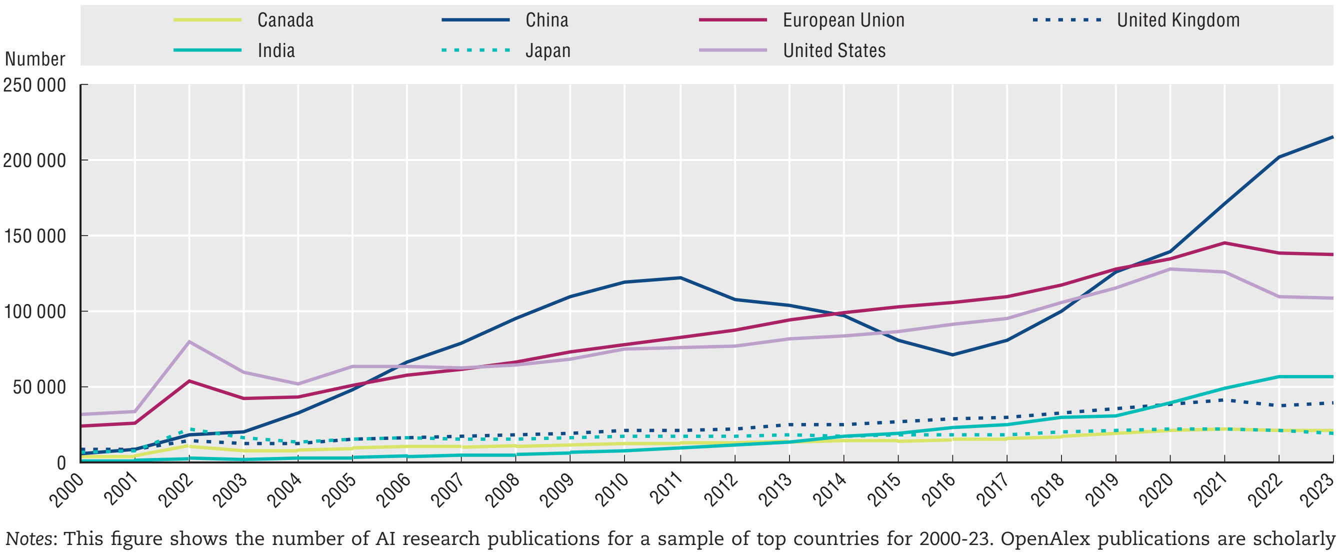
AI research and development priorities feature prominently on national policy agendas, with investments poised to continue in the years ahead

AI R&D investments feature prominently in national AI strategies. Governments and firms are redoubling efforts to leverage AI for productivity gains and economic growth and such trends are poised to continue. Entirely new business models, products and industries emerge from AI-enabled R&D breakthroughs. This underscores the importance of basic research, especially as policies emerge to consolidate R&D capabilities to catch up with the leading players: China, the United States and the European Union (OECD.AI, 2023[111]).

Progress in AI R&D can be measured by examining to what extent countries publish AI research. The United States and European Union have had steady growth in the number of AI research publications over past decades. These include journal articles, books, conference proceedings and publications in academic repositories like arXiv. Meanwhile, AI publications have increased dramatically in China, with India also making strides in recent years (Figure 2.4). Since mid-2019, China has published more AI research than either the United States or the European Union. India has also made significant advances, more than doubling its number of AI research publications since 2015 (OECD.AI, 2023[111]).

Figure 2.4. China, the European Union and the United States lead in the number of AI research publications, with India recently making strides

Number of AI research publications, 2000-23



Notes: This figure shows the number of AI research publications for a sample of top countries for 2000-23. OpenAlex publications are scholarly documents such as journal articles, books, conference proceedings and dissertations.

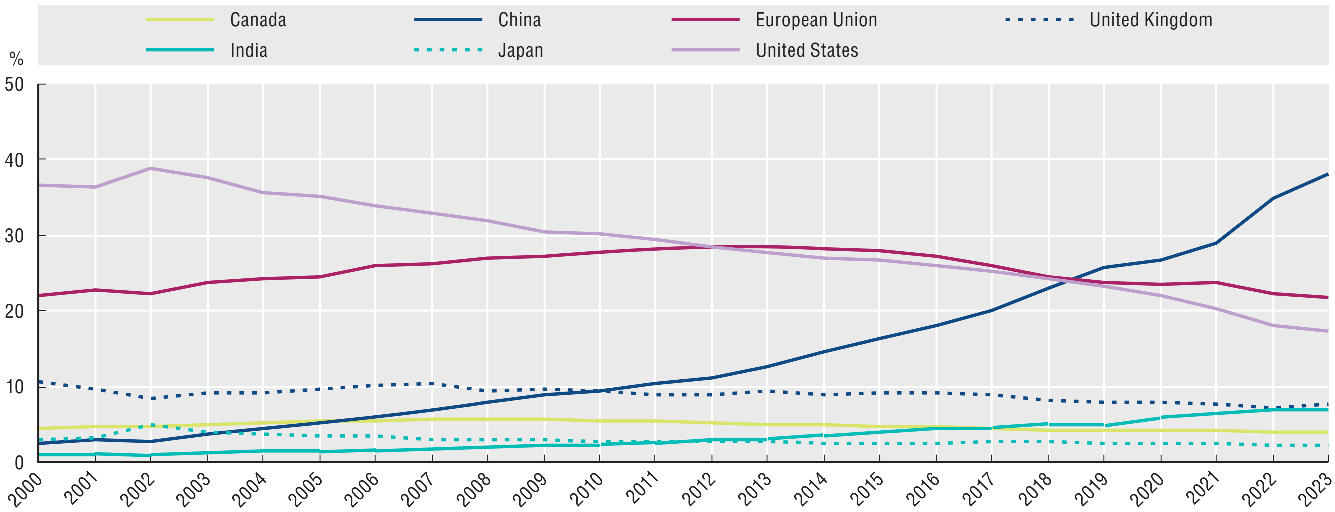
Source: OECD.AI (2023[111]) using data from OpenAlex available at: *www.oecd.ai/en/data?selectedArea=ai-research*. StatLink contains more data.

StatLink *https://stat.link/cbtjqd*

The number of AI publications alone does not provide a full picture of publication quality and impact. The number of citations can be a proxy indicator for "impact", with increased citations possibly indicating a higher impact. Since 2022, the share of total high-impact AI research publications in the United States has declined, while China's share has steadily risen. Notably, China had overtaken the United States and European Union by 2019 (Figure 2.5). In 2023, with respect to institutions most active in publishing AI research, seven of the ten leading AI research institutions were based in China, with one institution each in France, the United States and Germany[3] (OECD.AI, 2023[111]).

Figure 2.5. China's share of "high-impact" AI publications has steadily risen since 2000, notably overtaking the United States and European Union in 2019

Percentage of high-impact AI research publications by jurisdiction, 2000-23



Notes: This figure shows the percentage of "high-impact" AI research publications for a sample of top countries for 2000-23. OpenAlex publications are scholarly documents such as journal articles, books, conference proceedings and dissertations. A publication's impact is calculated by dividing the number of citations by the average citations in the subdiscipline, discounted by the number of years since the publication was published, so that older publications that have been around for longer are discounted accordingly. Publications are classified as "high impact" if its score falls in the highest quartile.

Source: OECD.AI (2023[111]) using data from OpenAlex available at: *www.oecd.ai/en/data?selectedArea=ai-research*.

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Countries dedicate significant funding for AI R&D through different instruments. The main trends include launching AI R&D-focused policies, plans and programmes, establishing national AI research institutes and centres, and consolidating AI research networks and collaborative platforms. Highlights from France, Korea, Türkiye, the United States, the European Union and China appear below.

France established its 2018 National AI Research Programme out of its National AI Strategy. The programme represented 45% of the National AI Strategy budget (about EUR 700 million) (INRIA, 2023[114]).

In 2021, **Korea** announced the AI promotion plan on the theme of "AI into all regions for our people". It focuses on creating an "AI cluster village" in Gwang-ju city to serve as a base for AI innovation as well as projects across the country considering each region's key strengths and industries (Ministry of Science and ICT, 2021[115]).

Türkiye has been funding AI R&D projects and programmes by launching calls for proposals or awarding grants, including multidisciplinary research that encourages collaboration across relevant fields. The Scientific and Technological Research Council of Türkiye and the National AI Institute have funded more than 2 000 R&D and innovation projects. Total funding for academic R&D projects amounted to more than USD 50 million. Meanwhile, industrial R&D projects received funding of more than USD 150 million (TÜBITAK, 2023[116]).

The **United States** introduced initiatives to retain its leadership position in AI R&D through the United States National AI Initiative Act of 2020. In 2023, the National AI Initiative Office helped manage billions of dollars for non-defence and defence-related AI R&D (NSTC, 2023[112]), following the 2016 and 2019 National AI R&D Strategic Plan. The 2023 budget includes funding for the National Science Foundation (NSF) that has long been supporting AI research, including through dedicated AI research grants. In 2018, the Defense Advanced Research Projects Agency announced an AI R&D

investment of more than USD 2 billion. The NSF and the White House Office of Science and Technology Policy (OSTP) recently proposed a National AI Research Resource (NAIRR) to provide researchers access to critical computational, data, software and training resources to support AI R&D (NAIRR Task Force, 2023[113]).

The **European Union** allocated EUR 1 billion per year for AI, including for R&D, within the broader EUR 100 billion budget for the Horizon Europe and Digital Europe programmes (European Commission, 2023[117]). This follows the Co-ordinated Plan on Artificial Intelligence, which was released in 2018. In this plan, member states emphasise co-ordination in AI R&D to maximise impact, including "shared agendas for industry-academia collaborative AI R&D and innovation" (OECD.AI, 2024[118]).

In 2018**, China** invested an estimated USD 1.7-5.7 billion in AI R&D spending. This estimate includes basic research through the National Natural Science Foundation of China and applied research through the National Key R&D Programmes. While precise estimates are challenging to validate, some researchers believe that China's AI R&D budget is closer to the upper bound estimate. Moreover, they believe it likely to have increased in recent years (Acharya and Arnold, 2019[119]). This investment is aligned with the country's ambitions, set in the 2017 New Generation AI Plan, to become the world's primary innovation centre by 2030.

Countries also establish national AI research institutes and research centres:

- The **Australian** AI Action Plan allocated USD 124 million to establish a National AI Centre to further develop AI research and commercialisation (DISR, 2021[120]).
- **Canada**'s Pan-Canadian AI Strategy emphasises research and talent, with the Canadian Institute for Advanced Research leading the strategy for the Government of Canada and three AI Institutes.
- **Japan**'s AI R&D Network provides opportunities to exchange information among AI researchers and promote co-operation in R&D in Japan and abroad.
- The Research Institutes of **Sweden** combine AI research with interdisciplinary research, a wide range of test beds, innovation hubs and educational programmes.
- Established in 2020, the National Artificial Intelligence Institute of **Türkiye** serves as a driving force in disseminating AI. Acting as a bridge between academic research and industry needs, the Institute serves as a key stakeholder in the implementation of Türkiye's National AI Strategy (2021-2025) (Scientific and Technological Research Council of Türkiye, 2023[121]).
- The **United States** National Science Foundation-led National AI Research Institutes Program is the nation's largest AI research ecosystem. It is supported by a partnership of federal agencies and industry leaders (National Science Foundation, 2023[122]).
- **Brazil**'s Ministry of Science, Technology and Innovation and partners are investing BRL 1 million annually for ten years to create up to eight AI Applied Research Centres, with partner firms matching investments.
- **India**'s 2021 Kotak-IISC AI-Machine Learning Centre offers education on AI and machine learning research (OECD.AI, 2021[123]). Other initiatives focus on reinforcing collaborative networks of experts and researchers.

While global venture capital investments in AI and overall have declined since 2021, investments in generative AI start-ups have boomed

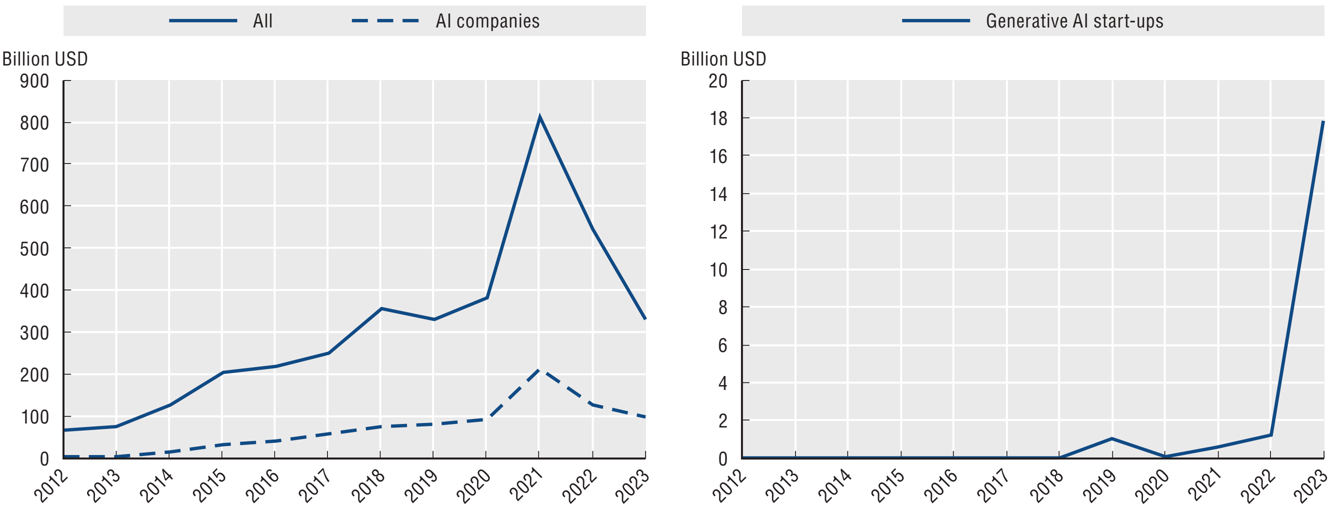
The annual value of global venture capital (VC) investments in AI start-ups[4] more than tripled between 2015 and 2023 (from more than USD 31 billion to nearly USD 98 billion) (Figure 2.6) (OECD.AI, 2024[124]). Notably, between 2020 and 2021, such investments jumped by over 2.3 times (from about USD 92 billion to USD 213 billion). Most of the funds flowed to AI firms in the United States and China. The United States has the advantage of a strong market for private sector R&D and VC funding, accounting for more than two-thirds of global private sector investment in software and computer services in 2022 (European Commission, 2023[125]).

Following trends in the global VC market, overall VC investments in AI firms experienced a significant drop of over 50% between 2021 and 2023 (from USD 213 billion to USD 98 billion (OECD.AI, 2024[124]). This reflects broader VC trends, with investors exercising caution after the technology boom of the COVID-19 pandemic, rising interest rates and inflationary pressures. Generative AI start-ups are one exception to this cooling trend in VC investments, jumping from USD 1.3 billion in 2022 to USD 17.8 billion in 2023, a large increase from 1% of total AI VC investments to 18.2%. The rise was spurred largely by Microsoft's USD 10 billion investment in OpenAI (Figure 2.6) (OECD, 2023[66]).

VC investments in AI have focused on different areas over the past decade. In 2012 and 2013, the largest investments were made in media and marketing, and in IT infrastructure and hosting. The following years saw a VC boom in AI for mobility and autonomous vehicles, but its share of total VC investments declined significantly after 2020. Unsurprisingly, the pandemic years saw an increase in VC investments in AI for health care, drugs and biotechnology (OECD.AI, 2023[126]).

Figure 2.6. VC investments in generative AI start-ups have boomed since 2022, while VC investments overall and in AI start-ups reached a peak in 2021

VC investments in AI and generative AI start-ups, 2012-23



Notes: AI start-ups are identified based on Preqin's cross-industry and vertical categorisation, as well as on OECD's automated analysis of the keywords contained in the description of the company's activities. AI keywords used include: generic AI keywords, such as "artificial intelligence" and "machine learning"; keywords pertaining to AI techniques, such as "neural network", "deep learning", "reinforcement learning"; and keywords referring to fields of AI applications, such as "computer vision", "predictive analytics", "natural language processing", "autonomous vehicles". Please see: *https://oecd.ai/preqin* for more information.

Source: OECD.AI (2024[124]) using data from Preqin. Also available at: *www.oecd.ai/en/data?selectedArea=investments-in-ai-and-data*.

StatLink *https://stat.link/d4hucr*

Governments are building human capacity for AI as demand for AI skills grows

AI is changing the nature of work. Countries have realised that both managing a fair labour market transition and leading in AI R&D and adoption requires solid policies to build human capacity and attract top talent. The AI workforce has grown considerably, almost tripling as a share of employment from less than a decade ago (Green and Lamby, 2023[127]). However, according to LinkedIn in 2023, men are about twice as likely to work in an AI occupation or report AI skills as women. This suggests a gendered skills gap in global AI labour markets (OECD.AI, 2023[128]).

AI talent is in high demand and remains a mobile workforce across economies, with countries competing for the small pool of highly skilled AI workers. For example, economies like Luxembourg, Canada, Germany and Japan attracted more AI talent than they lost in 2022 (Figure 2.7). In contrast, countries like India, Greece and Lithuania saw a net outflow of AI talent from their borders. This might indicate an AI "brain drain", where highly specialised workers move to another country for improved employment opportunities. India is noteworthy for its considerable AI talent growth rate in recent years. This rate is ahead of the United States, United Kingdom and Canada, as measured by the year-over-year change in LinkedIn members declaring to have AI skills (OECD.AI, 2022[129]).

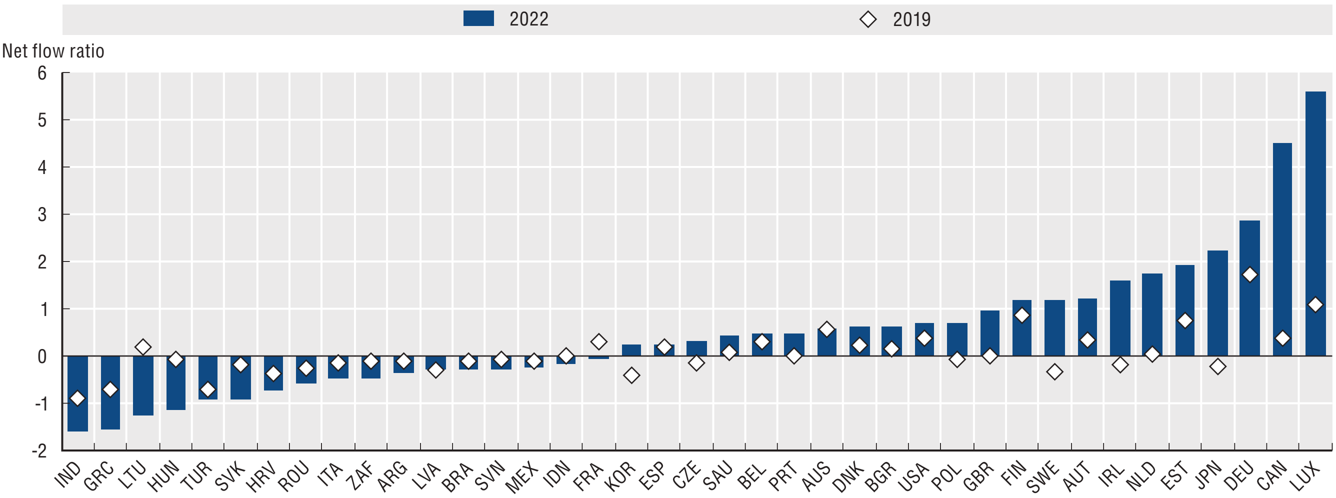
With industry outpacing academia in developing advanced AI, countries increasingly see AI compute capacity as a crucial resource to be managed

The demand for AI compute has grown dramatically as shown by valuations in the AI chip market. In 2021, some called the unfolding AI compute trends an "AI chip race"; the market value for AI chips was estimated at more than USD 10 billion with revenues expected to reach nearly USD 80 billion by 2027 (Pang, 2022[130]). Large technology companies have invested significantly to join the race.

The growing focus on AI compute is driven by a desire from AI developers to obtain the specialised hardware and software needed to train advanced AI. Industry, rather than academia, increasingly provides and uses compute capacity and specialised labour for state-of-the-art machine-learning research and for training AI models with a high number of parameters (Ahmed and Wahed, 2020[131]; Ganguli et al., 2022[132]; Sevilla et al., 2022[30]). Compute divides may emerge and worsen between the public and private sectors because, increasingly, public sector entities lack resources to train advanced AI (OECD, 2023[8]).

Figure 2.7. Advanced economies are competing for AI talent

Between-country AI skills migration in 2019 and 2022



Notes: This chart displays the net migration flows per 10 000 LinkedIn members with AI skills in 2019 and 2022 for a selection of countries with 100 000 LinkedIn members or more declaring to have AI skills both in 2019 and 2022. Migration flows are normalised according to LinkedIn country membership.

Source: OECD.AI (2022[129]) using data from LinkedIn, also available at: *www.oecd.ai/en/data?selectedArea=ai-jobs-and-skills*.

StatLink *https://stat.link/8c61e2*

Based on the number of "top supercomputers", the United States and China have led in compute capacity since 2012. According to the November 2023 Top500 list,[5] 35 economies have a top supercomputer. The highest concentration occurs in the United States (32%), followed by China (21%), Germany (7%), Japan (6%), France (5%) and the United Kingdom (3%). The remaining 29 economies on the list represent a combined 26% of supercomputers (Top500, 2023[133]). The United States and China have led in the number of supercomputers on the Top500 list since 2012, with China increasing its number of supercomputers significantly since 2015.

Analysis of top supercomputers through the Top500 list is a proxy for measuring national compute capacity. However, not all supercomputers on the list are specialised and used for AI. Moreover, some economies have slowed or refrained from submitting data to the list in recent years, posing challenges for cross-country comparisons. In addition, counting the number of supercomputers only provides a partial picture of national compute capacity because some supercomputers are more powerful than others.

Another proxy for national compute capacity is the share of the most powerful computers[6] on the Top500 list. The United States has the highest concentration of supercomputers among the world's leading economies with 53%, followed by Japan (10%) and China (6%) (Top500, 2023[133]). Such concentration of supercomputers is a proxy measure for benefits and risks from AI hardware "economies of scale". On the one hand, high concentration creates efficiencies by pooling resources in hyperscale computing centres. On the other, it indicates possibly worsening "compute divides" where leading economies have greater resources to invest in R&D and benefit from it, solidifying their leading positions for the foreseeable future.

Countries are striving to increase AI compute capacity available for research and academia, in addition to taking stock of their national AI compute capacity and needs:

- **Canada**'s Pan-Canadian AI Strategy (2017, 2021) leverages a national network of AI research institutes and supports acquisition of high-performance computing capacity for AI research. In 2020, the first Canadian Digital Research Infrastructure Needs Assessment was launched to identify future digital research infrastructure and service needs (Digital Research Alliance of Canada, 2020[134]).

- **Korea**'s K-Cloud Project aims to manufacture and deploy world-class AI chips domestically to provide improved national cloud computing infrastructure.
- The Turkish National e-Science e-Infrastructure (TRUBA) in **Türkiye** provides high-performance computing and data storage to research institutions and researchers. TRUBA seeks to expand and strengthen computing and data storage resources for researchers. It has a national network operating throughout the country (TRUBA, 2023[137]).
- In 2022, the **United Kingdom** conducted the Future of Compute review to examine its digital research infrastructure needs, including for AI. It called for an integrated compute ecosystem and significant investment in public AI infrastructure (The Alan Turing Institute, 2022[135]).
- The **United States** aims to make world-class computing resources and datasets available to researchers through the proposed NAIRR, supported by the 2023 United States Executive Order on AI (The White House, 2023[136]).
- The **European** High-Performance Computing Joint Undertaking (EuroHPC), established in 2018, co-ordinates and shares compute resources among EU members and partners with a 2021-27 budget of EUR 7 billion (EuroHPC, 2022[138]). At the end of 2023, the European Commission committed to widening access to EuroHPC's infrastructure for European AI start-ups, SMEs and the broader AI community as part of the EU AI Start-Up Initiative (European Commission, 2023[139]). EuroHPC also launched a new Research and Innovation call to establish a European support centre to assist European AI users in finding supercomputing capacity (EuroHPC, 2023[140]).

Countries are embedding values-based principles into AI legislation, regulation and standards, moving towards future-fit policies for trustworthy AI

As the first intergovernmental standard on AI, the OECD AI Principles cast a light on what OECD countries and partner economies rightly saw as an emerging but fundamental challenge and opportunity to economies and societies. The principles formed the basis for the G20 AI Principles. Currently, 46 countries adhere to the OECD AI Principles, including economies such as Argentina, Brazil, Peru, Romania, Egypt, Malta, Singapore and Ukraine.

Since the principles were adopted in 2019, AI policy initiatives have flourished across OECD and partner economies. Many countries now have learnings from implementation of their first national AI strategies. Indeed, many jurisdictions are moving from "principles to practice" by codifying the OECD AI principles into law, regulation and standards. As implementation continues, discussions are ongoing about related AI certification, standards assessments and enforcement bodies. In addition, questions also remain about interoperability with existing privacy, data and intellectual property regimes.

The field of responsible AI has grown dramatically. AI policy makers across disciplines are rallying to ensure that AI benefits not only the "bottom line" but also societies and the environment more broadly. In 2016, only a handful of countries had national AI strategies. In 2024, as an established hub for sharing experiences and best practices, the OECD. AI Policy Observatory documents over 1 000 AI-related policy initiatives across 70 jurisdictions. Of these, more than 354 initiatives relate to AI guidance and regulation (OECD.AI, 2024[118]).

Increasingly, countries are promoting AI governance by proposing or implementing AI principles, legislation, regulation and standards. Some jurisdictions are taking a cross-sectoral approach to AI regulation (Canada, European Union, Brazil), while others consider a more sectoral approach (United Kingdom, United States).

Since 2019, through its Directive on Automated Decision-Making, **Canada** has implemented regulations around automated decision-making systems for public services, including the requirement for algorithmic impact assessments (Government of Canada, 2019[141]). Canada has put forward the Digital Charter Implementation Act (Bill C-27) to regulate use of AI in the private sector and economy. The proposed legislation includes new rules for AI in the Artificial Intelligence and Data Act (Parliament of Canada, 2022[142]). Ultimately, Canada wants its rules and regulations to be interoperable with other emerging AI regulations, such as those in the European Union.

In 2019, **Japan** published a set of Social Principles for Human-Centric AI outlining three philosophies (dignity, diversity and inclusion, and sustainability) and seven principles on AI (human-centric, education and literacy, privacy, fair competition, security, innovation and fairness, accountability and transparency) (Cabinet Office, 2019[145]). In May 2023, under the Japanese presidency of the G7, leaders established the G7 Hiroshima AI Process to examine opportunities and challenges related to generative AI. In December 2023, G7 leaders agreed to publish the Hiroshima AI Process Comprehensive Policy Framework and its future "Work Plan" to advance the process. The Comprehensive Policy Framework comprises the OECD's Report towards a G7 Common Understanding on Generative AI; international guiding principles; an international code of conduct; and project-based co-operation on AI (G7 Hiroshima Summit, 2023[146]; OECD, 2023[66]).

In 2023, the **United Kingdom** put forward a context-specific regulatory framework for AI in a white paper ("A Pro-innovation Approach to AI Regulation"), which establishes outcomes-focused principles to be applied to AI in specific sectors. It proposes that regulators consider these principles when developing sector-specific definitions and policies. This approach also promotes use of regulatory experimentation in the form of testbeds and sandbox initiatives. These experiments would help AI innovators get new technologies to market, while testing possible regulatory approaches (DSIT, 2023[143]). In November 2023, the United Kingdom hosted the AI Safety Summit, which culminated in the establishment of the AI Safety Institute. The Institute will conduct advanced research, possibly with counterparts in other countries, and commission an AI "State of the Science" report (AI Safety Summit, 2023[65]).

In the **United States,** binding federal regulation includes sectoral or domain-specific regulations. These incorporate existing AI principles into their application, such as AI-specific initiatives to protect consumers by the Federal Trade Commission. In 2023, the White House released an Executive Order on the Safe, Secure and Trustworthy Development and Use of Artificial Intelligence. It directed various activities related to establishment of standards for AI safety and security. It also outlined various requirements for government entities and other relevant actors related to the protection of privacy, consumer, worker and civil rights, among others (The White House, 2023[136]; The White House, 2023[144]).

Since 2021, the **European Union** has advanced a Regulation on Artificial Intelligence (hereafter the "EU AI Act") that is globally influential. The EU AI Act accompanies the European Coordinated Plan on AI (2018, 2021). It thus aims to position Europe as a major world player in AI innovation, embedded with values (human-centric, trustworthy, secure and sustainable) and addressing AI risks through regulation and harmonised standards. The EU AI Act seeks to avoid regulatory fragmentation across member states to mitigate high-risk uses of AI, including potential threats to European values. It proposes obligations for certain AI applications that pose high risks, bans use of AI listed as carrying unacceptable risks (such as social scoring by governments) and establishes transparency obligations for AI uses that present limited risks (such as chatbots) (European Commission, 2021[147]).

Brazil has also proposed an AI regulation, inspired by the EU AI Act and based on three central pillars: protecting the rights of those affected by AI, risk-level grading and governance measures aimed at providers of AI (Agência Senado, 2022[148]).

In 2022, **Singapore**'s Infocomm Media Development Authority (IMDA) launched A.I. Verify, a voluntary AI governance testing framework and toolkit. It verifies the performance of an AI system against the developer's claims and against internationally accepted AI principles (IMDA, 2022[149]).

Technical standards will play a key role in the implementation of trustworthy AI

Standard-setting organisations play a key role in building consensus to promote interoperability between jurisdictions. They also offer market certainty for those using or developing AI in different parts of the world. Promoting wide participation from relevant parties in the establishment of such standards will be critical to ensure different perspectives are considered for effective risk management. The **United Kingdom** launched the AI Standards Hub in October 2022, which aims to champion use of technical standards as governance tools for AI by providing businesses, regulators and civil society organisations with the practical tools and information to apply AI standards effectively and contribute to their development (AI Standards Hub, 2022[150]). In the **United States,** NIST has established voluntary technical guidelines for AI risk management that have received broad support, building on the OECD Framework for the Classification of AI Systems. In the **European Union**, the European Committee for Electrotechnical Standardization (CEN-CENELEC) develops technical standards supporting the EU AI Act. The International Organization for Standardization (ISO) developed ISO/IEC 23053 (2022), establishing a Framework for AI Systems Using Machine Learning. This complements ISO 31000 (2009) for risk management that applies across sectors and activities (ISO, 2022[151]; 2009[152]).

Initiatives supporting international co-operation for trustworthy AI continue to grow

Since adoption of the OECD AI Principles in 2019, there have been numerous global initiatives and partnerships for trustworthy AI.

- In addition to adoption of the **OECD AI Principles** by the OECD countries and partner economies, **G20** members have committed to the same principles in the G20 AI Principles. Since adoption of the OECD AI Principles, the OECD has worked with the global AI community to put them into practice, launching the OECD.AI Policy Observatory and Network of Experts early in 2020. In 2022, the OECD subsequently established a new Working Party on AI Governance (AIGO). It has also continued expanding its AI Network of Experts (ONE AI), which includes hundreds of participants globally (OECD.AI, 2024[118]).
- The **Council of Europe**'s Committee on Artificial Intelligence is tasked with developing an AI legal instrument based on its standards for human rights, democracy and the rule of law (Council of Europe, 2023[153]).

- **Globalpolicy.ai** is a coalition of eight[7] intergovernmental organisations with complementary mandates on AI (GlobalPolicy.ai, 2023[154]).
- The **Global Partnership on AI (GPAI)** was launched in June 2020 as a multistakeholder initiative focusing on practical projects. Several expert working groups foster responsible AI development based on the OECD AI Principles (GPAI, 2023[155]).
- **UNESCO**'s 2021 Recommendation on the Ethics of Artificial Intelligence introduced principles for trustworthy AI and areas of policy action (UNESCO, 2022[156]).

Challenges lie ahead in crafting future-fit AI policies that also spur innovation

Frameworks for the governance of AI will continue to evolve. Many questions remain for crafting future-fit policies that can sufficiently address concerns raised by AI, while spurring innovation and standing the test of time. Several such questions are explored below, reflecting key considerations and trade-offs policy makers face in preparing for the future of AI.

How can policy makers be agile and keep pace with rapid AI advancements? The capabilities of generative AI took many policy makers by surprise in late 2022. Closing this information gap by promoting interdisciplinarity and collaboration between AI policy makers, developers and technical communities will be essential to build capacity and ensure governments keep pace with AI advancements. However, this can be challenging. AI developers often limit information disclosure to protect trade secrets, among other reasons. In future, national and regional regulations, as well as enforcement bodies, will be instrumental. They will need to protect developers and users from misuse of AI technologies, while enabling innovation and productivity gains. Nevertheless, *de jure* laws and regulations require time to develop. Large technology companies often race ahead and dictate *de facto* rules until such legislation and enforcement mechanisms are put in place.

How will jurisdictions regulate increasingly general AI, including foundation models, in an effective manner? Advanced AI, such as GPT-4 (OpenAI), can be used in and adapted to a wide range of applications for which it was not intentionally and specifically designed. This raises questions around how to create adequate rules for AI systems that can be applied generally across contexts. Concerns include how to craft regulation that ensures safe application of AI systems when used in contexts for which they were not expressly trained and tested.

How will jurisdictions avoid a patchwork of complex rules governing AI? International co-operation on AI policy is important because like the Internet, AI knows no borders. However, countries are competing to achieve global leadership in AI, leading them to adopt varying policy approaches. In a world where many firms do business internationally by default, interoperable standards for AI are critical. They provide businesses with stability and predictability, while assuring users that AI applications will not be misused. Many AI models and systems globally use the same core AI algorithms and datasets for their training. This makes many countries vulnerable to the same issues, including bias, security concerns and infringement of human rights. Some attempts at interoperability have already taken shape. For example, a potential "Brussels Effect" from the EU AI Act may be observed in other jurisdictions, namely in Canada and Brazil where a risk-based approach and other features of the EU model can be seen. International organisations like the OECD also play an important role with the OECD definition of an AI system informing the definition in the EU AI Act, helping to facilitate interoperability.

How will high-risk or unacceptable uses of AI be treated? Jurisdictions are trying to establish rules to promote trustworthy AI and to protect fundamental rights without creating undue barriers to innovation. If the treatment of high-risk or unacceptable uses of AI differs across jurisdictions, it may create loopholes and incentivise regulatory arbitrage. Creating minimum global standards to mitigate serious and unacceptable risks may help in this regard. Policy makers may wish to engage in a wider debate on how to address any long-term or broader-scale risks that prove well founded. In addition, they could explore approaches to mitigate and avoid current AI risks, such as adverse outcomes caused by bias in AI.

How will fundamental rights like privacy be upheld in a world where AI can infer undisclosed information about individuals? The considerable advancement of AI capabilities has included increased ability to make predictions and draw conclusions from vast amounts of training data – also known as "inference". This raises the question of whether AI, including large language models, could violate individuals' privacy rights by inferring personal information not shared with the model during its training (Staab et al., 2023[40]). Some research suggests that current large language models can infer personal data at a scale previously unseen. This calls for a broader discussion around privacy implications for language models, beyond what they "memorise" during training (Staab et al., 2023[40]). Questions also remain regarding how best to obtain individuals' consent when using personal data for AI training.

How will intellectual property rights be upheld? Mounting legal cases and policy proposals around upholding intellectual property rights, such as using copyrighted material to train AI, will help clarify these issues in the coming years. Such litigation highlights the need to develop solutions to addressing intellectual property considerations in AI training data across jurisdictions. Policy makers can further examine tools to ensure respect for intellectual property rights, while sufficient data are made available for AI training. Tools include setting rules and codes of conduct around "data scraping" and fostering fair and equitable data-sharing agreements.

How will different sectors of the economy apply their existing regulatory schemes to the use of AI? As AI tools diffuse across nearly every facet of economies, different sectors will likely apply their existing regulatory frameworks to the use of AI. This is already apparent such as in AI-specific initiatives to protect consumers undertaken by the Federal Trade Commission in the United States. Sector-specific AI strategies and approaches to AI governance are expected to continue emerging. This raises questions around promoting interoperability between sector-specific AI schemes, as well as interoperability with existing AI laws and regulations, such as those at national or regional levels.

How will emerging rules for AI be enforced effectively? Questions remain around enforcing AI laws. The emergence of varying regulatory approaches and combinations across mandatory and voluntary regulations, technical standards and policies, both within and across countries, will be a challenge for enforcement. For example, it is not clear how regulators will decide when conformity assessments will be needed. This may lead to overlap and duplication, such as between AI and data protection requirements. Policy makers and regulators will need to overcome any gaps, overlaps and contradictions in laws and regulations as they are implemented and enforced. In addition to paying compliance costs, companies may misinterpret complex regulatory requirements. Effective enforcement may also rely on standards yet to be established.

The future of AI is uncertain and complex, posing great opportunities but also risks for society and economies

Building trustworthy AI and using it responsibly are key to realising a future where AI is trusted and a force for good. To better understand the long-term implications of AI, researchers should engage in dialogue and collaboration with policy makers, practitioners, industry partners and civil society groups in multistakeholder forums such as the OECD. They need to ensure their findings are relevant, accessible and actionable to help address opportunities and risks posed by AI today and in the future. Interdisciplinary collaboration between technical and policy communities at national and international levels is critical. Such collaboration can foster mutual learning, trust and co-operation among different actors and stakeholders. Together, they can facilitate the development of inclusive, responsible and human-centric AI policies and practices that stand the test of time.

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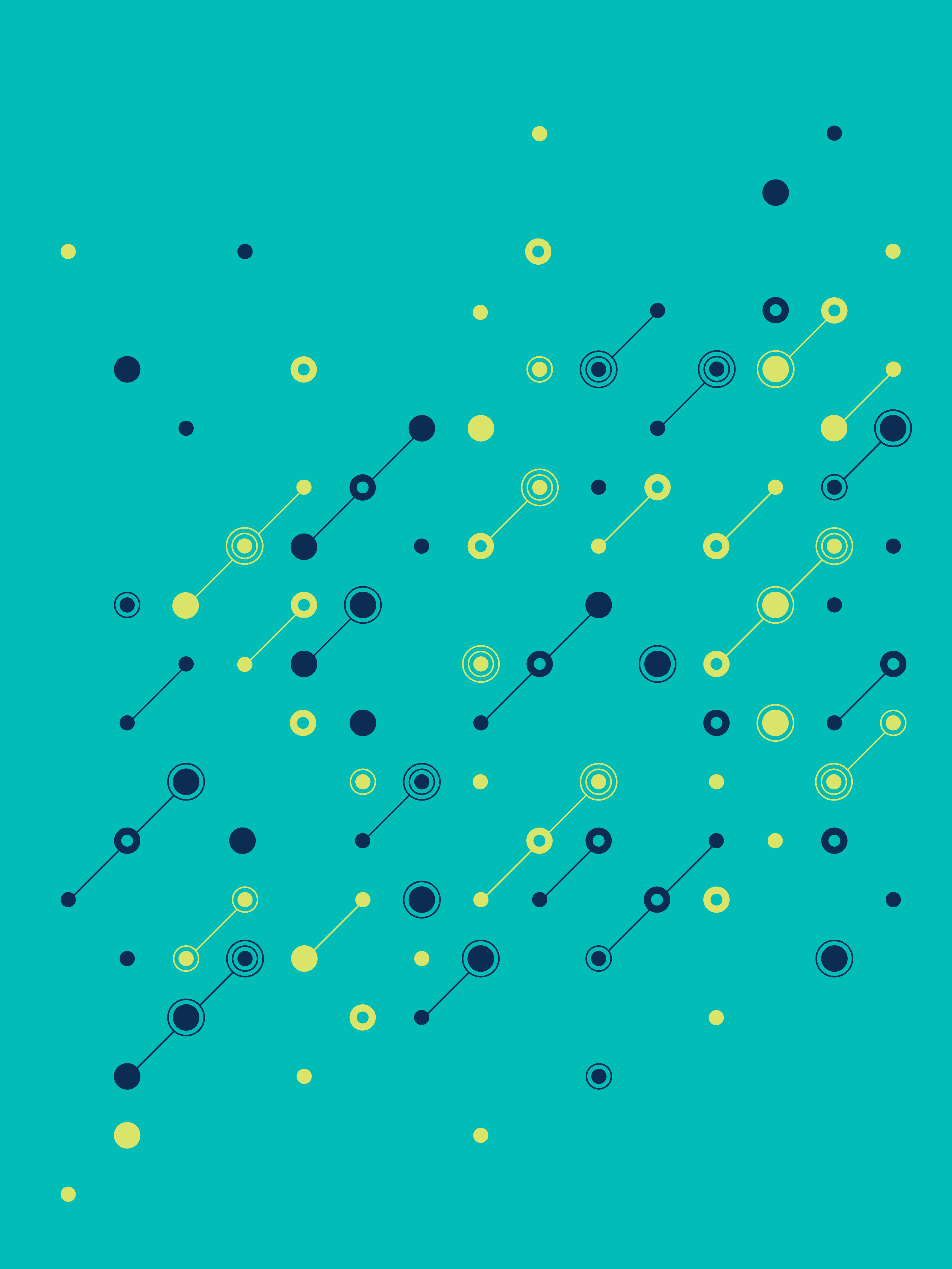
Notes

1. “Synthetic data is generated from data/processes and a model that is trained to reproduce the characteristics and structure of the original data aiming for similar distribution. The degree to which synthetic data is an accurate proxy for the original data is a measure of the utility of the method and the model.” (EU-US Trade and Technology Council, 2023[7]).
2. The initial set of potential future AI solutions can be found at: *https://easyretro.io/publicboard/Lg97hwaJe8MJWJTe5uKGfjjtInh1/f63b59a0-0531-456e-82f2-d9bea1463fb9*.
3. At the time of writing, top research institutions in 2023 according to data from OpenAlex available on OECD.AI include Chinese Academy of Sciences (China), French National Centre for Scientific Research (France), Tsinghua University (China), Shanghai Jiao Tong University (China), Zhejiang University (China), Harbin Institute of Technology (China), Beihang University (China), Huazhong University of Science (China), Stanford University (United States) and the Max Planck Society (Germany). Publications are in multiple languages, not just in English. Data available at *https://oecd.ai/en/data?selectedArea=ai-research&selectedVisualization=ai-publication-time-series-by-institution*.
4. AI keywords used include: generic AI keywords, such as “artificial intelligence” and “machine learning”; keywords pertaining to AI techniques, such as “neural network”, “deep learning”, “reinforcement learning”; and keywords referring to fields of AI applications, such as “computer vision”, “predictive analytics”, “natural language processing”, “autonomous vehicles”.
5. In recent years, supercomputer systems have been increasingly updated to also run AI-specific workloads. However, the list does not distinguish supercomputers according to workload capacity specialised for AI. Drawing conclusions from the list should thus be made cautiously: the list does not define “supercomputers” for AI but uses a benchmark methodology (Linpack). This means any supercomputer can make it into the Top500 list if it can solve a set of linear equations using floating point arithmetic. As submitting to the list is voluntary, some countries have reportedly slowed or stopped submissions of top supercomputers to the list in recent years. Thus, country comparisons using this data are limited and should be considered with this caveat. Analysis of the Top500 list can serve as a proxy measure to observe emerging or deepening compute divides between economies. However, such figures should be supplemented by AI-specific analysis as countries reflect on their specific national AI compute needs.
6. Maximum achieved performance measured by Rmax in tera floating-point operations per second (TFLOPS).
7. Members include the Council of Europe, the European Commission, the European Union Agency for Fundamental Rights, the Inter-American Development Bank, the OECD, the United Nations, UNESCO and the World Bank.



Spotlight

Next generation wireless networks and the connectivity ecosystem

This Spotlight examines emerging trends in next generation wireless networks that are shaping the connectivity ecosystem. These trends raise questions about how to make the next generation of wireless technologies a commercial and ubiquitous reality. The Spotlight dives into research initiatives, market trends and developments towards integration of terrestrial wireless connectivity solutions like 5G and 6G with non-terrestrial technologies, such as satellites and other aerial platforms. In so doing, it identifies challenges for spectrum policy, regulatory collaboration, interoperability, environmental sustainability, safety and digital security, and digital divides. These issues, both technical and regulatory, must be addressed to realise future visions.

The future of wireless connectivity

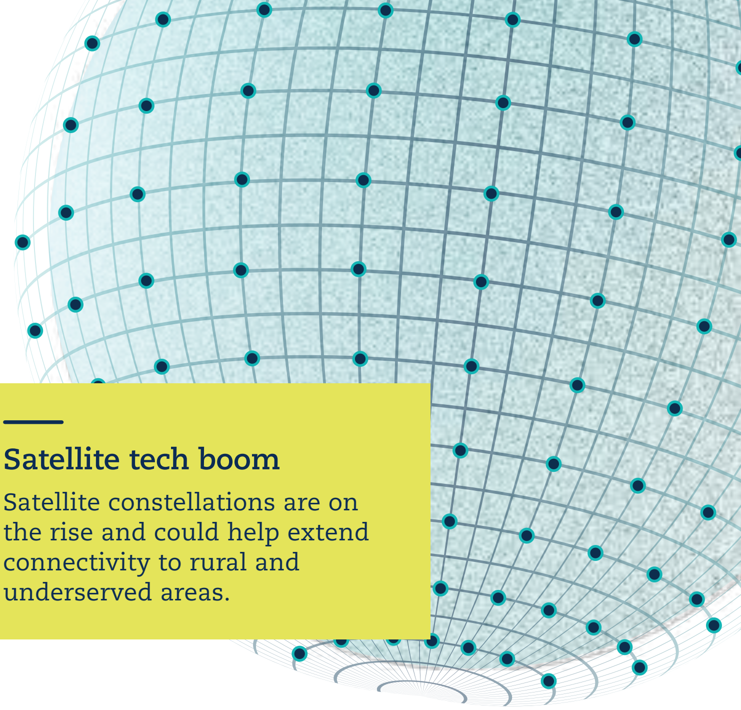
Lightning-fast networks

Research on

6G

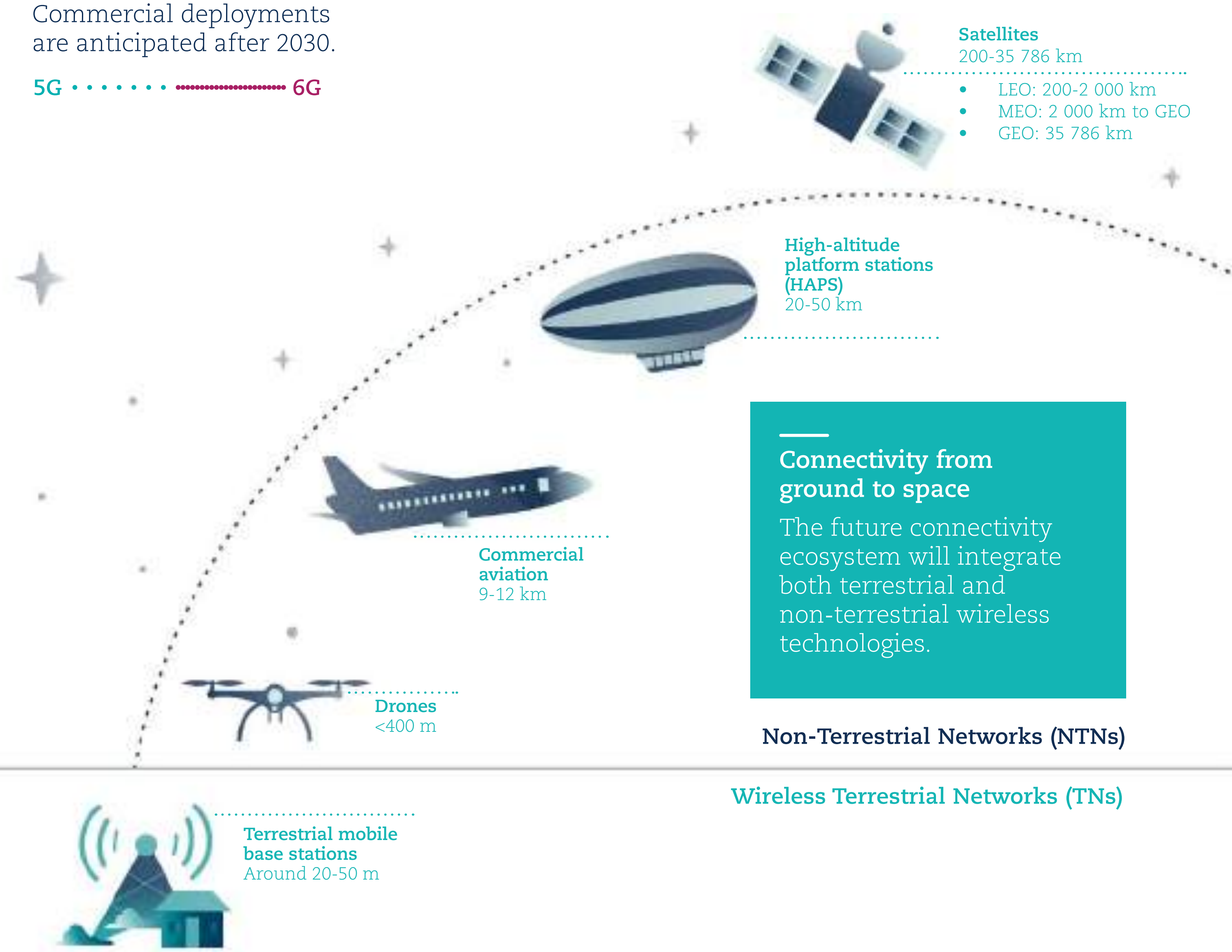
is underway globally and in 15 OECD countries. Commercial deployments are anticipated after 2030.

5G • • • • • • • ••••••••••••••••••• 6G



Satellite tech boom

Satellite constellations are on the rise and could help extend connectivity to rural and underserved areas.



Connectivity from ground to space

The future connectivity ecosystem will integrate both terrestrial and non-terrestrial wireless technologies.

Source: OECD elaboration based on multiple sources, including Ofcom, the European Space Agency and GSMA.

Next generation communication networks are driven by technological developments in the communications industry, as well as current and anticipated demand on networks. The amount of data sent over communication networks has increased steadily for both consumer and business use cases. This growing volume has been spurred by developments in artificial intelligence (AI) systems and the Internet of Things (IoT), and other emerging technologies. Enhanced machine and human communications and interactions, as well as human-augmenting technologies for sensorial communication, including haptics (Internet-of-senses), are likely to influence future demand on networks. In addition, fully automated vehicles, for example, will shape future demand on wireless networks.

The combination of virtual reality (VR), augmented reality (AR) and extended reality (XR) environments and applications is shaping human communications. Moreover, it influences the way humans communicate with machines and their environments as the digital, human and physical worlds merge (Hexa-X, 2022[1]). These trends in immersive technologies, a topic explored in Chapter 4 on virtual reality, will require broadband networks to adapt. Moreover, haptic technologies – which are relatively nascent – are advancing together with AR applications. They are starting to be used in areas such as surgery simulations, immersive communication and health care, and for vision- and hearing-impaired people.

All these advances have important implications for future networks: they generate large amounts of data, leading to higher bandwidth and data processing requirements. Most of these applications also rely on improved broadband performance, i.e. higher speeds and lower network response times (latency). On top of these network performance requirements, increased network resilience will be needed, not only for critical applications, but for all use cases. Most importantly, broadband networks have evolved from connecting people to connecting "everything", a step towards unlimited and embedded connectivity "everywhere" in the future. As such, a key question is how to prepare networks, and in particular wireless networks, to respond to these technological developments.

Extending connectivity is both necessary and desirable as digital transformation depends on it. Continuing to grow an understanding of the connectivity ecosystem is therefore essential to ensure evidence-based policy making in this area. That said, the OECD sets policy rather than technological standards, and technological futures are highly uncertain in a dynamic area such as communication infrastructures and services. With this in mind, the Spotlight sheds light on possible developments in next generation wireless networks in the next five to ten years, highlighting the potential to extend high-quality connectivity "everywhere". As such, it complements OECD work on trends driving the networks of the future. These include a higher level of integration of cloud into networks, edge computing, virtualisation and network automation (OECD, 2022[2]). While the Spotlight concentrates on wireless networks, extending fibre deeper into networks is critical to increase network performance and reliability of all broadband access technologies.

The Spotlight focuses on two important developments likely to shape wireless communications in the next decade. First, "beyond 5G" terrestrial technologies are expected to push performance boundaries in wireless communications. Second, non-terrestrial networks (NTNs),[1] including low Earth orbit (LEO) satellite constellations and different types of aerial platforms, will also shape the future of wireless communications.

The integration of wireless terrestrial networks (TNs)[2] and NTNs raises new challenges, both from technical and policy perspectives. Emerging research explores how to integrate these network types (i.e. hybrid connectivity topologies). In the future, hybrid satellite and terrestrial wireless networks could, for example, provide connectivity solutions for customers using IoT, maritime and aviation applications (OECD, 2022[2]).

Terrestrial connectivity: Beyond 5G technologies

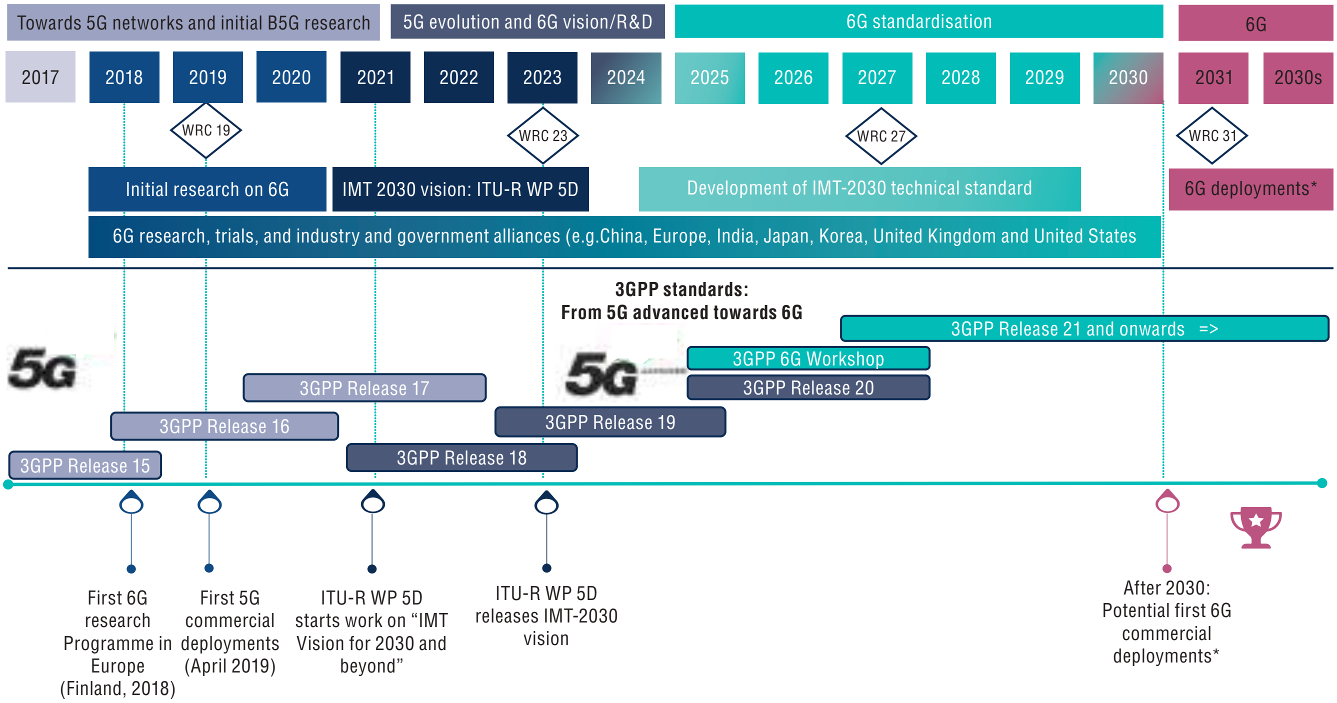
"Beyond 5G" – sometimes called "6G" – technologies have not yet been defined. Several countries, research institutes and the communication sector (including operators and equipment manufacturers) are conducting research and development on beyond 5G technologies with an expected commercial launch at the end of this decade (OECD, 2022[2]). Research is taking place in such countries as the People's Republic of China (hereafter "China"), Finland, Germany, Japan, Korea, Singapore, the United Kingdom and the United States, as well as in the European Union. In the OECD area, 15 countries have government initiatives and/or industry alliances working towards development of 6G technology.[3] The ITU-R Working Party 5D, for example, started work on the "Vision of IMT beyond 2030" in 2021 (ITU, 2021[3]). It has set a timeline to complete the International Mobile Telecommunications (IMT) 2030 specifications by the end of 2029 (ITU-R, 2022[4]).[4]

Figure 1.S.1 illustrates a potential timeline of 6G development. While 6G research is ongoing, the vision for the next evolution of mobile networks is being conceived in the context of 5G network deployments. As of January 2024, 5G commercial deployments were available in 37 of 38 OECD countries in some form. Most 5G commercial networks are based on non-standalone (NSA)-5G (i.e. relying on a 4G core network and using NSA-5G standards in the radio interface known as New Radio).[5] However, standalone (SA)-5G deployments are on the rise.

Many of the promised transformational aspects of 5G are likely to commence with SA-5G networks that use both the 3rd Generation Partnership Project (3GPP)[6] core network architecture standards for 5G (i.e. 5G Core), as well as the 5G radio interface (i.e. New Radio) (OECD, 2022[2]). As such, the 5G standard will continue to evolve. The 3GPP has already announced "5G advanced" for upcoming releases of the standard (3GPP Releases 18 to 20 for "5G Advanced") that will lead to 6G.

The vision of IMT beyond 2030, expected from the ITU-R Working Party 5D by the end of 2023, sets the main specifications for beyond 5G technologies. This will allow standard-setting bodies to work on mapping these identified key values and specifications into technical standards. The standardisation process of 6G will likely commence after 2025, with the first commercial deployments occurring perhaps after 2030. With regards to spectrum allocation, preparatory work to identify possible additional spectrum for 6G ("IMT 2030 Framework") is ongoing (ITU-R, 2023[5]). This was discussed during the ITU World Radiocommunication Conference 2023 (WRC-23) with a view to potentially incorporating it as an agenda Item for WRC-27. During the WRC-23 in November 2023, discussions centred on what the appropriate frequencies might be, and whether the IMT badge would be required (Figure 1.S.1). The WRC-23 concluded with an agreement to analyse the 7 to 8.5 GHz band for 6G services for the next WRC conference taking place in 2027 (LightReading, 2023[6]).

Figure 1.S.1. The road to 6G: Potential timeline



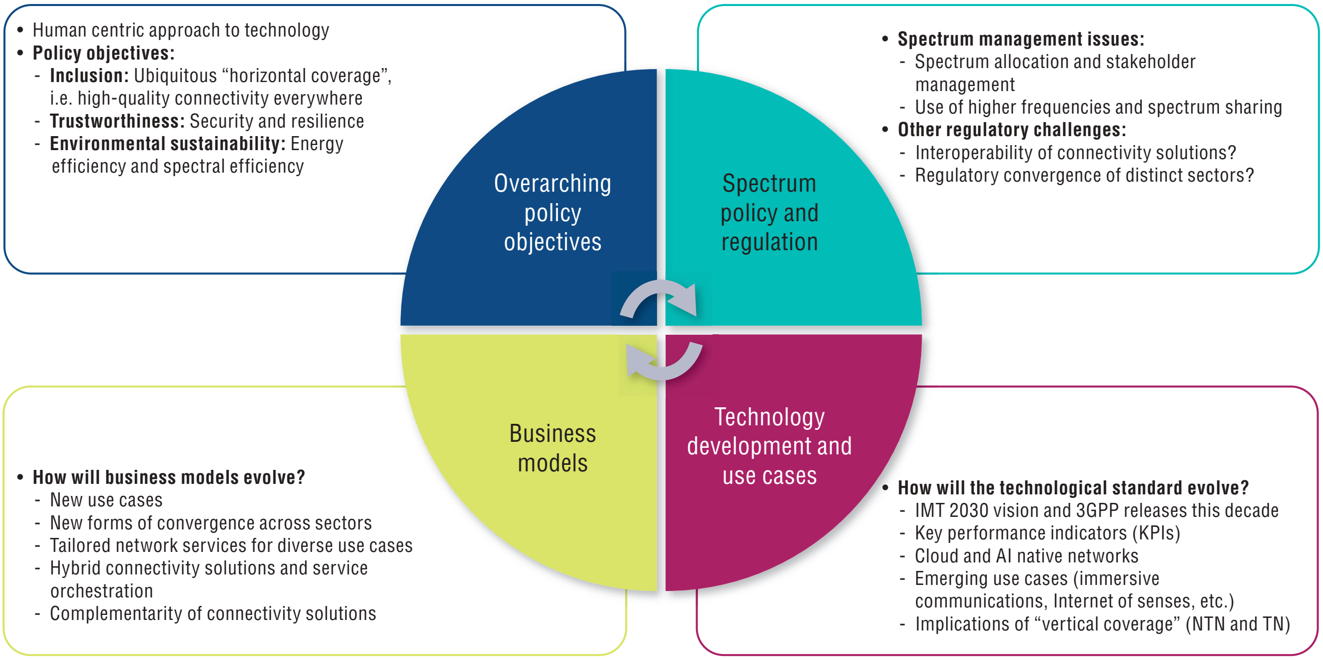
Notes: B5G = Beyond 5G.
*Descriptive and tentative timeline for illustrative purposes. Development and commercial launch of 6G depends on multiple factors, including when different countries start to deploy.

Source: OECD elaboration based on desk research from several sources: presentations from different stakeholders at the June 2022 ITU-R Workshop "IMT for 2030 and Beyond" (ITU-R, 2022[7]) [e.g. Wireless World Research Forum, Samsung Research, HAPS Alliance, European 6G Flagship Hexa X, NextG Alliance (United States); Beyond 5G Promotion Consortium (Japan), one6G Association (Greece); "6G: Building Metaverse ready Mobile Networks" and "Use cases" (several universities), Finish Transport and Communications Agency; Telecommunications Standards Development Society in India]; Ahokangas, Matinmikko-Blue and Yrjölä (2023[8]), "Envisioning a Future-Proof Global 6G from Business, Regulation, and Technology Perspectives"; Qualcomm (2022[9]), "Vision, market drivers, and research directions on the path to 6G", *www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/Qualcomm-Whitepaper-Vision-market-drivers-and-research-directions-on-the-path-to-6G.pdf*; Ericsson (2022[10]), "6G: Connecting a cyber-physical world", *www.ericsson.com/4927de/assets/local/reports-papers/white-papers/6g--connecting-a-cyber-physical-world.pdf*; and 3GPP (2023[11]), "Releases", *www.3gpp.org/specifications-technologies/releases*.

While 6G discussions are nascent, they will combine evolutionary and revolutionary aspects. On the one hand, they will build on 5G wireless networks. On the other, they will rely on wireless applications combining communication and sensing, and increased use of higher frequency bands, such as terahertz spectrum (OECD, 2022[2]). Researchers assume the integration of sensing information and time synchronisation may enable new applications for interactive and multiparty connectivity, within and between virtual and physical worlds (ITU-R, 2022[7]).

Like previous generations of mobile networks, several interrelated factors will likely shape the future of mobile wireless networks and their impact on the evolving connectivity ecosystem. This evolution will likely include integration of various wireless connectivity solutions beyond mobile connectivity (e.g. Wireless Local Area Networks [WLANs], such as Wi-Fi, and NTNs) together with terrestrial connectivity solutions, such as submarine cables, and an increased focus on indoor connectivity. As networks become more sophisticated, the move towards a "network of networks" (also referred to as "multi- layered networks") will raise new challenges. Factors shaping future mobile networks include i) the overarching policy objectives or key values being considered for the next generation of mobile networks; ii) spectrum management and other regulatory challenges; iii) the evolution of the technological standard itself based on research, trials and emerging use cases; and iv) implementation of use cases through evolving business models (Figure 1.S.2).

Figure 1.S.2. Interrelated factors that will likely shape 6G during the next decade



Notes: NTN = Non-terrestrial network; TN = Terrestrial network. Definitions: *Resilience* of communication networks refers to the ability of a network to cope with shocks, while maintaining an acceptable level of service. It can be strengthened by ensuring network diversity and redundancy when planning and rolling out infrastructure. A *digital security incident* is an intentional or unintentional event that can disrupt the availability, integrity and confidentiality of data, information systems and communication networks.

Sources: OECD elaboration based on desk research on the different 6G visions being discussed (as of February 2023). Sources include: presentations from different stakeholders at the ITU-R Workshop "IMT for 2030 and Beyond" (ITU-R, 2022[7]); Ahokangas, Matinmikko-Blue and Yrjölä (2023[8]), "Envisioning a Future-Proof Global 6G from Business, Regulation and Technology Perspectives"; and Policy Tracker (23 January 2023[12]), "Do 5G and 6G change spectrum policy?", *www.policytracker.com/blog/our-new-podcast-spectrum-policy-101*.

Overarching policy objectives. The work towards 6G focuses on the values of sustainability and digital inclusion, as well as increased network security. Environmental sustainability, for example, aims at a higher energy and spectral efficiency than previous mobile network generations. For its part, digital inclusion focuses on bridging connectivity divides through "horizontal" coverage everywhere for everyone. Another fundamental aspect is increased digital security and network resilience, both reflecting the value "trustworthiness". As such, several institutes and researchers involved in recent 6G initiatives underscore that new applications and technologies should follow a human-centric approach (6GSymposium, 2021[13]; OECD, 2022[2]). The values of sustainability, inclusion and trustworthiness, all part of a human-centric approach, have been prominent in the 6G visions of researchers, industry alliances and countries. Nevertheless, how these values will manifest in the standardisation phase through key performance indicators remains to be seen.

In this regard, Digital and Tech Ministers of G7 countries noted their common "Vision for future networks in the Beyond 5G/6G era" in 2023. The statement highlights the importance of high-capacity and ultra-low latency networks to enable critical applications, the role of "multi-layered networks" that marry TN and NTN solutions to ensure universal "digital connectivity", the need to minimise the environmental impacts of networks, and the importance of spectrum efficiency, modularity, and interoperability to reach policy objectives (G7, 2023[14]).

Spectrum management and regulatory issues. A range of factors will influence the management and regulation of spectrum. These include research into 6G, the continued relevance of low- and mid-band spectrum, and the higher profile of policies to improve wireless networks, allocate spectrum, manage stakeholders and ensure interoperability. Some use cases being researched for 6G include higher spectrum bands, such as millimetre wave (above 24 GHz) and Terahertz spectrum (above 100 GHz).[7] For example, in December 2022, the European Telecommunications Standards Institute launched an industry specification group on Terahertz communications as a potential candidate for 6G. It focuses on data-intensive applications such as VR and AR, as well as applications merging sensing and communication functionalities, such as holographic telepresence (ETSI, 2022[15]). Low- and mid-band spectrum will likely continue to play a key role (GSMA, 6 February 2023[16]).

Overall, spectrum policies that fundamentally affect the improvement of wireless networks will become more relevant. For example, spectrum-sharing models will only increase in importance. The same is true for equipment standards not directly related to the operation of a communication network but affecting spectrum efficiency (e.g. receiver performance).[8] Flexibility in spectrum management, including flexible access spectrum sharing, will be key given the considerable uncertainty in demand, both in terms of new applications and services, as well as the diverse options to deliver next generation wireless communication services (Ofcom, 2023[17]). As new players from outside communication sectors become more prominent in the wireless broadband connectivity ecosystem, spectrum allocation and stakeholder management will become even more critical. Apart from spectrum policy, other regulatory challenges include how to ensure the interoperability of diverse connectivity solutions, and how to deal with the convergence of distinct sectors that may be outside the remit of communication regulators.

Technology development and use cases. Some researchers believe that 6G may foster new use cases providing ubiquitous communication, as well as high accuracy and low-latency joint communication, sensing and positioning systems (Bourdoux et al., 2020[18]; Ofcom, 2021[19]).[9] Two factors may enable ubiquitous coverage and enhanced quality of experience. First, research is exploring use of smart surfaces made of artificial materials ("metamaterials") deployed along streets and buildings to go beyond the traditional physical wireless limits. Second, research is also moving towards hybrid terrestrial-aerial topologies (Ofcom, 2021[19]). Examples of potential applications for 6G technologies include advanced multimedia services such as immersive XR, holograms, digital twins, three-dimensional (3D) calls, haptic communication (i.e. the transmission of touch and motion), fully automated mobility solutions and nano-technology-inspired IoT sensors (Alleven, 2021[20]).

Researchers also point to the need for 6G to be cloud- and AI-native from the start. Such an approach could optimise network management, energy consumption and spectral efficiency, as well as provide enhanced digital security. The use of AI combined with "idle" or "sleep mode", already available for 5G (OECD, 2022[2]), are also being considered for future wireless networks to improve energy efficiency. In the advent of quantum computing, "security by design" will be key for 6G, including features robust to quantum attacks (Fitzek et al., 2022[21]). In addition, given that countries are likely to deploy 6G networks at different stages, fully virtualised and software-defined networks may support cost-effective and backward compatible solutions to achieve inclusion objectives (Wireless World Research Forum, 2022[22]). Applications are also emerging in the automotive sector (fully automotive vehicles), health care (AI-tailored wireless hospitals) and industry (VR, AI, edge computing and robotics) (6G Flagship, 2023[23]). The use of increasingly higher frequency bands to achieve more throughput coupled increased coverage requirements may impact energy consumption of networks. In this sense, 6G research is focusing on reconciling the trade-off between communication and sensing requirements of 6G applications and energy efficiency (Fitzek et al., 2022[21]). Moreover, ongoing research on 6G has also focused on expanding "vertical coverage" with the integration of cellular TNs with NTNs. This could include satellites in LEO, medium Earth orbit (MEO), geostationary orbit (GEO), air-to-ground (A2G) networks and other aerial platforms possibly resembling high-altitude platform stations (HAPS).

Business models. Multiple issues affect the emergence of business models for 5G and 6G, including the iterative rollout of 5G and its widespread impact across economies, and the kinds of partnerships needed to fully exploit the potential of 6G. Given that standalone 5G is yet to become a reality in most countries, some stakeholders are considering first how 5G will affect digital transformation prior to 6G networks becoming widely accessible. Namely, SA-5G use cases may shed light on future applications and business models for 6G where connectivity may become "network-as-a-service" for tailored use cases. With SA-5G deployments, the promise of the revolutionary aspects of 5G would spread across all economic sectors. Thus, it may help to consider some challenges associated with this deployment when identifying the type of partnerships required to reap the societal benefits of 6G. New forms of collaboration will likely develop across different sectors with the advent of hybrid connectivity solutions and multi-layered networks. Questions of whether different connectivity solutions are complements or substitutes will likely shape business models. Moreover, models to monetise projected use cases, which is a contemporaneous concern for 5G, will likely also be a main discussion point for business models in the next generation of wireless networks.

This section has focused on "beyond 5G" mobile technologies, but other wireless connectivity solutions alongside cellular (mobile) and non-terrestrial wireless networks, are important. These can help meet performance requirements of a variety of use cases stemming from the digital transformation. WLANs, such as Wi-Fi, are a particularly important use case. They benefit from unlicensed spectrum to support connectivity, primarily indoors, for residential home fixed networks, as well as local area networks for enterprises. Wi-Fi networks are also instrumental to offload mobile traffic (OECD, 2022[24], 2022[2]). Building upon previous Wi-Fi generations, the Wi-Fi 6[10] technological standard aims to improve performance, especially for large outdoor Wi-Fi deployments (e.g. outdoor hotspots). It also seeks to increase throughput in dense deployments and reduce device power consumption (Oughton et al., 2021[25]). Early discussions of Wi-Fi 7[11] have focused on further increasing performance to support use cases with more stringent service requirements for throughput and latency, e.g. virtual and AR applications (Oughton et al., 2021[25]). The Wi-Fi 7 standard is expected to be published in May 2024 (IEEE, 2022[26]; OECD, 2022[24]).

The development of next generation wireless technologies, such as 6G, provokes an array of questions. Will the world be hyper-connected in 2030? If so, what are the implications? Are there new risks and challenges for networks? What are the key concerns with regards to security, resilience and data capacity? How can policy makers and regulators ensure appropriate levels of spectrum access for the variety of use cases within the context of a constrained resource?

Moreover, many questions surround the need to bridge connectivity divides. The digital divide especially affects vulnerable segments of the population, such as rural and low-income households. By the end of 2022, 34% of the world's population remained "offline" (ITU, 2023[27]). As such, how can policy makers promote investment and effective competition to expand affordable and high-quality broadband connectivity to all, regardless of where people live? In addition, how can countries build an ecosystem together where trustworthy AI and IoT applications that transcend national borders can flourish? Common approaches to regulation and policy across countries are needed, as well as interoperable standards.

Non-terrestrial connectivity: Developments in satellites and other non-terrestrial wireless technologies

Satellites are already providing broadband connectivity to end-users, especially in under- or unserved areas by TNs (e.g. rural and remote areas) and support TNs by offering backhaul services. In addition, other aerial technologies are under development to bridge connectivity divides, and first efforts are taking place to integrate TNs and NTNs.

High-throughput geostationary satellites and non-geostationary orbit satellite constellations

Advances in satellite technology, coupled with improvements in launch capabilities and the reduced cost and size of terminal devices, have lowered barriers to entry and expanded the array of satellite-based connectivity solutions. Different constellations are emerging. Some aim to provide end-user communication services (e.g. Starlink or Kuiper), especially in rural and remote areas. Others (Oneweb, Telesat, O3B, Rivada, Kuiper) look to extend the reach of TNs. Together, they complement the connectivity ecosystem. Moreover, an increasing number of satellites provide IoT solutions in remote areas or aim for the logistics sector, including for aircraft and maritime coverage (e.g. Swarm Technologies, Hiber, Kinéis and Globalstar). All these applications strive at achieving connectivity "everywhere".

In the past, satellites in GEO, synchronised with the Earth's rotation, largely provided satellite connectivity. While GEO satellites have a large coverage area, they are typically more expensive to build. They also suffer from higher latency as radio signals must travel back and forth to the geostationary orbit in 36 000 km altitude. Newer approaches propose satellites in LEO or MEO, also known as non-geostationary orbit (NGSO) satellites. These are cheaper to build and launch, depending on their size and complexity (OECD, 2017[28]). However, their lower orbits require many more satellites to provide uninterrupted services due to smaller coverage areas globally. As a result, this drives overall costs to generally exceed those of a geostationary satellite fleet.

Several companies plan or have already launched LEO constellations to offer satellite connectivity, including Starlink, OneWeb, Boeing, Telesat and Amazon's Project Kuiper. Starlink and OneWeb launched their first satellites in 2019. While Starlink and OneWeb have completed their first-generation constellations and are already looking to "Gen2", Project

Kuiper plans to launch its first commercial services in mid-2025. Kuiper successfully launched its first two prototype satellites in October 2023 (Amazon, 2023[29]), and will begin to offer beta services to customers in 2024. As of January 2024, Starlink had 5 374 satellites in orbit and OneWeb 634 satellites in orbit (McDowell, 2024[30]). In December 2022, SpaceX's Starlink launched 54 second generation satellites to new orbits, adding capacity to its network using the 27-30 GHz bands. SpaceX noted those will allow them to "add more customers and provide faster service, particularly in areas that are oversubscribed" (Howell, 2022[31]).

The new generation of satellites for both GEO and NGSO constellations, known as high-throughput satellites (HTS), offer a host of emerging possibilities. HTS satellites typically use the 10.7-12.7 GHz, 13.75-14.5 GHz, 17.8-18.6 GHz, 18.8- 20.2 GHz, 27.5-30 GHz, 37.5-42 GHz, 47.2-50.2 GHz and 50.4-52.4 GHz bands, with wide beams, spot beams, steerable beams and frequency-reuse technology. This could enable satellites to increase performance and capacity per satellite and focus additional capacity in areas where it is most needed.[12] Consequently, smaller remote terminals can be used. Increased power and bandwidth provide faster speeds, lowering equipment cost in the case of geostationary satellites (OECD, 2022[24]). In addition, inter-satellite links are advancing to allow for quicker transmission between satellites. This is particularly useful for constellations as data/content can be routed to the right part of the world (IETF, 2022[32]). For example, inter-satellite links can be used to transfer data more rapidly from Earth observation satellites via communication satellites to the ground. In this way, communications and sensing networks merge in space, as well as on the ground.[13]

New advances point to using connectivity from satellites for mobile terminals through messaging services facilitated by including satellites in the 3GPP standard Release 15 and onwards.[14] Some mobile communication operators are striking partnerships with satellite providers to expand coverage of their networks. For example, T-Mobile in the United States partnered with Starlink (SpaceX) to provide text service to its clients in all US areas, including national parks and other remote regions (T-Mobile, 2022[33]). There is also increasing momentum from the device ecosystem. Several smartphone equipment manufacturers (e.g. Apple or Samsung), chipset providers (MediaTek, Qualcomm) and mobile operators have announced developments to link mobile phones to satellites for emergency communications (Apple, 2023[34]; Browne, 2023[35]; McGregor, 2023[36]; Qualcomm, 2023[37]).

In the United States, the Federal Communications Commission (FCC) created a "space bureau" to support the burgeoning satellite industry. This decision responded to increased applications for satellites that featured new commercial models, players and technologies. The FCC has also adopted rules to shorten the deorbiting period for LEO satellites from 25 to 5 years. In December 2022, it issued a Notice of Proposed Rulemaking to streamline its review processes for satellite applications (FCC, 2022[38]). Furthermore, in March 2023, the FCC proposed a new framework (Notice of Proposed Rulemaking) to facilitate innovative collaborations between satellite operators and mobile providers. It will allow space-based services to connect directly to smartphone users in remote, unserved and underserved areas. The FCC proposed to allow authorised NGSO operators to apply to access terrestrial spectrum under certain conditions (FCC, 2023[39]). Companies like AST Spacemobile and Lynk have been testing their satellite-to-phone services in the United States through experimental licences (Clark, 2023[40]).

OECD countries, including Canada, Colombia, France, Germany and the United Kingdom, have already authorised NGSO constellations to leverage satellites' potential to help meet domestic connectivity goals, given how satellites can reach remote areas that are under- or unserved by TNs (OECD, 2022[24]). For example, in Colombia in February 2022, the Ministry of Information and Communication Technologies issued a new regulatory regime for satellite services to encourage development of satellite connectivity in the country, especially for hard-to-reach areas (MinTIC, 2022[41]).

The European Commission recently announced plans for an "EU space-based secure connectivity system" leveraging satellite connectivity (European Commission, 2022[42]). In November 2022, the EU Parliament and EU Council announced a provisional agreement for a satellite constellation, IRIS, which will include GEO, MEO and LEO satellites (Evroux, 2023[43]). This will support EU priorities for connectivity – for government, residential and enterprise users – to support the economy, environment, security and defence (European Commission, 2022[44]).

Developments in satellites raise both technical and regulatory challenges, especially for spectrum policy.[15] Regulating satellites' use of spectrum to manage radio interference takes place on two axes. The International Telecommunication Union (ITU) co-ordinates the international level, while regulatory authorities manage the national level (OECD, 2022[24]). The ITU maintains the Master International Frequency Register to record the use of spectrum in space (ITU, 2022[45]). Meanwhile, national communication regulators, including spectrum managers, oversee filings for proposed satellite systems. They submit requested frequencies to the ITU but authorise Earth stations (OECD, 2022[24]). Regulators also consider dangers from space debris when studying the feasibility of proposed satellites (OECD, 2022[24]).[16]

High-altitude platform stations

High-altitude platform stations (HAPS) are flying base stations or network nodes that operate in the stratosphere 20 km above the ground (ITU-R, 2020[46]).[17] They show promise to bridge connectivity divides in rural and remote areas (OECD, 2021[47]). Their cell radius can be up to 100 km, compared to 8 km in rural areas for IMT 2020,[18] creating a cell area equivalent to the city of Paris (1 000 km^2) (ITU-R, 2022[48]).[19] HAPS have recently become more viable due to technological advances in energy efficiency, among other factors (ITU, 2022[49]).[20] Namely, developments in HAPS technologies may enable high-altitude IMT base stations (HIBSs) – or “HAPS as IMT base stations” as labelled by the ITU-R. This brings them a step closer to connecting the unconnected (RSPG, 2021[50]).

In addition to improving coverage and capacity on the ground, HAPS – like satellites – can help provide connectivity to lower-level aircrafts and drones. This can enable connectivity corridors outside of TN coverage (e.g. over the sea). When used with TNs, such corridors can improve reliability and resilience.

Given that HAPS are flying objects, they are subject to both aviation and spectrum regulations. They can be lighter than air, like balloons, or heavier-than-air, like motorised gliders. As the wind speed is less intense in the stratosphere than in lower altitudes, HAPS can maintain their position in the higher airspace while consuming less energy. As another advantage, they have a large coverage area for mobile connectivity (Araripe d’Oliveira, Cristovão Lourenço de Melo and Campos Devezas, 2016[51]).

During the past decade, several attempts have been made to commercialise HAPS solutions to bridge connectivity divides. Google’s Loon project, for example, was withdrawn in 2021 (Reynolds, 2018[52]; Singh, 2021[53]). SoftBank, through its subsidiary HAPS Mobile, has worked in developing various parts of the HAPS ecosystem (HAPS Mobile, 2023[54]). As one possible explanation for limited use of aerial platforms to date, integration of HAPS/HIBS into mobile networks can create potential interference. It also requires that frequency bands allocated for mobile communications do not restrict use of aeronautical mobile services[21] (ITU-R, 2022[48]).

The economic viability of aerial platforms also depends on spectrum availability for these services (OECD, 2022[24]). Policy makers expected to study possible new identifications for using HIBSs as part of IMT networks during WRC-23 (ITU, 2022[49]). HAPS/HIBSs may be deployed more widely as they could provide cost-effective connectivity for consumers in rural areas with limited or no access to communication services.

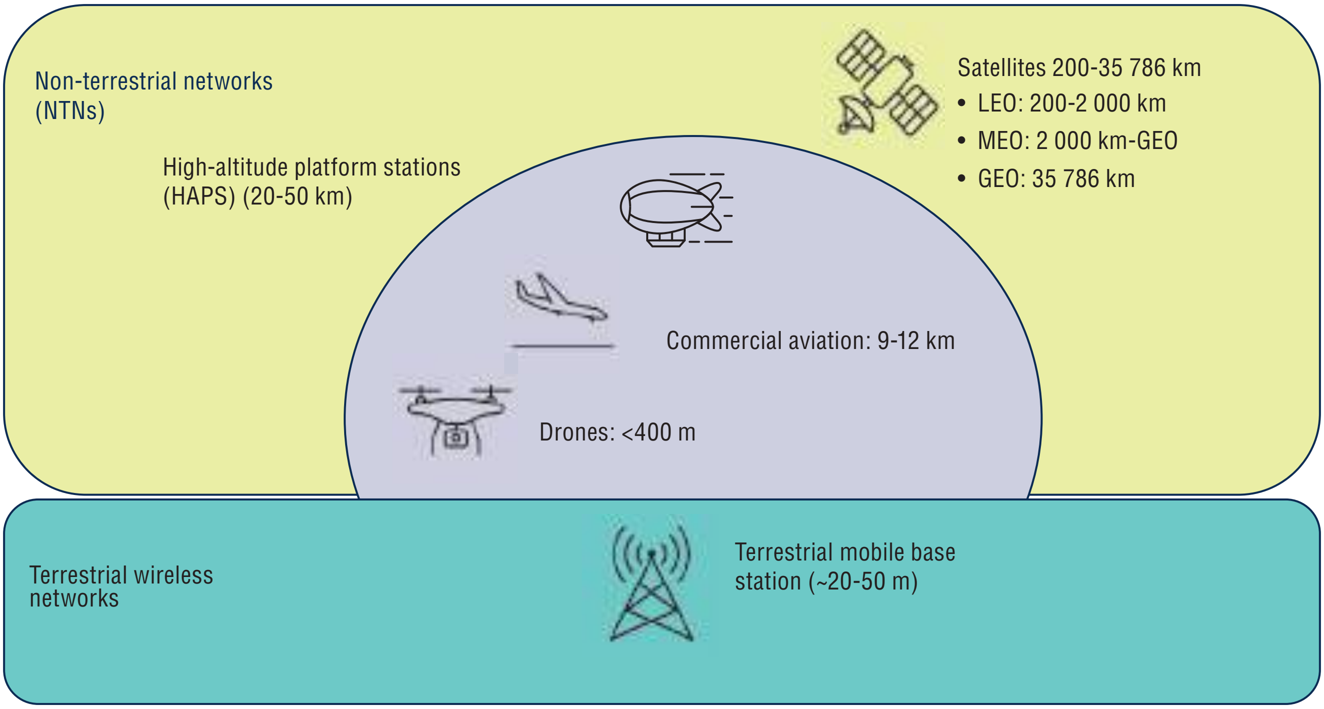
Hybrid topologies for connectivity: Towards the integration of terrestrial and non-terrestrial network technologies

Integrating different terrestrial and non-terrestrial wireless technologies is a next step in expanding the connectivity ecosystem. Some broadband providers have begun exploring how satellite connectivity and other aerial communication technologies might complement TNs to provide seamless communication with extended coverage. They might do this, for example, through backhaul solutions (Fletcher, 2021[55]) or through hybrid satellite and ground networks for IoT applications (Erwin, 2021[56]). Deutsche Telekom claims to have achieved the world’s first seamless 5G connection through different network layers to the stratosphere, space (Intelsat satellite network) and back to the mobile network (HT Group, 2023[57]).[22]

The communication industry also aims to integrate TNs and NTNs within the scope of 6G projects (Figure 1.S.3).[23] This would support global, ubiquitous and continuous connectivity both on the ground and for aerial users. To that end, it would integrate mobile terrestrial connectivity solutions with MEO, GEO, air-to-ground (A2G) networks, HAPS and other aerial platforms. Integrated networks in 3D with a multi-layered architecture would combine the advantages of TNs and NTNs (aerial platforms as well as satellite networks). In this way, they would provide improved reliable, secure and robust connectivity for aerial and ground users through flexible and adaptive network architectures with multiple technologies (Ozger et al., 2023[58]). However, this integration is not without challenges. These technologies differ greatly, do not provide the same performance features and are not all operated by the same company.

The multi-layered architecture requires an interplay between the aviation, the terrestrial mobile communication sector and space industries. This calls for collaboration between different sectors that over the years have been competing for spectrum. The aviation community, for example, is facing several challenges as its legacy communication systems have a low rate of technology development. It may also have difficulty operating in parts of the spectrum allocated for aeronautical services. At the same time, the aviation industry is advancing in its digitalisation, requiring higher efficiency in the use of airspace with connected aircrafts and the emergence of a wide variety of flying objects. Unmanned vehicles and electric vertical take-off and landing aircrafts such as “flying taxis” could contribute to a more social and healthier environment in cities (Box 1.S.1) (EASA, 2022[59]). In November 2022, for example, France opened a hub for testing electric air taxis (Bloomberg, 2022[60]).

Figure 1.S.3. Towards vertical coverage: Convergence of terrestrial and non-terrestrial networks



Note: LEO = Low Earth orbit; MEO = Medium Earth orbit; GEO = Geostationary orbit.

Source: Authors' elaboration based on several sources, including: Ofcom (2021[19]), "Technology Futures – spotlight on the technologies shaping communications for the future", European Space Agency (2020[61]), "Types of orbits"; GSMA (2021[62]), "High Altitude Platform Systems: Towers in the skies".

Box 1.S.1. Flying taxis with electric vertical take-off and landing aircrafts for future transportation

Research continues into the integration of terrestrial and non-terrestrial networks that would marry airborne transport systems with urban air mobility together with flying vehicles. Several manufacturers plan to launch commercial operations of electric vertical take-off and landing (eVTOLs) aircrafts, or "flying taxis", around 2025-26. For example, companies working on developing eVTOLS include Airbus SE in France, Archer Aviation and Joby Aviation in the United States, Lilium and Volocopter in Germany and Vertical Aerospace in the United Kingdom (NASA, 2020[63]).The 2024 Paris Olympic Games aims to be the first to provide transportation with eVTOLs (Alcock, 2022[64]). The eVTOLs will be managed by a pilot on board and could eventually become autonomous.

The eVTOLS will take off and land at so-called vertiports.* With the growing number of unmanned aerial vehicles in the lower airspace, airspace management is critical. This is done through unmanned aircraft system traffic management (UTM) (FAA, 2023[65]). The UTM complements the Air Traffic Management (ATM) system, which manage aircrafts in the airspace.** The eVTOLs will have advanced flight decks with a communication system that combines legacy aviation systems with satellite and mobile communication networks. As such, different frequency bands allocated to mobile networks, satellite and aviation will be needed.

A fundamental shift in airspace regulation is under way in response to these developments. Moreover, security concerns of flying objects over cities need to be addressed to guarantee safe and reliable air traffic. The aviation sector foresees largely using commercial mobile networks to handle growing demand for data transmission from aircrafts. They would rely on legacy aviation systems as fall-back solutions (EASA, 2022[59]).

Notes:

* The European Union Aviation Safety Agency (EASA) defines a vertiport as "an area of land, water or structure used or intended to be used for the landing and take-off of eVTOL aircraft" (EASA, 2022[59]).

** According to EASA, "an ATM aggregation of the airborne and ground-based functions (air traffic services, airspace management and air traffic flow management) is required to ensure the safe and efficient movement of aircraft during all phases of operations" (EASA, 2022[59]).

Connectivity provided by terrestrial mobile communication operators can be an interesting solution for the aviation sector. At the very least, it could support communication services that are not mission critical and as such could be offloaded from their legacy systems. This would be more cost effective than developing propriety systems for the aviation sector (EASA, 2022[59]).

One example of ongoing research in this field is the European Union-financed Single European Sky Air Traffic Management Research (SESAR) 3 Joint Undertaking. SESAR 3 aims to modernise Europe's air and ground Air Traffic Management (ATM) infrastructure and operational procedures. In so doing, it would contribute to smarter, more sustainable, better connected and more accessible air transport systems (SESAR 3, 2022[66]). Under that scenario, multi-layer broadband connectivity (e.g. future 6G networks) would need some form of integration with digitalised aviation systems. The expansion of communication services in airborne networks, along with future air urban mobility, drones and other unmanned air vehicles, will drive demand for a wide range of broadband communication services. The goal is to allow for limitless communication in and between terrestrial, airborne and satellite networks (Celtic-Next, 2022[67]).

The satellite industry is seeking to develop new business models and connectivity solutions. Although the inclusion of satellite in the 3GPP standard has led to more interaction between terrestrial mobile operators and satellite companies, more opportunities and partnerships may arise in the future. Examples of recent partnerships include Starlink with operators KDDI and Salt (KDDI, 2022[68]; Swinhoe, 2023[69]), and OneWeb with the operator VEON (OneWeb, 2023[70]). Kuiper has also announced agreements with Verizon and Vodafone to extend the reach of their mobile networks (Vodafone, 2023[71]; Verizon, 2021[72]).

The development of user terminals that follow standardised radio interfaces, offering seamless connection on both terrestrial and satellite networks, is paving the way for a more integrated ecosystem between TNs and NTNs. Countries and industry players would do well to follow the process for evaluating IMT Terrestrial and Satellite Radio Interfaces led by the ITU-R Working Parties 5D and 4B (ITU-R, 2022[73]).

The foundation for hybrid topology wireless networks that integrate terrestrial and non-terrestrial networks rests on a combination of three elements: an aviation sector facing increased data demand, a satellite sector looking for new use cases and a terrestrial wireless communication sector wrestling with exponential growth in mobile traffic. Moreover, the combination of different connectivity solutions, relying on different technologies, industry structures, and customer interfaces, impacts market dynamics. This raises both technical and regulatory challenges related to regulatory collaboration, spectrum management, digital security and digital divides, among others.

Collaboration. Policy makers could facilitate a constructive regulatory collaboration between three distinct sectors: space, aviation and mobile communications. Responsibilities are currently divided between different sector authorities.

Spectrum policy. The emergence of hybrid topology networks extending across national borders and stretching from the ground through aerospace may call for more dynamic and flexible access to spectrum and improved spectrum sharing to provide benefits to all users.

Digital security. Apart from physical security and safety issues for traditional aircrafts and other flying objects, digital security is of great concern for the next generation of wireless networks. This could also involve satellite communication and data processing in cloud solutions in the airspace.

Digital divides. Coupled with the promising technology advances shaping the connectivity ecosystem this next decade, policy makers need to continue bridging connectivity divides through the expansion of high-quality broadband infrastructure and services at competitive prices.

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Notes

1. According to 3GPP, NTN refers to networks, or segments of networks, using an airborne or spaceborne vehicle for transmission (Chuberre and Michel, 2018[75]).
2. The ITU Radio Regulations defines terrestrial radiocommunication as any radiocommunication other than space radio communication or radio astronomy. See ITU Radio Regulations, article 1, section 1 "General terms", Sub-section 1.7 (ITU-R, 2020[46]).
3. Based on the CISP Regulatory questionnaire for the DEO and upcoming reports 2023-24, where 37 of 38 OECD countries replied.
4. With previous mobile generations, such as 4G and 5G, 8-12 years elapsed between setting the "technology" vision and agreeing upon the technological standard and the first commercial deployments. For example, for 5G, the ITU-R Working Party 5D defined the vision for IMT-2020 (5G) in 2012, and the first commercial deployments started in April 2019, with many networks launching during 2020.
5. Non-Standalone (NSA) 5G means that much of the network will rely on presently deployed 4G technology, but that devices can use the "5G New Radio" standard in the Radio Access Network (RAN). Two important milestones of the 5G standardisation process by 3GPP include the "non-standalone 5G" (NSA-5G) specifications, completed in December 2017, and the "standalone 5G" (SA-5G) specifications completed in June 2018. These two milestones are part of 3GPP's Release 15 of the "5G standard" and marked the first phase of the 5G standardisation process complying with the ITU IMT-2020 requirements. Therefore, the difference between NSA-5G and SA-5G is that the former requires current 4G core network equipment to be deployed, and the latter requires deploying an entire new network (OECD, 2019[78]).
6. The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organisations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC). 3GPP specifications cover cellular telecommunications technologies, including radio access, core network and service capabilities (3GPP, 2023[76]).
7. In addition, equipment and devices capable of operating in the terahertz range will rely on advanced semiconductors potentially increasing the challenges for spectrum monitoring.
8. For more information on the latest developments in spectrum policy in OECD countries, see OECD (2022[24]).

9. Historically, radar or sensing systems were developed independently from mobile communication technologies. There is growing interest in merging these two technologies. Namely, the use of mmWave or terahertz frequencies used in combination with massive MIMO and machine-learning techniques may enable a finer spatial resolution to detect even subtle movements, such as finger gestures. Communication systems using terahertz spectrum may allow for very high throughput and very low latency, providing an opportunity to conceive joint communication, sensing and positioning systems. Thus, it is a promising technology for future 6G systems (Ofcom, 2021[19]).
10. Wi-Fi 6 refers to the networking standard IEEE 802.11ax.
11. Wi-Fi 7 refers to the networking standard IEEE 802.11be.
12. This would enable a move from wide beams to multiple smaller spot beams and concentrate power on a smaller area, increasing link performance, as well as making it possible to reuse spectrum multiple times, increasing the amount of capacity per satellite.
13. The allocation of spectrum for Inter satellite network links in satellite bands around 12, 18 and 28 GHz were part of the ITU's World Radiocommunication Conference 2023 (WRC-23) Agenda Item 1.17. WRC-23 took place on 20 November-15 December 2023.
14. 3GPP Release 17 (frozen in 2022) offers two forms of satellite communications to mobile devices: IoT-NTN, which will provide low data-rate narrow band communications, and NR-NTN, which will provide broadband communications for high data-rate communications, such as video calls (McGregor, 2023[36]).
15. Different stakeholders are engaging on this topic, such as the European Conference on Postal and Telecommunication Administrations (CEPT) (CEPT, 2022[77]).
16. The United Nations Committee on the Peaceful Uses of Outer Space is responsible for space object and space debris. At a national level, agencies or ministries in charge of space regulate space objects.
17. High-altitude platform stations are defined by the ITU's Radio Regulations as radio stations located on an object at an altitude of 20-50 km and at a specified, nominal, fixed point relative to Earth (ITU-R, 2020[46]).
18. IMT-2020 are the requirements of the ITU-R in 2015 for 5G networks, devices and services.
19. The idea of using platforms in the stratosphere to provide communication services goes back to the end of the 1960s with the first experimental projects. R&D on aerial platforms, given different labels over time, have been ongoing ever since (Araripe d'Oliveira, Cristovão Lourenço de Melo and Campos Devezas, 2016[51]).
20. High-altitude platform stations (HAPS) are defined by the ITU's Radio Regulations as radio stations located on an object at an altitude of 20-50 km and at a specified, nominal, fixed point relative to Earth (ITU-R, 2020[46]). The initial definition of HAPS was established at the World Radio Conference (WRC) 1997 and spectrum was allocated in the 47-48 GHz-band (ITU-R, 1997[74]). The ITU later redefined it.
21. A mobile service transmitting signals between aeronautical stations and aircraft stations.
22. The European Space Agency and DT agreed to work on hybrid networks of the future for more resilient and secure connectivity solutions (HT Group, 2023[57]).
23. For example, see: German Federal Ministry of Education and Research (2023[79]).

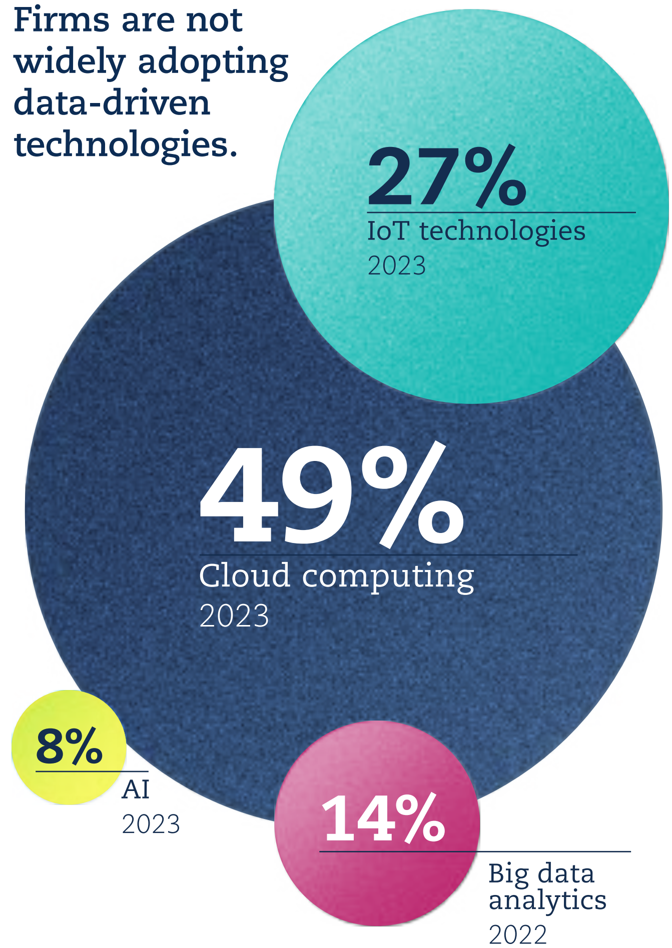
Chapter 3

Digital technology diffusion and data

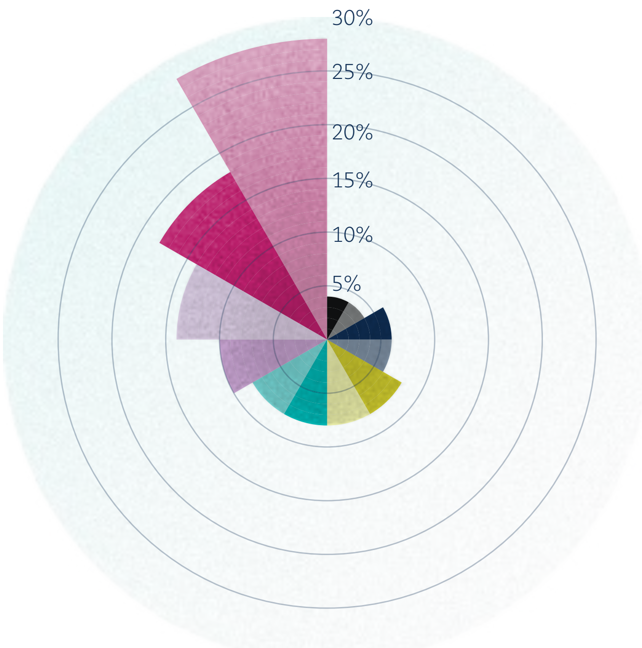
Digital technologies and data have dramatically changed the way people live and work, how and in which markets firms operate, and the ways in which governments interact with citizens. This brings many opportunities, as well as new challenges. As governments and the private sector increasingly shift from offline to online service provision, access and effective use of digital technologies become critical for equal opportunity and inclusion. Technologies such as cloud computing and Internet of Things (IoT) have diffused rapidly in recent years. However, productivity growth remains slow, including in digital-intensive sectors. Adoption of data-dependent technologies also remains low. This chapter considers both issues in turn before highlighting policy actions to make digital technologies and data more inclusive and productive.

Technology is spreading fast, but gaps remain

Firms are not widely adopting data-driven technologies.



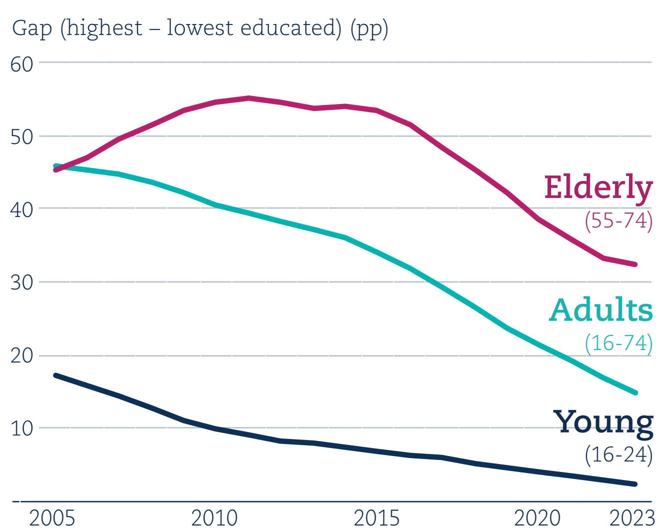
28% of ICT firms used AI in 2023 in the OECD, higher than any other sector.



- 4% Construction
- 4% Accommodation and food services
- 6% Retail trade
- 6% Transportation and storage
- 8% Administration and support
- 8% Manufacturing
- 8% Electricity, gas, water and waste mgt.
- 8% Wholesale trade
- 10% Real estate
- 15% Professional and technical activities
- 18% Finance and insurance
- 28% Information and communications tech.

Highly educated adults are 15 percentage points (pp) more likely to use the Internet.

Gap in Internet usage between high and low levels of education, by age group



Key findings

Access to online services and the ability to use them effectively are critical for equal opportunity and inclusion

- Divides in Internet use are pronounced by age, education and income. Younger and more educated Internet users engage in a wider range of online activities.
- Those with the requisite skills are typically in a better position to use digital technologies to their advantage, something highlighted during the COVID-19 pandemic.
- Uptake of specific online services increased during the COVID-19 pandemic, chiefly among those already on line, raising the expectation that this trend may continue. Moreover, two or three days of teleworking per week are now common among those with jobs that allow for it.
- Not all effects of the pandemic may be long lasting, as the share of retail e-commerce is converging to pre-pandemic trends.

Data-dependent technologies are diffusing at a slow pace

- While the adoption of cloud computing and IoT technologies is strong across the OECD, adoption of big data analytics and artificial intelligence (AI) remains low.
- AI adoption is concentrated in the information and communication technology (ICT) sector, where an average of 28% of ICT firms used AI in 2023 in the OECD, higher than any other sector.
- Firm size is a more important predictor of adoption for data-dependent technologies than for cloud computing and IoT technologies.
- While the number of IoT devices has been growing rapidly, it has slowed in the wake of the semiconductor shortage.

Policies should aim to boost equitable uptake of online services, technology diffusion and the potential of data

- To boost equitable uptake of online services, governments should lead by example, providing user-centric, inclusive online services. They should invest in people's skills, while supporting those most at risk of being left behind.
- Technology diffusion can be accelerated by creating a level playing field among firms for access to key inputs, including data.

How quickly are individuals, consumers and firms adopting digital technologies? Who is benefiting from them and who is at risk of being left behind? This chapter first looks at Internet adoption and use of online services by individuals, highlighting differences across socio-demographic and socio-economic groups and the impact of COVID-19. It then looks at the diffusion of digital technologies across firms – with a focus on data-dependent technologies such as big data analytics and AI – before turning to policy implications.

The ability to use the Internet effectively is key for equal opportunity and inclusion

Digital technologies provide opportunities to improve the lives and well-being of people. Yet there have also been three long-standing concerns, notably about their impact on equal opportunities and inclusion. These concerns are highlighted below.

First, to the extent that digital technologies offer sizeable benefits to those who know how to use them effectively, they might deepen long-standing divides. Online education programmes, for instance, offer the opportunity to access quality educational content at low cost and in a flexible way. However, if skills or formal education are a prerequisite to making effective use of these programmes, they offer fewer benefits to those that are already at a disadvantage (OECD, 2020[1]).

Second, ever more services – from written correspondence to shopping to banking and interactions with the government – are offered on line and ever more people are using them. As a result, the per-interaction cost of providing these services off line increases. Consequently, the physical counterparts of online services and their infrastructure – brick-and-mortar post offices, banks, bookstores and so on – are in decline across much of the OECD.[1] The number of bank branches per 10 000 inhabitants in Germany, for example, decreased from more than 7.0 in 1995 to less than 2.5 by 2021. Over the same period, the number of bookstores in the United States decreased from 5.0 per 100 000 inhabitants to 1.7.

This "dematerialisation of services" threatens to leave the unconnected and those that lack the resources to use online services with less choice and higher transaction costs (Défenseur des Droits, 2022[2]).

Finally, as social interactions and cultural activities are increasingly moving on line, access to digital technologies and the ability to use them effectively are becoming key for social inclusion. There are many dimensions of digital exclusion: politicians addressing the public via social media; families and friends congregating in chat groups; and people unable to take part in real-life conversations about online-only cultural phenomena, to name a few. The more social interactions and cultural phenomena move on line, the more important universal access and use become.

The long-standing trends described above accelerated with the onset of the COVID-19 pandemic. At its height, lockdowns shifted everything from office work to school classes and doctor appointments on line. Those that lacked quality access or the requisite skills to use digital technologies were at a severe disadvantage. Those in occupations more suitable to teleworking – typically occupations that require higher levels of educational attainment – were more likely to continue working (Dey et al., 2021[3]). Further, online retail spending increased more in economies with higher pre-pandemic e-commerce shares, exacerbating the digital divide across countries (Cavallo, Mishra and Spilimbergo, 2022[4]).

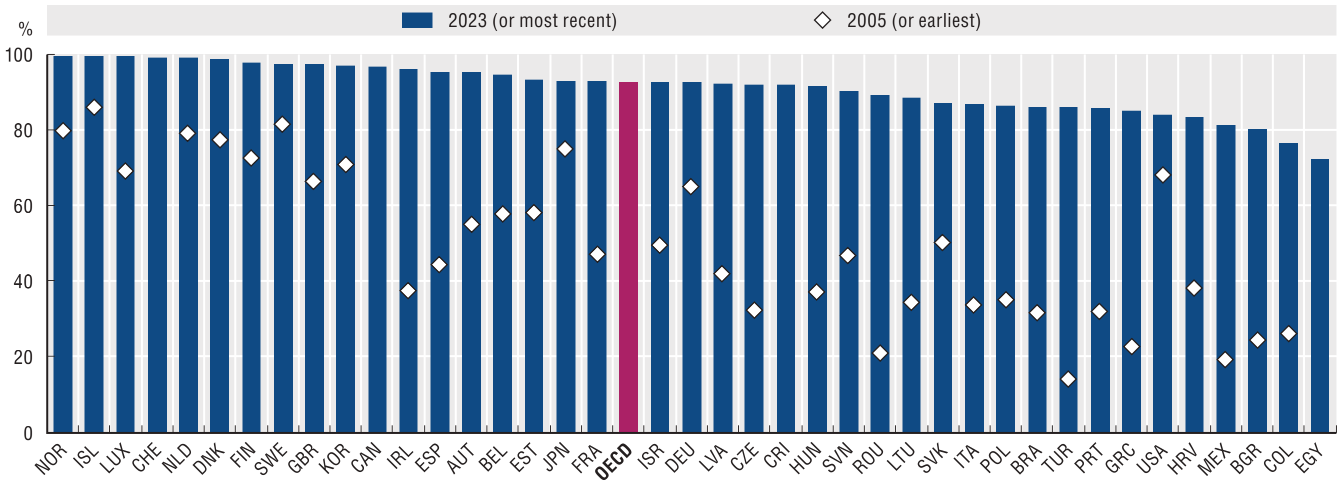
The incidence and frequency of Internet use have increased, but gaps remain

The incidence and frequency of Internet use have increased rapidly across OECD countries. Among adults aged 16-74, more than nine out of ten (93%) – or 945 million people – used the Internet at least once in the past 12 months.[2] More than four in five (87%) – or 888 million people – used the Internet daily or almost every day. By comparison, the rates were only one in two (52%) and one in three (32%) in 2005, respectively.

In ten OECD countries – Denmark, Finland, Iceland, Korea, Luxembourg, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom – more than 97% of the population used the Internet over the last three months (Figure 3.1). By contrast, more than 15% of the adult population had not used the Internet in the past three months in Colombia, Greece, Mexico and the United States. However, countries that had lower usage rates in the past often have seen the largest increases. In Türkiye, for instance, only 7% of the population used the Internet daily in 2005, but 82% did by 2023.

Figure 3.1. Internet adoption has increased

Internet use at least once during the last three months among adults (aged 16-74), 2005 (or earliest) and 2023 (or most recent)



Note: See endnote 3.

Source: Authors' elaboration based on data from OECD (2023[5]).

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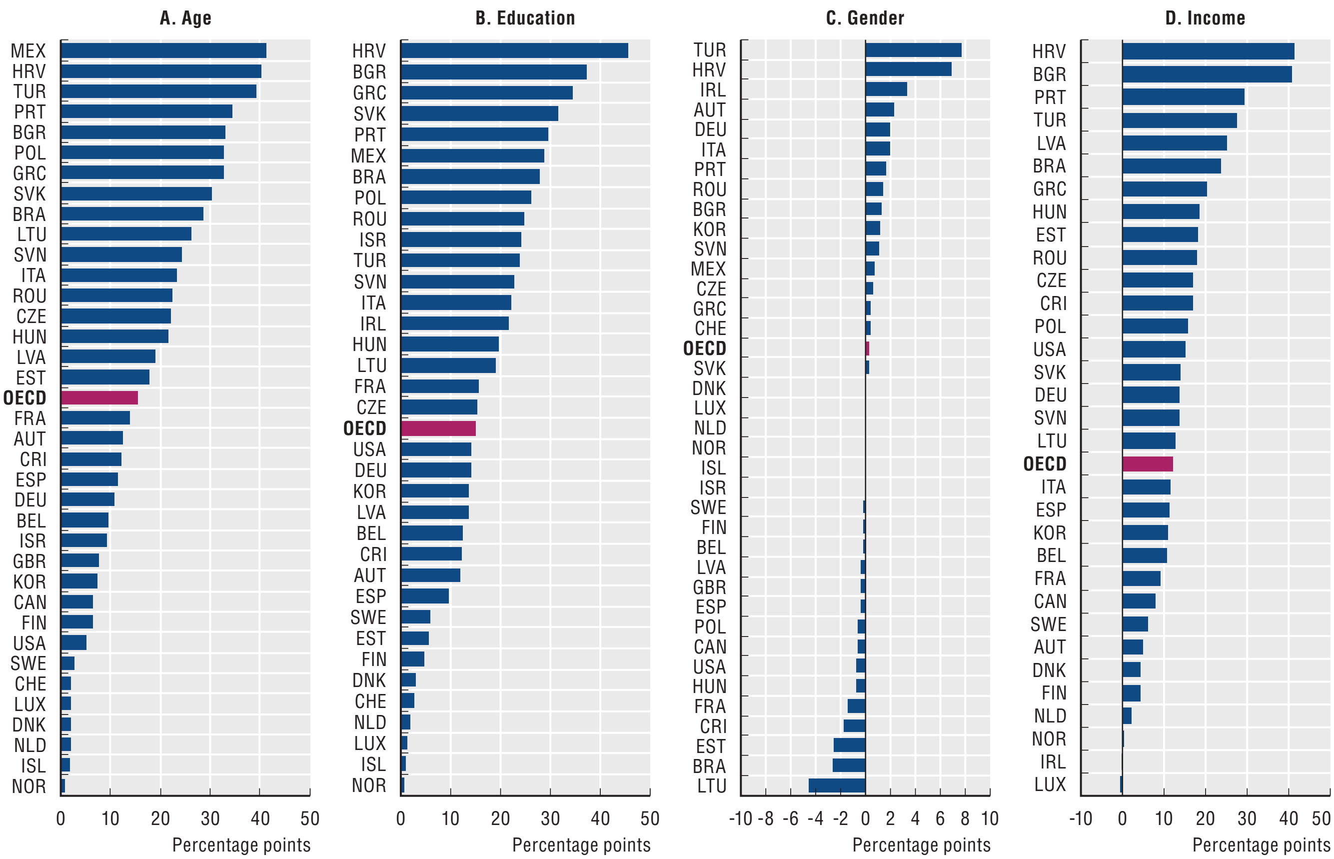
Internet adoption rates have been converging within OECD countries. However, a significant digital divide remains in relation to the rest of the world, where more than 80% of the global population lives. Only half of the population of today's low- and middle-income countries is on line (ITU, 2022[6]). Across the population of the 28 low-income countries, only one in five used the Internet in the last three months.

Figure 3.2 shows gaps in Internet use between different socio-economic and socio-demographic groups, where gaps are defined as the difference in uptake rates by age, education, gender and income quintiles.[4] Divides in Internet use are pronounced between age groups and between individuals with different levels of educational attainment. On average, the young (ages 16-24) are 15 percentage points more likely to have used the Internet than the elderly (ages 55-74). Meanwhile, those with high levels of educational attainment are 15 percentage points more likely to use the Internet than those with low levels. Differences by gender are less pronounced. In fact, women are more likely to use the Internet in just over one-third of the countries for which data are available. Finally, the difference between those in the fifth quintile of the household income distribution and those in the first quintile is 12 percentage points on average.

Figure 3.2. Divides in Internet use are pronounced by age, education and income

Differences in the share of adults using the Internet at least once over the last three months, 2023 (or most recent)



Note: See endnotes 4 and 5.

Source: Authors' elaboration based on data from OECD (2023[5]).

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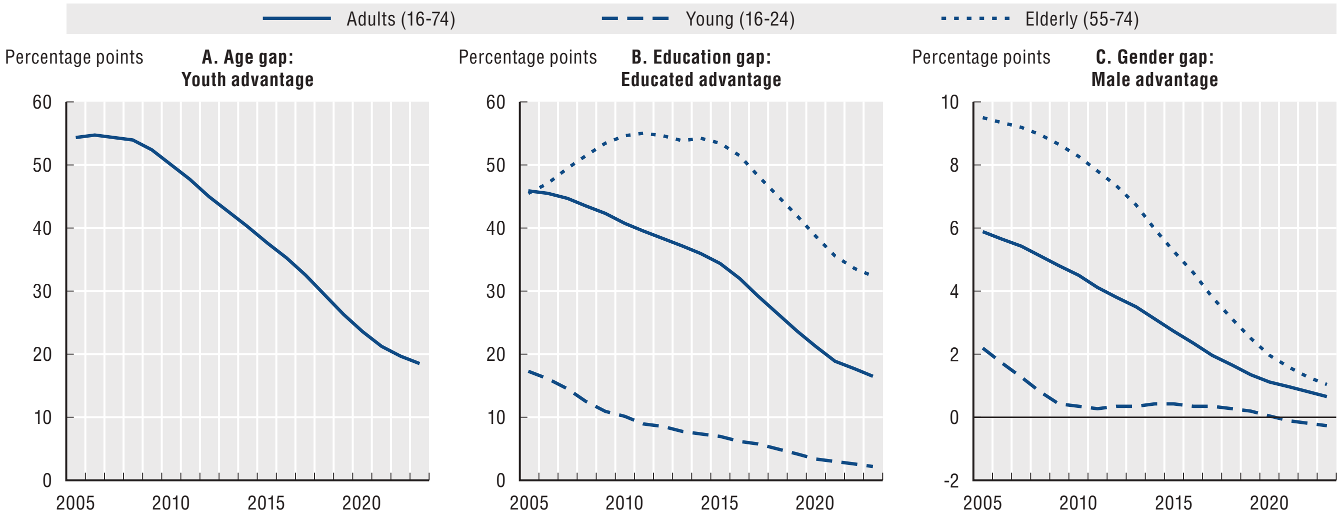
These findings are also in line with other evidence. A 2021 survey found that only 7% of adults in the United States are non-adopters, but that the share rises to 25% for adults aged 65 and older (Perrin and Atske, 2021[7]). Educational attainment and household income were also found to be linked to the likelihood of being on line. On the other hand, there were no statistically significant differences in Internet use by gender, race and ethnicity, or community type.

Figure 3.3 depicts the evolution of average gaps in Internet use (at least once in the last three months) across all OECD countries for which data are available. The average age gap and the average education gap have narrowed at a rate of about 3 percentage points per year since 2010. The average gender gap in Internet use, already much narrower than in the past, is also closing, albeit at a slower pace. The second and third panels of Figure 3.3 plot trends in the average gender and education gaps by age group. A gender gap favouring men is still discernible among the elderly whereas on average there has been no significant gender gap among the young since about 2010. Similarly, education gaps among the young are approaching zero on average, although progress has slowed in recent years. After peaking at around 55 percentage points during the first half of the last decade, the average education gap among the elderly is also narrowing but remains large at about 32 percentage points.[6]

Figure 3.3. Gaps in Internet use are narrowing but remain pronounced among the elderly

Average gaps across OECD countries, 2005-23



Notes: Estimates based on a local polynomial with a bandwidth of unity. See also endnote 4.

Source: Authors' elaboration based on data from OECD (2023[5]).

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As divides across key dimensions tend to increase in age, they can be expected to narrow. How long will it take? The finding reported above suggests that age gaps in Internet use are closing at a rate of about 3 percentage points per year. This implies the average gap across countries may be closed by the end of the decade. However, this finding may be misleading as the data only cover those up to age 74. The population share of those 75 and older ranges from about 3% in Colombia, Mexico and Türkiye to more than 12% in Italy and Japan (UN DESA, 2022[8]); it is increasing in all OECD countries.

Non-adoption rates in this age group in 2020-22 across nine OECD countries for which data are available vary from 9% in Norway to 90% in Mexico, averaging 64%. They are on average five times higher than those for people between the ages of 55 and 74. A projection using data from Italy, where nearly four in five aged 75 and older in 2021 said they had never used the Internet, suggests that about one-quarter of them might remain off line by 2030.[7] In other words, non-adoption rates could remain elevated among the oldest well into the next decade.

Online activities differ in the extent to which they require education and ICT skills

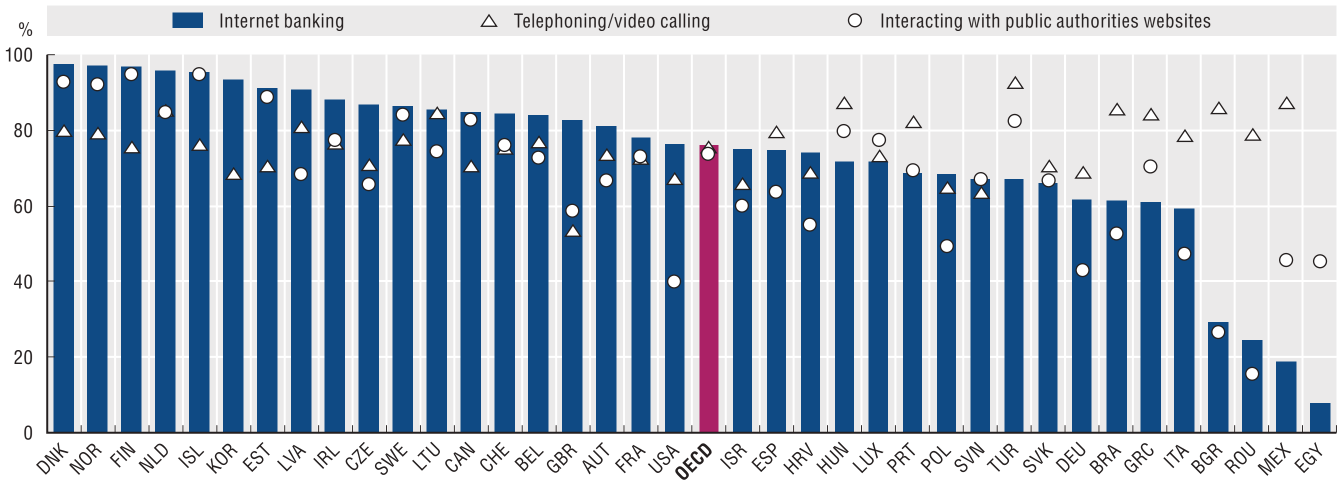
While Internet use has become the norm for a large majority of people in OECD countries, it is important to understand how they use it. Today, connectivity offers a broad range of opportunities from basic communication and information gathering to leisure activities, the purchase of goods and services, education and job hunting, and interactions with the government.

Across countries, uptake of specific online services can vary significantly. For instance, average uptake rates among Internet users of video calls and Internet banking are both around 76% (Figure 3.4). However, while uptake rates of Internet banking range from 8% to 97%, uptake rates of video calling are above 50% in all countries included here, ranging from 53% to 93%. When compared to Internet banking, an activity that would seem to require similar skills, uptake of online government services is of the same magnitude, averaging 74%. In 28 of the 37 countries for which data are available, Internet users are more likely to use Internet banking than online government services. There is also substantial variation across countries in the use of online government services, with uptake rates ranging from 15% to 95%.

Uptake rates among Internet users before the onset of the COVID-19 pandemic were regressed on three variables to better understand the forces behind the different uptake of online services across countries. These variables are the share of adults that completed tertiary education; the share of adults that have computer experience and did not fail a basic test on information and communication technologies (ICTs); and per-capita income. Results are summarised below and reported in Figure 3.5 and Annex Table 3.A.1.

Figure 3.4. Uptake of Internet banking and online government services varies across countries

Uptake of Internet banking, video calls, and interactions with public authorities' websites among adult Internet users, 2023 (or most recent)



Note: See endnote 8.

Source: Authors' elaboration based on data from OECD (2023[5]).

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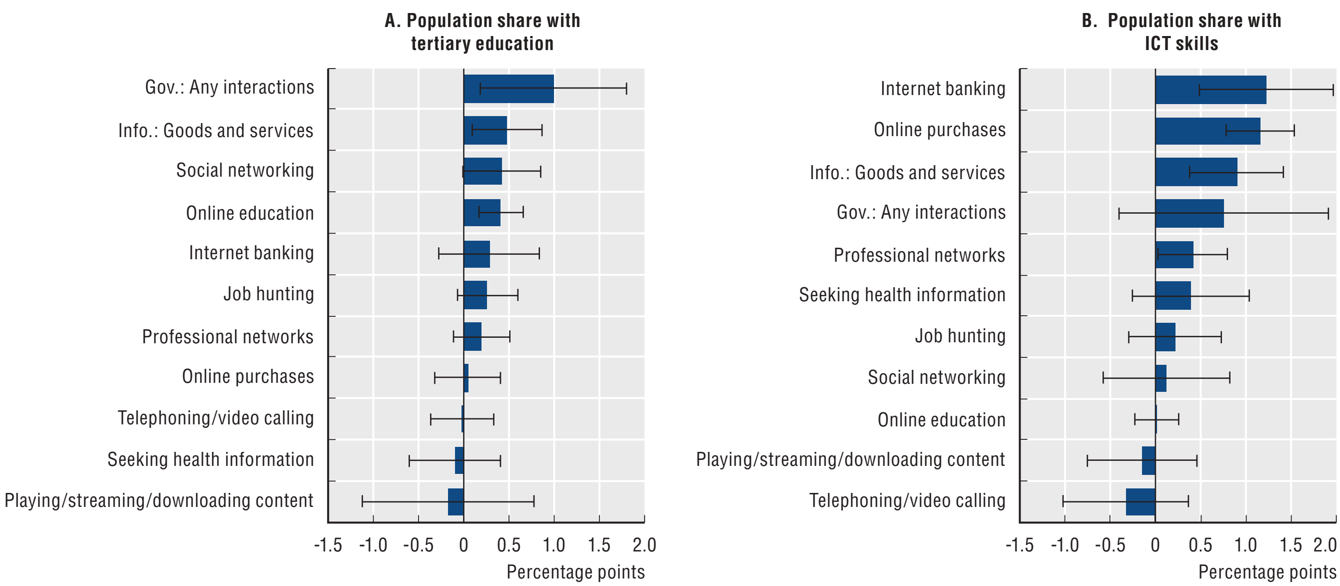
Figure 3.5. Online activities such as Internet banking and online purchases are correlated with formal education and ICT skills

Coefficient estimates from regressions of uptake rates of online services among Internet users, 2015-19; on formal education, 2015; share of the population with basic ICT skills, 2011-18; and GDP per capita, 2015



Note: See Annex Table 3.A.1.

Source: Authors' elaboration based on data from OECD (2023[12]; 2023[11]; 2023[5]; 2016[9]).

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First, results show that uptake of activities such as video calling or streaming or downloading content among Internet users is uncorrelated with either formal education or ICT skills. However, formal education matters for the propensity to interact with websites of public authorities. A 1 percentage-point increase in the share of the adult population that has completed tertiary education, for example, is associated with a 1 percentage-point increase in the share of Internet users that interact with the government via the Internet. Formal education is also associated with a higher incidence of Internet use to find information about goods and services and social networking, although the effects are smaller.

Finally, there is a highly statistically significant relationship between formal education and uptake of online education services. While the effect on education is smaller here than for other activities, the estimate is large relative to the lower rate of uptake of online education – only 12 percentage points on average.

Second, even after controlling for formal education and gross domestic product (GDP) per capita, ICT skills tend to be highly correlated with activities that set up or involve monetary transactions: Internet banking, online purchases and the search for information about goods and services. The effect sizes are large: a 1.0 percentage-point increase in the share of the adult population with ICT skills is associated with a 1.2 percentage-point increase in both uptake of Internet banking and online purchases. There is also a positive, albeit smaller, partial correlation between ICT skills and participation in professional networks.

Finally, there is little to suggest that GDP per capita determines online behaviour once the effects of education and skills have been considered. Half of the coefficient estimates are negative, and most are statistically insignificant. Weak statistical significance is only observed for uptake of video calls and online purchases: a 10% increase in GDP per capita is associated with decreased uptake of video calls by 1.7 percentage points and increased uptake of online purchases by 1.3 percentage points.

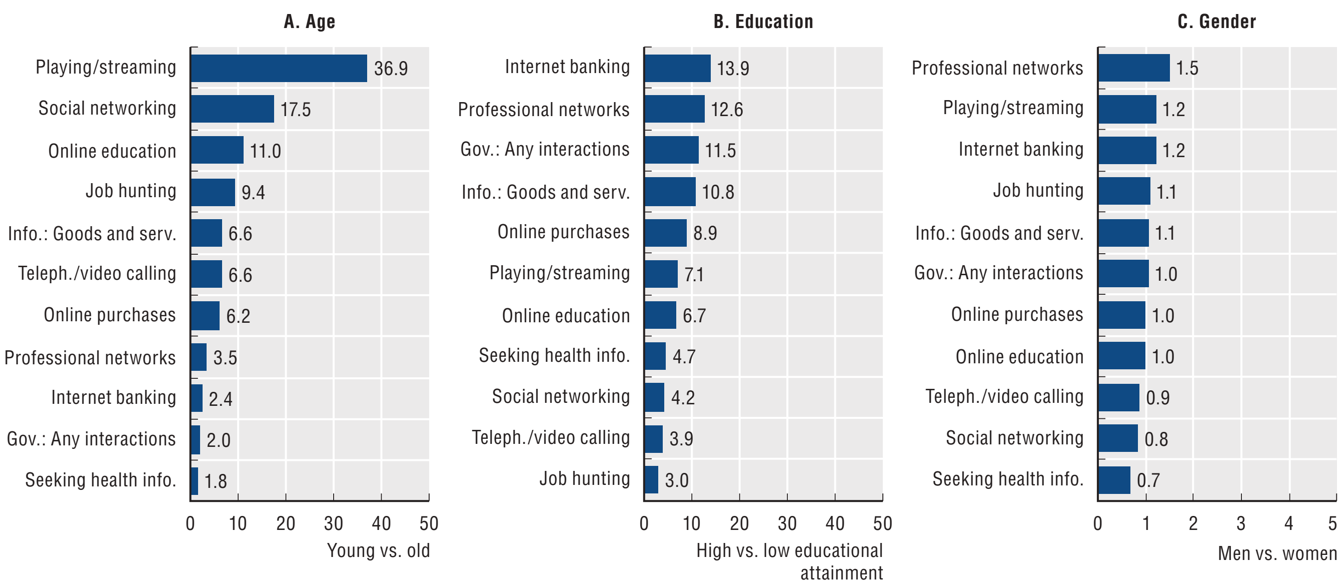
Younger and more educated Internet users engage in a larger variety of online activities

Differences across groups in uptake rates depend on the level of uptake. For instance, differences will necessarily be small if the overall uptake level in a population is either close to 100% or close to 0% (Oster, 2009[14]; Klasen and Lange, 2012[13]). Uptake rates will also depend on recall periods – the time period respondents are asked to consider in survey questions. These are typically 3 months, but this chapter uses 12 months for some indicators. It can thus be misleading to compare either absolute differences in uptake rates (i.e. in percentage points) or relative differences across different activities.

Comparing odds ratios provides a better way of understanding specific socio-economic and socio-demographic characteristics. For example, the odds of uptake among the young and elderly can be compared, where the odds are the adoption rate divided by the non-adoption rate. An odds ratio greater than unity would indicate higher uptake among the young, while a ratio below one would indicate higher uptake among the elderly. Figure 3.6 compares average odds ratios in uptake across different online activities between the young and the old; between high and low levels of educational attainment; and between men and women.

Figure 3.6. Younger and more educated Internet users engage in a larger variety of online activities

Average odds ratios for uptake rates of online services, adult Internet users, 2023 (or most recent)



Note: See endnote 8.

Source: Authors' elaboration based on data from OECD (2023[5]).

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Overall, younger and more educated Internet users have consistently higher odds of engaging in online activities, suggesting they are more likely to embrace a larger variety of online activities. However, the importance of age and education for uptake varies significantly across different online activities. For instance, differences in the odds for Internet users from different generations are particularly large for online leisure activities and participation in social networks. They are less pronounced for activities such as online interactions with government authorities, Internet banking and participation in professional networks. The differences are the least pronounced for Internet use to access health information, for which demand will likely increase with age.

As expected, given the cross-country results above, education is associated with a higher likelihood of uptake of certain activities. These include participation in professional networks, Internet banking, interactions with government, search for information about goods and services, and online purchases. Educated Internet users also have seven times larger odds on average of using the Internet to access online education services.

Interestingly, educated Internet users have only three times larger odds on average to use the Internet for job hunting. This finding seems to result from counteracting forces. On the one hand, individuals with lower levels of educational attainment tend to face higher unemployment risks. Consequently, they are associated with a higher demand for any type of job search services (Mincer, 1991[16]; OECD, 2023[15]). On the other hand, those with higher levels of educational attainment are more likely to use online job search services. Online job advertisements also tend to be skewed towards occupations that require high levels of education (LMIC, 2020[17]).

Finally, differences in the odds of uptake of online services are far less pronounced between men and women. Female Internet users tend to be more likely to seek health information on line and to engage in social networking and video calling. Male Internet users tend to be more likely to engage in gaming and streaming, Internet banking and professional networking. Among others, this is consistent with results from a study in Norway that finds that adolescent boys are five times more likely than girls to play online video games, while girls were more likely to use social media (Leonhardt and Overå, 2021[18]).

COVID-19 led people to rely more on online services… at least temporarily

From the first few months of 2020 onward, the COVID-19 pandemic shaped trends in the usage of online services. Demand for broadband communication services soared, with some operators experiencing as much as 60% more Internet traffic than before the onset of the pandemic (OECD, 2020[19]). Telework and remote schooling became the norm for many workers and students during lockdowns. Higher demand for video conferencing services, in turn, contributed to the sharp increase in Internet traffic (Ker, Montagnier and Spiezia, 2021[20]; Aksoy et al., 2022[21]).[9] E-commerce sales also increased sharply as consumers avoided indoor venues. In the European Union, retail sales via mail order houses or the Internet in April 2020 increased by 30% year-on-year (OECD, 2020[22]). In the United States, they surged by more than 40% in 2020 (Brewster, 2022[23]). Governments were at the forefront of responding to the pandemic, including by setting up dedicated online information portals and apps to support contact tracing, store vaccination certificates, or to support working and learning from home.

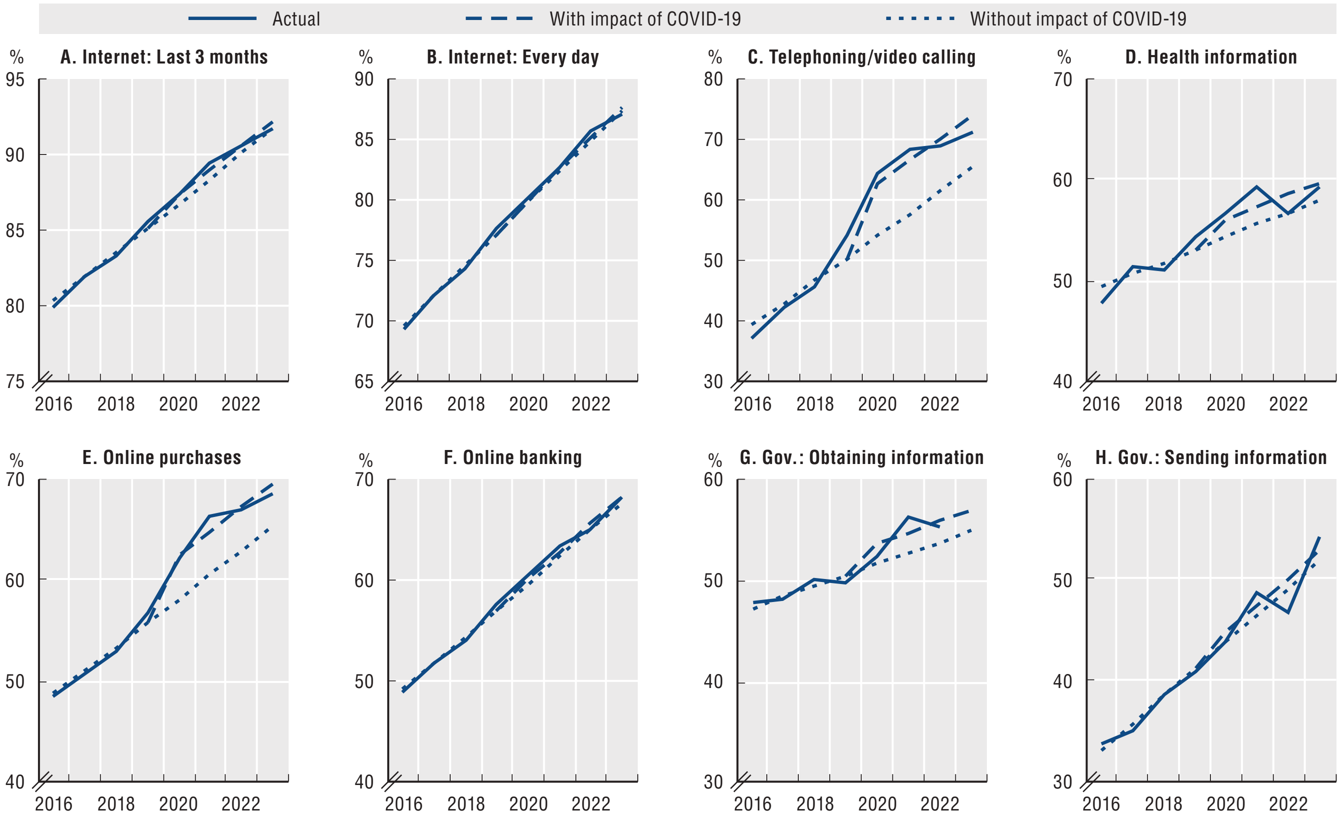
Are these changes also reflected in uptake rates? The first two panels of Figure 3.7 show that before the pandemic, Internet use in the three months preceding the survey increased on average by 1.6 percentage points per year. Meanwhile, daily Internet use increased at a rate of 2.6 percentage points per year (see also Annex Table 3.A.2). For both indicators, as well as online banking, the onset of the pandemic did not significantly change this trend, suggesting that pandemic restrictions did not sway any additional non-adopters to go on line.

There is clear evidence, however, of the pandemic's impact on use of online services. Uptake rates of video calling had already increased by an average of 3.7 percentage points before the onset of the pandemic. However, the pandemic led to an additional increase by about 8.6 percentage points (panel C). In other words, the pandemic propelled uptake rates of video calls by about 2.5 years. Similarly, uptake rates of online purchases (panel E) also increased with the onset of the pandemic in 2020 by an additional 4.4 percentage points.

The pandemic also resulted in an increased share of the adult population interacting with government authorities through their websites. Uptake of any of the three interactions with the websites of government authorities covered by the data (i.e. obtaining information, downloading forms and sending information) increased by 1.8 percentage points on average prior to the pandemic (not shown). With onset of the pandemic, uptake increased by an additional 2.1 percentage points. The effects seem primarily due to an increased share of adults obtaining information through government websites in 2021 rather than more adults sending information via government online portals (see last two panels of Figure 3.7). However, after peaking in 2022 at 56%, it appears that the share of individuals obtaining information through government websites is now returning to its pre-pandemic trend. In contrast, the share of adults sending information to government authorities now exceeds the post-COVID trend.

Figure 3.7. Uptake of online services increased during the pandemic

Average uptake rates of online services and pre-pandemic trends across countries, 2016-23



Notes: Averages reported for the "Actual" series are adjusted for variation in sample sizes across years. See also notes to Annex Table 3.A.2.

Source: Authors' elaboration based on data from OECD (2023[5]).

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More surprisingly perhaps, the pandemic had a very small and weakly significant effect on the propensity of adults to search for health information (panel D). After peaking at 59% in 2021 amid the pandemic, this rate appears to have returned to its post-pandemic trend in 2023. However, uptake rates do not capture the intensity of use. A more nuanced understanding of the effect of the pandemic on specific online activities requires different data. The likely persistence in increased use of online services is also unclear: did the pandemic increase uptake permanently or will use patterns return to the pre-pandemic trend (suggested by some of the series in Figure 3.7)? In what follows, two activities supported by digital technologies and connectivity – telework and e-commerce – are analysed more closely.

While more telework seems to be here to stay…

More telework has been positive for many people during the COVID-19 pandemic and may have brought significant welfare and productivity gains. While employers likely need to balance potential cost savings against what may be adverse effects on productivity, workers clearly value the option of working from home for two or three days every week. In a survey by Barrero, Bloom and Davis (2021[24]) among workers in the United States, half said they would be willing to forgo a 5% increase in their salary to work at home part time.

The experience with large-scale teleworking led many to wonder whether remote work is becoming a permanent feature of the future of work (OECD, 2020[25]). A pair of empirical studies by the OECD suggest the answer is "yes". The first, Adrjan et al. (2021[26]), looks at the share of online job postings in 2020 and 2021 that advertise telework, a forward-looking indicator of the adoption of telework. The authors find the share of postings advertising remote work more than tripled during the pandemic, from 2.5% in January 2020 to 8.5% in December 2021. However, while the tightening of pandemic restrictions was associated with an increased share of postings advertising remote work, the subsequent easing of restrictions did not have an analogue negative effect. In other words, while the pandemic was a catalyst for a shift towards remote work, the effect appears to be long-lasting.

In the second study, Criscuolo et al. (2021[27]) report results from an OECD survey on teleworking of both workers and managers in 25 countries. While they find differences between the two groups, with workers hoping for more telework than managers, most respondents in both groups seemed to agree on two to three working days as the ideal intensity of remote work. Empirical work based on a monthly survey in the United States suggests that preferences between managers and workers converged over the course of the pandemic. It suggests that workers have continued to supply about 30% of workdays from home from early 2022 onward (Barrero, 2022[30]; Barrero, Bloom and Davis, 2021[24]).

However, the most recent data from the monthly survey suggest the gap between employees' desired teleworking days and employers' plans has remained constant at about half a day. Moreover, recent evidence suggests a negative effect on productivity of telework (Atkin, Schoar and Shinde, 2023[28]; Emanuel and Harrington, 2023[29]). It will thus be interesting to see whether the incidence of teleworking will fall further from its pandemic peak, especially once labour markets are cooling. Finally, the benefits of telework will be distributed unequally as better paid and more educated workers are generally more likely able to work from home (Brussevich, Dabla-Norris and Khalid, 2020[31]; Garrote Sanchez et al., 2021[32]). This raises issues about equal opportunity.

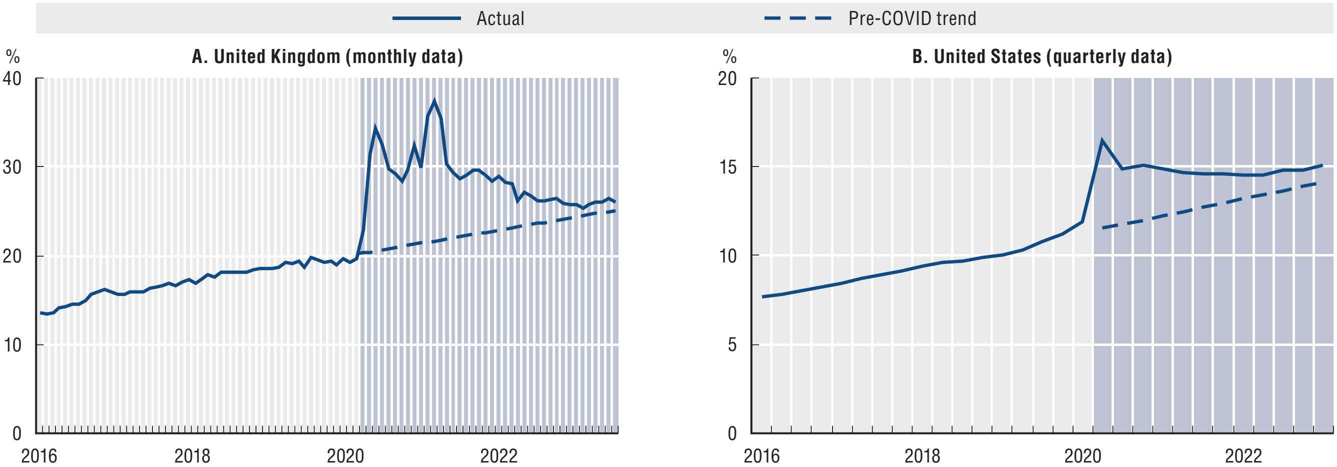
...the large uptick in e-commerce seems to be fading

While more teleworking than in the pre-pandemic era seems here to stay, the sharp increase in e-commerce observed during the pandemic seems to have been transitory. A study based on data from a major credit card provider first shows that, overall, the online share of total spending rose from 10.3% in 2019 to 14.9% at the peak of the pandemic (Cavallo, Mishra and Spilimbergo, 2022[4]). However, the most recent data (for September 2021) suggest these spikes in online spending shares were already dissipating at the aggregate level. While online spending shares remained above the pre-pandemic trend in about half of the 47 countries examined, the difference was only 0.6 percentage points on average.

This is in line with more recent data from the United Kingdom and the United States on (the narrower category of) e-commerce retail sales (Figure 3.8). At its peak in February 2021, the share of e-commerce in total retail sales in the United Kingdom had increased by 16 percentage points above the previous trend but reverted as pandemic restrictions were eased. By mid-2023, the share of e-commerce was only 0.9 percentage points above the previous trend. In the United States, for which quarterly data are available, the percentage of e-commerce in total retail sales peaked at 5 percentage points above the pre-pandemic trend. It then stabilised at about 1 percentage point above the trend during the first half of 2022. While the share of e-commerce in total retail sales continues to increase, it does so broadly in line with trends observed prior to the pandemic.

Figure 3.8. Much of the initial increase in e-commerce during COVID-19 has dissipated

E-commerce retail sales as a percentage of total sales, Q1 2016 – Q2 2023, United Kingdom and United States



Notes: Both series are seasonally adjusted. Pre-pandemic trends are estimated based on a regression of the share of online sales on the time variable for the period Q1 2016 to Q4 2019 (United States) and January 2016 to February 2020 (United Kingdom).

Source: Authors' elaboration based on ONS (2023[33]) and US Census Bureau (2023[34]).

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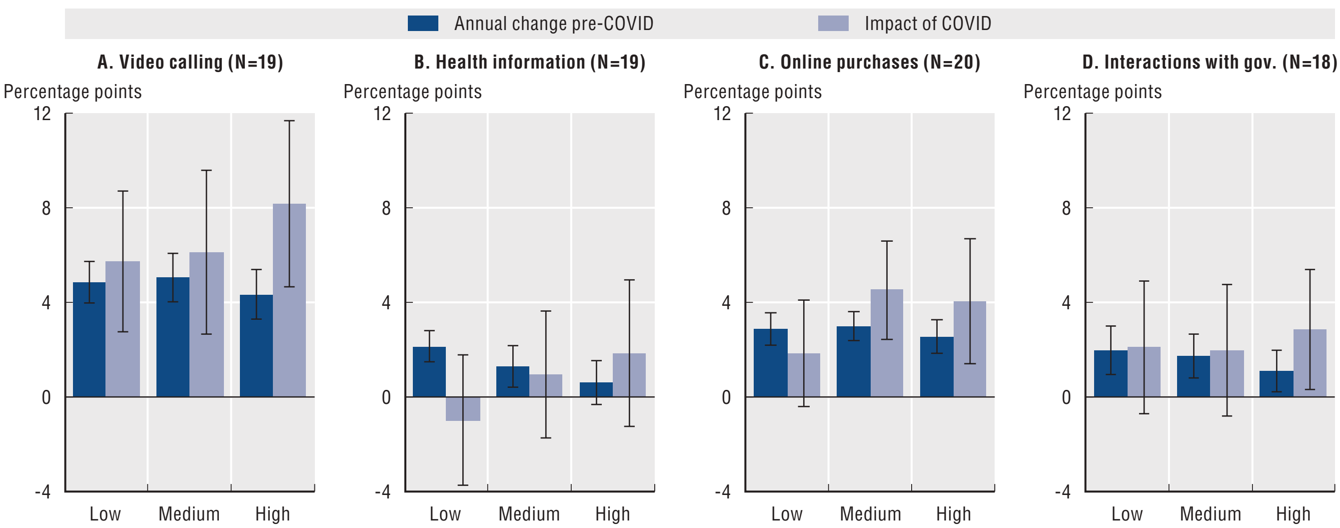
During the pandemic, those with the requisite skills were in a better position to use online services to their advantage

When COVID-19 forced people into lockdowns, the status of many online services turned from amenity to necessity. While significant digital divides were evident prior to the pandemic, evidence regarding the impact of the pandemic on these divides is only now emerging. One way to approach this question is to ask whether the onset of the pandemic affected patterns of convergence. Convergence in uptake rates between different groups can be expected at higher levels of overall uptake: those with higher levels of uptake run out of room to push the uptake rate up any further (Oster, 2009[14]).

Figure 3.9 and Annex Table 3.A.3 report estimates of the average annual change in the uptake rate prior to the onset of the pandemic and the one-off change brought about by the pandemic by level of educational attainment. Before the COVID-19 pandemic, uptake rates of those with low and high levels of educational attainment often converged, i.e. the former have tended to see large increases in uptake. This is the case for video calling; use of the Internet to access health information; and interactions with government authorities through their websites. Increases in uptake of online purchases were more evenly distributed.

Figure 3.9. COVID-19 was often associated with slowing convergence in uptake of online services

Annual changes in uptake rates and impact of COVID-19 by educational attainment, adults aged 16-74, 2016-23



Note: See Annex Table 3.A.3.

Source: Authors' elaboration based on data from OECD (2023[5]).

StatLink https://stat.link/7gnxyz

The onset of COVID-19 changed this pattern. All groups saw an additional increase in uptake of video calls, online purchases and interactions with government through their websites. However, individuals with higher levels of education typically saw the largest increase. However, in the case of Internet use to seek health information, there is no evidence for a significant increase for any group (see also Figure 3.7). This is consistent with recent research based on web search data from the United States. This research shows that individuals living in postal-code areas with lower average incomes intensified their online searches for health information to a smaller extent than those living in areas with higher incomes (Suh et al., 2022[35]).

Other indications the pandemic has further deepened digital divides. Data from a survey in Germany, for instance, suggest that women, the young, the well-educated and, most importantly, those with confidence in their digital skills, were far more likely to state that the Internet became more important for them during the pandemic (Bürger and Grau, 2021[36]).[10] Only 17.5% of those that said they had "very bad" or "rather bad" knowledge of digital technologies – nearly three in ten Germans – said the Internet had become more important for them during the pandemic. Similarly, those with university degrees were more likely to say they had used the Internet in new ways during the pandemic than those with lower levels of educational attainment (McClain et al., 2021[37]). Meanwhile, children in low-income households faced more obstacles to remote learning than those in high-income households (McClain et al., 2021[37]).

Data-dependent technologies are diffusing at a slow pace

The previous sections argued that effective use of digital technologies is becoming an important determinant of people's capacity to take part in society and make the most of economic opportunities. While uptake of online services has increased rapidly, important gaps remain that are often linked to differences in education and skills. The following section looks at adoption of digital technologies by firms.

Uneven diffusion of data-dependent digital technologies may undermine productivity growth

Sustained long-run growth depends on productivity growth, which in turn requires firms to adopt new technologies (Stokey, 2021[38]). Yet despite the increasing prominence of digital technologies in firms, labour productivity growth across OECD countries has slowed after 2005 and has not recovered (Goldin et al., 2021[39]). While there are many possible explanations for the productivity slowdown, empirical studies have pointed to faltering business dynamism (Calvino, Criscuolo and Verlhac, 2020[40]) and a pattern consistent with slowing technology diffusion from firms at the productivity frontier to those less technologically advanced (Andrews, Criscuolo and Gal, 2016[41]).

While digital-intensive sectors are on average more dynamic than other sectors of the economy – exhibiting higher firm entry, exit and job reallocation rates – they have not been exempted from the slowdown. In fact, business dynamism in digital-intensive sectors has been declining at a faster rate than in other sectors (Calvino, Criscuolo and Verlhac, 2020[40]; Calvino and Criscuolo, 2019[42]). Low-productivity firms, which tend to be younger and smaller than those at the productivity frontier, are finding it harder to catch up to the frontier in digital-intensive industries (Berlingieri et al., 2020[43]; Corrado et al., 2021[44]). Empirical work has linked the increase in productivity dispersion and market concentration, as well as faltering business dynamism, to the rise of intangible capital (which includes software and data) (Crouzet and Eberly, 2019[45]; Corrado et al., 2021[44]); the combination of proprietary software systems, data and organisational capital (Bessen, 2022[46]); or the increasing role of data in the economy (Arrieta-Ibarra et al., 2018[48]; Akcigit and Ates, 2021[47]).

Complementing these studies, this section looks at adoption rates for different digital technologies, the speed with which they are diffusing across firms and patterns of adoption by industry and firm size. It focuses on three clusters of technologies: cloud computing, a technology that relies critically on connectivity and that can be thought of as enabling flexible access to a range of other ICTs; the IoT, a suite of innovations that relies on a combination of hardware (devices equipped with sensors and microchips), software and connectivity; and big data analytics and AI, technologies that depend critically on data as an input.[11]

Uptake of data-dependent technologies such as big data analytics and AI remains low

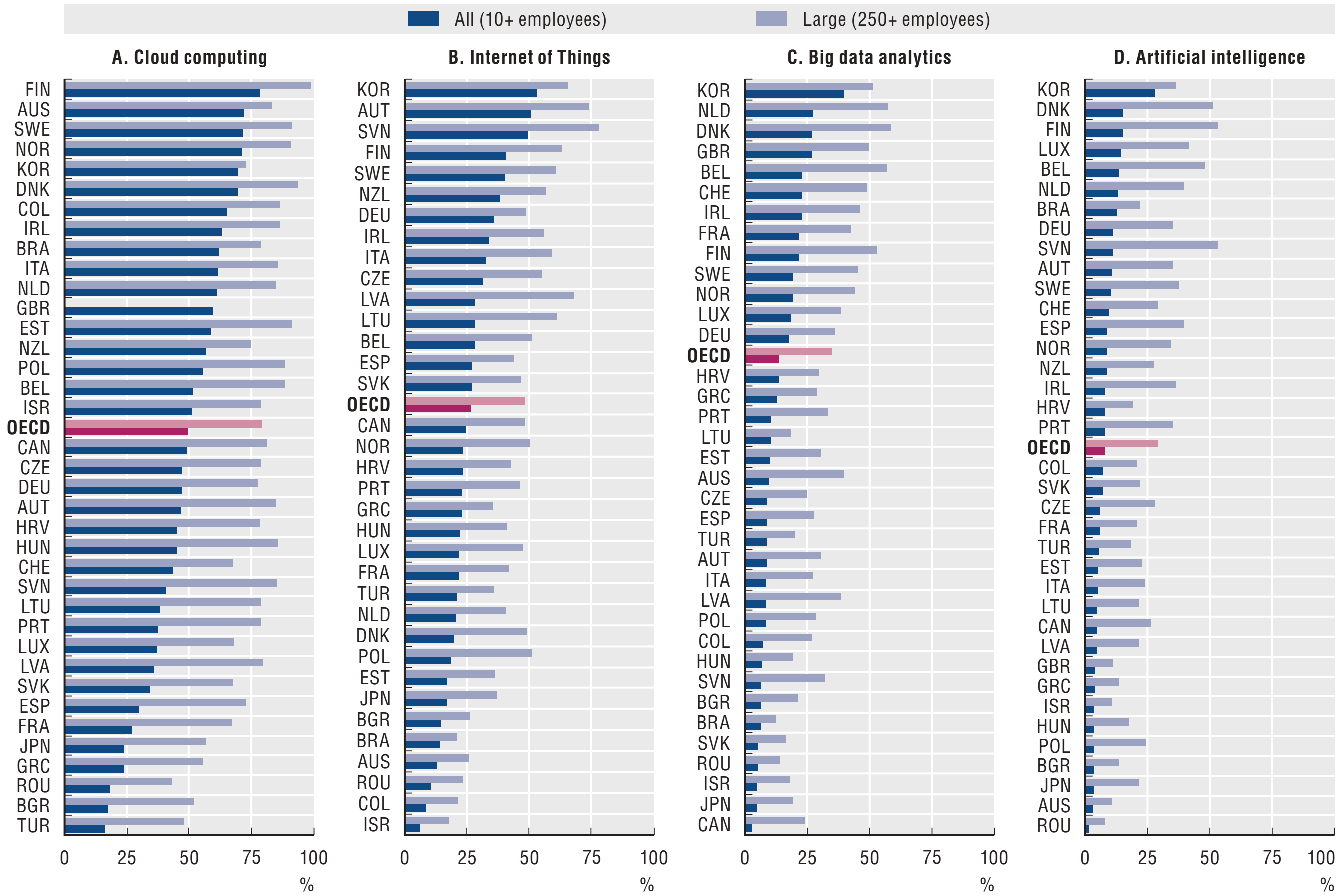
Cloud computing, IoT technologies and data-intensive technologies all had precursors, ranging back decades in some cases.[12] However, they only became available in their modern form and at scale after 2005. Nevertheless, their adoption by firms varies considerably: in the OECD, cloud computing is already used by an average of 49% of firms with ten employees and more, with adoption rates ranging from 16-78% (Figure 3.10). Adoption of IoT technologies among firms averages 27%, ranging from 6 to 53%.

By contrast, adoption rates of big data analytics and AI remain low. As of 2022, approximately 14% of enterprises with ten or more employees have embraced big data analytics on average, ranging from 3%[13] to 40%. Only 8% of firms on average used AI in 2023, with a range from 2 to 28%.[14] While the data displayed in Figure 3.10 do not include the United States, data from the Census Bureau's 2018 *Annual Business Survey* indicate that only 2.9% of firms had adopted machine learning – the data-driven subfield of AI – and only 0.7% were testing its application (Zolas et al., 2020[49]).

The use of cloud computing has been increasing since 2015 in nearly all countries for which data are available, often dramatically. Australia, Estonia, Germany, the Netherlands and Sweden all saw adoption rates increase by 30 percentage points or more. In countries with low levels of adoption in 2015 (e.g. Bulgaria and Romania), adoption rates often increased by more than 5 percentage points over just six years.

Figure 3.10. Adoption of data-driven technologies remains low

Adoption rates of cloud computing, IoT technologies, big data analytics and AI by enterprises with ten employees or more in the business sector (excluding financial services), 2023 (or most recent)



Note: See endnote 15.

Source: Authors' elaboration based on data from OECD (2023[5]).

StatLink https://stat.link/1foqhj

While data for a sufficiently large number of countries are only available for 2021 and 2022, there are several indications that IoT deployment has also increased rapidly in recent years. The number of machine-to-machine (M2M) subscriptions on mobile networks per 100 inhabitants[16] has been increasing across OECD countries between 2010 and 2021 at a rate of 19.3% per year on average (Annex Table 3.A.4). M2M is measured as the number of subscriber identity module (SIM) cards used in machines and devices (e.g. cars, smart meters or consumer electronics) that are not part of a consumer subscription.

However, from 2020 onward, IoT deployment has faced headwinds in the form of the global shortage of semiconductors, a key input in the production of IoT devices. The data on M2M SIM cards suggest the onset of the global semiconductor shortage in 2020 was associated with a one-off slowdown in the growth of M2M subscriptions per inhabitant to about 10.6% in 2020. This is substantially lower than the average over 2010-19 (Annex Table 3.A.4).

These estimates are well in line with projections by IoT Analytics, a market research firm. According to IoT Analytics (2020[51]), the number of connected IoT devices increased from 3.6 billion to 11.3 billion over 2015-20, an annual growth rate of 26%. Such devices exclude computers, laptops, fixed phones, cell phones and tablets, and one-directional devices such as those based on Radio Frequency Identification technology. However, IoT Analytics also estimates the shortage of semiconductors slowed growth in the deployment of IoT devices between 2020-21 to 8%.

Cloud computing has been diffusing three times more rapidly than big data analytics

While adoption rates for big data analytics and AI remain behind those of cloud computing and IoT technologies, they are arguably also more recent technologies. How rapidly are these technologies diffusing? Are there differences between technologies that can help explain why overall productivity growth has been slow?

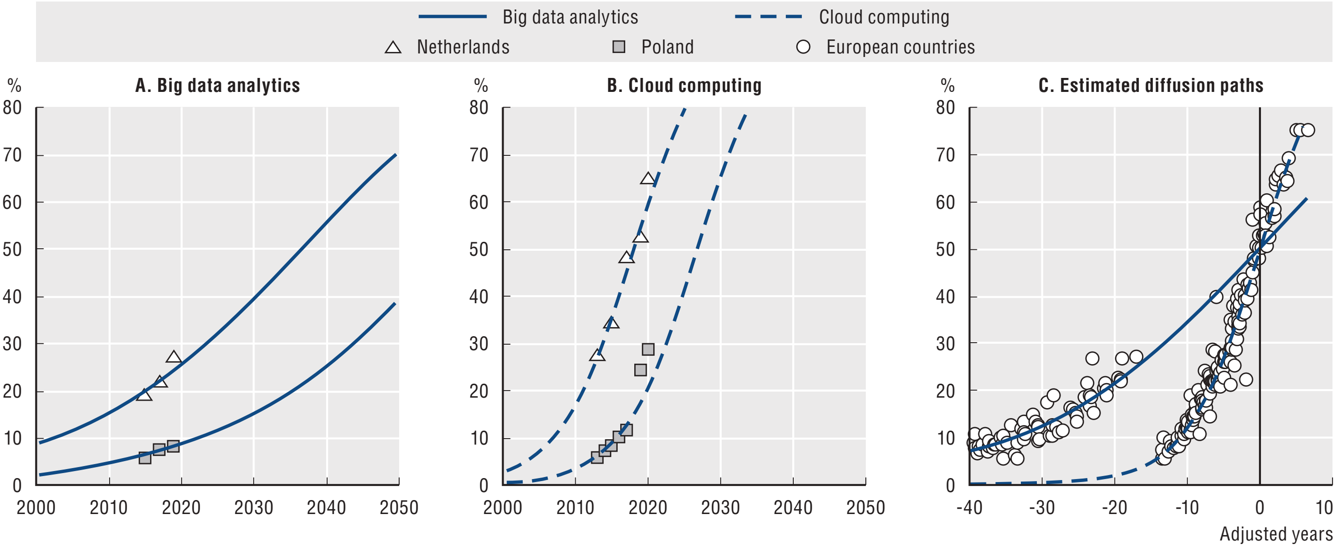
In comparing trends over time between technologies at different levels of adoption, it is important to account for different stages of diffusion. Adoption rates tend to follow an S-shaped path over time (Griliches, 1957[52]; Mansfield, 1961[54]). In other words, the relative diffusion speed, or the growth rate of the share of adopters, is high initially but converges to zero as adoption approaches 100%. Absolute changes in adoption rates, on the other hand, will initially increase and then decrease. Hence, the *level* of adoption should be considered in any comparison of how quickly new technologies diffuse. This can be done using logistic growth models that approximate the pattern described above. Figure 3.11 displays logistic functions fitted to the data on the adoption of big data analytics and cloud computing from 25 and 26 European OECD countries, respectively.[17] These functions differ across countries in terms of their location but not their shape. In other words, these technologies are assumed to diffuse at the same rate across countries for a given level of adoption.[18]

Using two countries as examples, the first two panels show that adoption of both technologies is higher in the Netherlands than in Poland. However, in line with decreasing relative diffusion speed, the relative rate of change was generally *higher* in Poland for both big data analytics and cloud computing, while the change in terms of percentage points was *lower*. Adoption of big data analytics among firms increased by 8.2 percentage points in the Netherlands over 2015-19, from 19% to 27%, corresponding to a relative change of 42.8%. In Poland, the relative increase was still higher, 43.5%, while the absolute change was substantially lower (2.6 percentage points).

Figure 3.11 (panel C) depicts the entire data for European countries and adjusts the year variable. In this way, country-specific diffusion paths are aligned and intersect at “adjusted year” zero and an uptake rate of 50%.[19] Adjusted years can be interpreted as the years passed since 50% of firms adopted a specific technology. The graph visualises the large difference in diffusion speeds between the two technologies in Europe. Based on these estimates, an increase in adoption rates from 5% to 50% takes only about 12 years on average for cloud computing. The same increase in adoption of big data analytics takes 36 years. In other words, cloud computing has been diffusing at a rate three times faster than big data analytics.[20]

Figure 3.11. Cloud computing has been diffusing three times more rapidly than big data analytics

Adoption rates of big data analytics and cloud computing by enterprises, 2000-50



Notes: Based on columns (2) and (6) of Annex Table 3.A.5. See also notes to the table.

Source: Authors’ elaboration based on data from Eurostat (2022[55]).

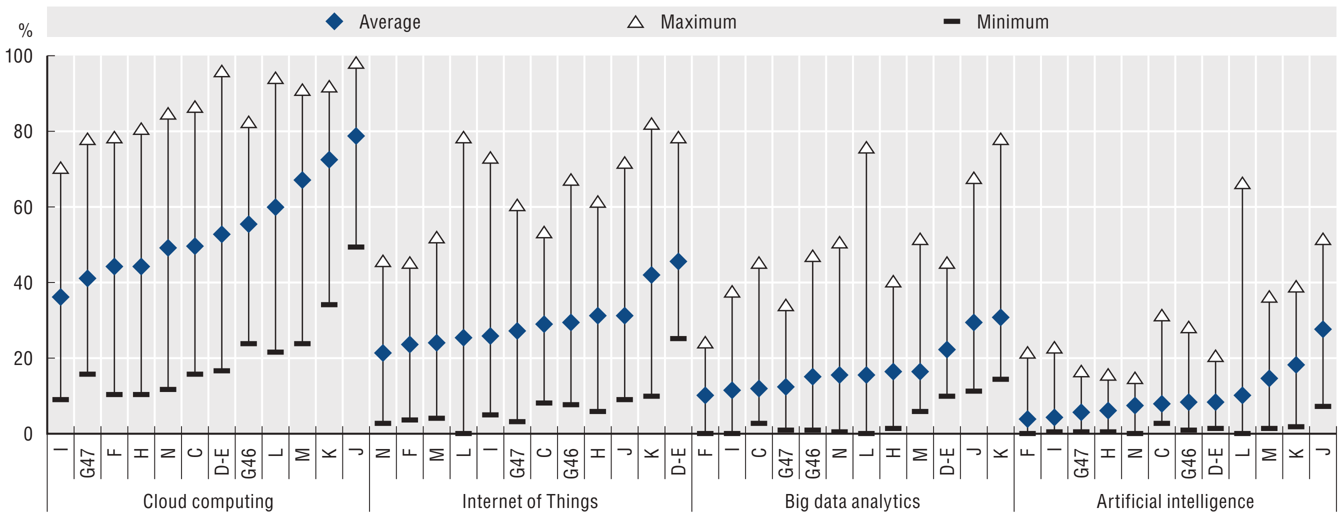
StatLink https://stat.link/s2kc7x

AI adoption is concentrated in the ICT sector

Widespread adoption of cloud computing across countries and industries underpins its rapid diffusion. Using the fourth revision of the International Standard Industrial Classification of All Economic Activities (ISIC), it is possible to identify sectors with the highest and lowest adoption rates. The highest adoption rates are typically in three main sectors: information and communication (Section J), finance and insurance (Section K) and other professional services (Section M). Meanwhile, the lowest adoption rates are found in industries such as accommodation, and food and beverage services (Section I) and retail trade (Class G47) (Figure 3.12). However, even in these industries, adoption rates are as high as 78% in some economies. This suggests that cloud computing is useful in a wide range of different settings and straightforward to adopt.

Figure 3.12. Adoption of cloud computing and IoT technologies is distributed evenly across sectors

Adoption of digital technologies by industry (ISIC codes), enterprises with ten employees or more in the business sector, 2023 (or most recent)



Note: See endnote 21.

Source: Authors' elaboration based on data from OECD (2023[5]).

StatLink https://stat.link/x4erv6

Adoption of IoT is far advanced in financial and insurance activities, as well as in the utilities sector (Sections D-E), where on average nearly half of all firms use them (OECD, 2023[50]). Apart from that, adoption of IoT technologies is remarkably evenly distributed across sectors. It ranges from an average of 21% in administrative and support service activities (Section N) to 31% in transport and storage (Section H). As expected, adoption is above average in sectors that produce and move physical objects (transport and storage, manufacturing, wholesale and retail trade) and below-average in white-collar service sectors such as real estate, and administrative and support services.

Data are abundant in the ICT sector, utilities and finance, a sector with a long history of innovation around data-driven technologies (e.g. cryptocurrencies and robo-advisers). In line with this, firms in these sectors have on average the highest adoption rates for big data analytics. Adoption of AI remains concentrated in the ICT sector, where on average nearly 28% of firms are using the technology. Beyond that, adoption rates are high in white-collar service sectors such as finance and professional services (respectively at 18% and 15%). Conversely, adoption rates are low in construction and hospitality (both at 4%). There is remarkably high variation in AI use among firms in the real estate sector, with rates ranging from 0% to 66% across countries. Overall, the finding that AI is comparatively concentrated in specific sectors is also in line with other research.[22]

Firm size is more important for adoption of data-dependent technologies and software than for IoT or cloud computing

Small firms, especially young ones, have historically played a crucial role in product innovation and productivity growth. To do so, however, they need access to recent technologies. To what extent do small, medium-sized and large firms differ in the adoption of recent digital technologies?

Across countries, larger firms tend to be more likely adopters of new technologies, including cloud computing, IoT technologies, big data analytics and AI. However, it is difficult to draw conclusions about the importance of firm size for adoption in this way as focusing on either absolute or relative differences can be misleading. In Canada, for instance, the absolute difference in adoption rates between large and small firms is 35 percentage points for cloud computing but only 23 percentage points for big data analytics. However, large firms are 15 times more likely to use big data analytics than small firms and only 1.7 times more likely to use cloud computing.

As in the case of uptake of online services, it is preferable to compare odds ratios, which under reasonable assumptions about the diffusion process will not depend on the level of uptake.[23] Large firms are three and four times more likely to adopt IoT technologies and cloud computing, respectively, than small firms on average (Figure 3.13). However, for big data analytics and AI, they are five and six times more likely, respectively.[24] Still, large firms are almost 13 times more likely to use enterprise resource planning software than small firms. Hence, firm size is a more potent predictor of adoption for data-dependent technologies in relation to IoT technologies or cloud computing but no more important than long-standing software solutions.

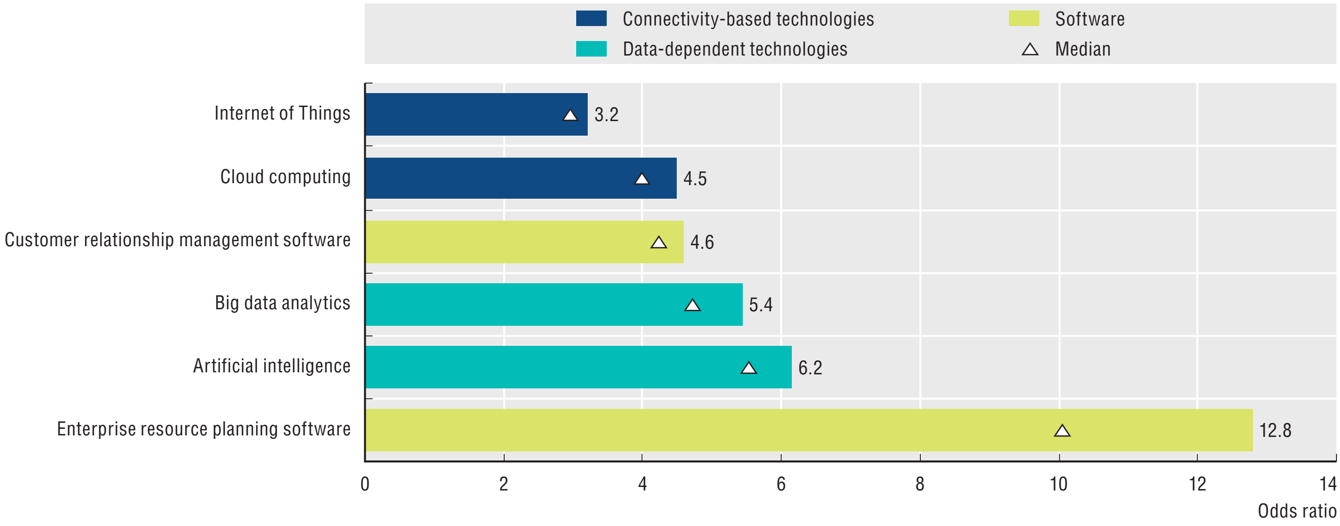
Slower diffusion of data-dependent technologies might be linked to scale economies, financial frictions or lack of access to data

The above results suggest that something about intangibles such as data and software make them less amenable to rapid diffusion. What explains these differences in diffusion speeds and uptake between small and large firms? Three possible factors are explored below.

First, the cost structure associated with the use of a technology is important. OECD (2014[56]) hypothesised that firms can leverage cloud computing solutions to reduce fixed costs by shifting capital expenditure to operating expenses. Hence, the cost of adopting cloud computing might be comparatively low for both small and medium-sized firms and start-ups. This could be critical as both are more likely to be constrained in terms of access to finance (Holton and McCann, 2021[57]).

Figure 3.13. Firm size is a more important predictor of adoption for data-dependent technologies and software than for IoT technologies or cloud computing

Average odds ratios of adoption in large enterprises vs. adoption in small enterprises, 2013-23



Note: Odds ratios are defined as the odds of large enterprises (250 employees and more) adopting a specific technology divided by the odds of small enterprises (10-49 employees).

Sources: Authors' elaboration based on OECD (2023[5]) and Eurostat (2024[95]).

StatLink https://stat.link/ivxyd1

Data-dependent technologies and software, on the other hand, have large economies of scale – the combination of high fixed costs and low costs per additional unit (Shapiro and Varian, 1999[59]; Haskel and Westlake, 2018[58]). AI and data analytics require complementary investments, not least to bring together relevant data from different silos and change organisational processes (Nolan, 2021[60]). Consequently, fixed costs will be high relative to other technologies. At the same time, marginal costs tend to be low.

For instance, a retailer that collects data from its stores to predict demand faces low costs of producing a prediction for an additional outlet. Additional computer power and data storage is cheap – not least because of cloud computing – and larger datasets typically do not require more data scientists to analyse them. In fact, adding data from further locations will typically *improve* forecasts for similar stores in different locations. Hence, the relevant variables for adoption of such a zero-marginal-cost technology are fixed costs and operational scale. Firms with larger scale face lower per-unit costs (or higher benefits relative to the fixed costs) and will thus be more likely to adopt. This logic applies to both software (a technology) and data (an input into AI and data analytics).

Second, high fixed costs point to the importance of access to funding. Smaller and younger firms typically find it more difficult to secure funding than large, well-established ones (Holton and McCann, 2021[57]). As an additional challenge, intangible assets such as data and (own-produced) software are often difficult to value, not least because their value is highly uncertain and often closely tied to their use. Banks will thus find it more difficult to accept them as collateral (Demmou and Franco, 2021[63]; Demmou, Franco and Stefanescu, 2020[62]). Hence, financial frictions that usually put smaller and younger firms at a disadvantage tend to be exacerbated when it comes to funding digital technologies based on intangible assets.

Third, large-scale firms might be in a better position to access data, which are only rarely sourced through markets but generated as a by-product of economic production (Spiekermann, 2019[67]; Cosgrove and Kuo, 2020[66]; Koutroumpis, Leiponen and Thomas, 2020[65]; OECD, 2022[64]). Larger firms tend to produce more units and have more customers and suppliers, all of which are potential datapoints. Hence, the larger the scale of a firm, the more data it can access.

A lack of access to external data would explain both slow diffusion and lower uptake among small firms. Several reports note the importance of data access, especially in the context of competition in digital markets (Furman et al., 2019[68]). However, few studies look at the impact of access to data on uptake of digital technologies or other relevant outcomes. A notable exception is Bessen et al. (2022[69]), who show that sole access to data is associated with a higher propensity to obtain venture capital funding.

Far-ranging adoption of AI might require yet more experimentation and co-invention

Finally, far-ranging adoption of AI might be premised on more experimentation and co-invention. AI has often been discussed as a general-purpose technology (GPT) (Cockburn, Henderson and Stern, 2018[70]), a term that describes a new method of producing and inventing important enough to have a protracted aggregate impact (Jovanovic and Rousseau, 2005[71]). Other GPTs such as electricity or the computer have often seen large gaps between their demonstrated potential and broad-based adoption. For instance, while the commercial potential of electricity was first demonstrated around 1880, it took another four decades before the uptake of the technology made itself felt in economic statistics (David, 1989[72]). Similarly, the ENIAC – the first programmable, electronic general-purpose digital computer – was built in 1945. Yet, in 1984, nearly 40 years later, only every fifth worker in the United States used a computer at work (Kominski, 1988[73]). Meanwhile, productivity effects associated with the computer were only observed from the mid-1990s onward (Stiroh, 2002[74]).

Agrawal, Gans and Goldfarb (2022[75]) argue that harnessing the potential of a GPT requires moving from its deployment in "point solutions" to "system solutions". Point solutions are comparatively easy to implement but have limited returns. Conversely, system solutions require substantial experimentation, co-invention and systemic changes. Point solutions that use AI comprise a far wider range of tasks in the financial industry – from fraud detection to assessment of default risks. Adopting AI for these kinds of tasks was comparatively easy as datasets were already in place and prediction was at the heart of the process.

It took system solutions for productivity gains from other GPTs to materialise. In other words, entrepreneurs had to figure out what types of systems could make the most of the new technology before they could implement these systems at scale. Yet this process requires substantial experimentation and co-invention, as well as changes to roles and up-skilling of the workforce. All that is costly, both in terms of funding and of dealing with resistance to operational changes. Data-driven technologies – and AI in particular – could well be at the same stage as electricity in the late 1800s and computers perhaps in the 1970s. The potential of the technology has been amply demonstrated. However, the introduction of system solutions that could boost productivity growth might require yet more experimentation and innovation (Juhász, Squicciarini and Voigtländer, 2020[76]).

Boosting equitable uptake and diffusion of digital technologies are vital to bridging digital divides and fostering productivity growth

This chapter finds that individuals' uptake of digital technologies continues at a rapid pace. However, it also notes challenges, including risks to equal opportunity and inclusion. The picture is more mixed across firms. Some innovations such as cloud computing and IoT technologies are spreading rapidly. Others, such as big data analytics, are diffusing far more slowly, especially among small and medium-sized firms. While these findings potentially point to a wide range of policy areas, five stand out.

First, the largest digital divides – both across and within countries – are often related to education and skills. This points to the need for education policies that better prepare individuals for an increasingly digital future. Education systems should enable individuals to use today's digital technologies effectively. However, to better prepare individuals for future technological change, these systems should also focus on metacognitive skills needed for lifelong learning. These could include learning-to-learn skills and the ability to reflect effectively on one's own knowledge, skills, attitudes and values (OECD, 2018[77]).

Second, uptake of online government services lags behind uptake of other online services such as Internet banking. This suggests that using government online services can remain cumbersome and that governments continue to find it challenging to provide public services that deliver on the potential of digital technologies (Welby and Tan, 2022[78]). Governments should lead by example in providing user-centric, inclusive online services.

Third, as pressure on service providers to shift on line increases, those most at risk of being left behind must be supported. For instance, non-adoption rates remain high among the elderly, especially women and those with low levels of education. They might continue to be elevated for years to come. Governments will need to find the right balance between investing in people's skills and ensuring they have sufficient offline support to access key services for as long as needed.

Fourth, adoption of digital technologies tends to be lower among smaller firms, especially for technologies associated with intangibles such as data and software. Smart small-business policies will aim to level the playing field for young and small firms by facilitating access to key inputs, especially finance.

Finally, adoption of data-dependent technologies is predicated on access to relevant data. Policy makers have two levers here that correspond to different data sources: increasing the sharing and re-use of data collected by private entities; and enhancing access to and usability of publicly held data. With respect to the former, the concept of data portability – the ability of a user to request that a data holder transfer to the user (or a third party) data concerning that user – has received much attention recently (OECD, 2021[79], 2021[80]).

Annex 3.A. Regression tables

Annex Table 3.A.1. Effect of education, ICT skills and income on uptake of online services

OLS regressions, adult Internet users (aged 16-74), 2019 (or most recent)

Dep. Variable: share of adult Internet users engaging in online activities	Adult population share with tertiary education		Adult population share with ICT skills		Log GDP per capita		Regression statistics	
	Estimate	SE	Estimate	SE	Estimate	SE	R-sq.	Obs.
Visiting/interacting with gov. websites (last 12 months)	0.99**	(0.41)	0.76	(0.59)	-0.02	(0.15)	0.60	22
Information about goods and services	0.47**	(0.20)	0.90***	(0.26)	-0.06	(0.11)	0.51	24
Social networking	0.42*	(0.22)	0.12	(0.36)	-0.17*	(0.09)	0.15	27
Online education	0.40***	(0.13)	0.01	(0.12)	0.02	(0.03)	0.66	24
Internet banking	0.28	(0.28)	1.23***	(0.38)	0.14	(0.13)	0.69	27
Looking for a job or sending a job application	0.26	(0.17)	0.22	(0.26)	-0.07	(0.06)	0.13	25
Participation in professional networks	0.20	(0.16)	0.41**	(0.19)	0.05	(0.04)	0.60	22
Online purchases (last 12 months)	0.04	(0.18)	1.16***	(0.19)	0.13*	(0.07)	0.82	24
Telephoning/video calling	-0.03	(0.18)	-0.33	(0.35)	-0.04	(0.10)	0.18	26
Seeking health information	-0.10	(0.26)	0.39	(0.33)	-0.05	(0.11)	0.05	26
Playing/streaming/downloading content	-0.18	(0.49)	-0.15	(0.31)	0.12	(0.11)	0.05	25

Notes: An estimate of 0.99 indicates that a 1 percentage-point increase in the share of the adult population with tertiary education is associated with a 0.99 percentage-point increase in the share of adult Internet users that use government websites. Robust standard errors (SE) in parentheses. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. All regressions include a constant. Explanatory variables are i) the share of the adult population that completed tertiary education (2015); ii) the share of the adult population with basic ICT skills (2011-18); and iii) GDP per capita (2015, measured at constant prices and constant purchasing power parities). The share of the population with basic ICT skills refers to the share of those with computer experience and did not fail the OECD's Survey of Adult Skills' core ICT test (OECD, 2016[9]). In the case of online education, an observation from Mexico was excluded as an outlier. As the COVID-19 pandemic affected uptake rates at least temporarily (see below), the focus here is on uptake rates prior to the onset of the pandemic.

Source: Authors' elaboration based on data from OECD (2023[12], 2023[11], 2023[5], 2016[9]).

Annex Table 3.A.2. Effect of COVID-19 on uptake of online services

Fixed-effects OLS regressions, adult Internet users (aged 16-74), 2016-23

	Internet: Last 3 months	Internet: Daily	Video calling	Health information	Online purchases	Online banking	Gov.: Any interaction	Gov.: Obtaining information	Gov.: Sending information
Year	1.63*** (0.25)	2.56*** (0.30)	3.70*** (0.35)	1.24*** (0.39)	2.37*** (0.26)	2.67*** (0.34)	1.81*** (0.40)	1.08** (0.44)	2.67*** (0.38)
COVID-19 (=1 in 2020-22)	0.58 (0.61)	0.23 (0.58)	8.58*** (1.39)	1.72* (0.96)	4.36*** (0.61)	0.58 (0.48)	2.10** (0.97)	2.10 (1.47)	0.97 (1.32)
R-squared	0.92	0.92	0.87	0.86	0.97	0.97	0.98	0.96	0.97
Countries	37	36	34	37	36	37	34	32	34
Observations	254	250	228	246	250	247	171	169	177

Notes: An estimate of 3.70 on the year variable (column: video calling) indicates that uptake increases on average by 3.7 percentage points per year. An estimate of 8.58 on the COVID-19 variable indicates that uptake increased by an additional 8.6 percentage points in 2020. An estimate of the change in 2020 is the sum of both coefficients, 12.3 percentage points. Robust standard errors clustered at the country level are reported in parentheses. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. All regressions include country-fixed effects. Countries comprise OECD countries, Brazil, Bulgaria, Croatia and Romania.

Source: Authors' elaboration based on data from OECD (2023[5]).

Annex Table 3.A.3. Effect of COVID-19 on uptake of online services by level of education attainment

Fixed-effects OLS regressions, adult Internet users (aged 16-74), 2016-23

Level of educational attainment:	Telephoning/video calling			Finding health information			Online purchases			Interactions with government		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Year	4.85*** (0.46)	5.06*** (0.52)	4.34*** (0.53)	2.14*** (0.33)	1.27** (0.45)	0.59 (0.47)	2.90*** (0.35)	2.99*** (0.31)	2.55*** (0.36)	1.97*** (0.51)	1.72*** (0.48)	1.09** (0.44)
COVID-19 (=1 in 2020-22)	5.75*** (1.52)	6.13*** (1.76)	8.18*** (1.80)	-1.00 (1.42)	0.94 (1.38)	1.84 (1.59)	1.85 (1.15)	4.52*** (1.06)	4.06*** (1.34)	2.10 (1.44)	1.98 (1.43)	2.84** (1.30)
R-squared	0.91	0.86	0.83	0.95	0.91	0.78	0.98	0.96	0.88	0.97	0.98	0.95
Countries/observations		19/133			19/133			20/140			18/108	

Notes: An estimate of 4.85 on the year variable indicates the share of adults that use the Internet for video calling increases on average by 4.85 percentage points per year. An estimate of 5.75 on the COVID-19 variable indicates that, in 2020, uptake increased once by an additional 5.75 percentage points on average. Robust standard errors clustered at the country level are reported in in parentheses. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. All regressions include a full set of country-fixed effects.

Source: Authors' elaboration based on data from OECD (2023[5]).

Annex Table 3.A.4. Effect of the semiconductor shortage on M2M SIM cards

Fixed-effects OLS regressions, 2010-21

	Log M2M subscriptions per 100 inhabitants			Log M2M subscriptions	
	All	Excluding Iceland	Excluding Iceland	All	Excluding Iceland
Year	0.193*** (0.018)	0.192*** (0.019)		0.198*** (0.018)	0.197*** (0.019)
Shortage in 2020-21 (=1 in 2020-21)	-0.087 (0.068)	-0.135*** (0.048)	-0.138*** (0.041)	-0.088 (0.069)	-0.136*** (0.048)
Country-specific linear trends	No	No	Yes	No	No
R-squared	0.890	0.907	0.984	0.967	0.969
Countries/observations	34/339	33/328	33/328	34/339	33/328

Notes: An estimate of 0.193 on the year variable indicates the number of M2M subscriptions per 100 inhabitants increased by approximately 19.3% per year on average. An estimate of -0.087 on the shortage variable indicates a reduction by approximately 8.7 percentage points in this growth rate in 2020. Robust standard errors clustered at the country level reported in parentheses. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. See also endnote 16 for more information on the data.

Source: Authors' elaboration based on data from OECD (2022[81]).

Annex Table 3.A.5. Diffusion of big data analytics and cloud computing

Fixed-effects OLS regressions, European countries, 2015-19 and 2013-20

	Big data analytics			Cloud computing		
	(1)	(2)	(3)	(4)	(5)	(6)
	All (2015-19)	OECD (2015-19)	All (2015-17)	OECD (2015-17)	All (2013-20)	OECD (2013-20)
Year	0.061* (0.033)	0.064* (0.035)	0.074 (0.045)	0.068 (0.053)	0.194*** (0.012)	0.196*** (0.010)
R-squared	0.825	0.800	0.918	0.881	0.952	0.958
Countries/observations	29/82	24/67	29/53	24/43	34/199	25/151

Notes: The dependent variable is the logit-transformed adoption rate, i.e. log $(S_{it}/(1-S_{it}))$, where S_{it} is the adoption rate in country i in year t. An estimate of 0.061 indicates that uptake increases by approximately 6.1% if the adoption rate is close to zero. The rate of increase halves (i.e. 3.05%) if the adoption rate reaches 50% and converges to zero as adoption approaches 100%. Robust standard errors clustered at the country level in parentheses. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. All regressions include a full set of country-fixed effects.

Source: Authors' elaboration based on data from Eurostat (2022[55]).

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Notes

1. Authors' elaboration based on data from Universal Postal Union (2022[91]), Bundesbank (2022[82]) and US Census Bureau (2022[90]) and population figures come from the UN DESA (2022[8]). Data from the Universal Postal Union (2022[91]) show a decrease in the number of permanent postal offices per inhabitant in most OECD countries since at least 2017.
2. Estimates based partly on imputations and using population data from UN DESA (2022[8]) accessed on 24 January 2024.
3. The most recent observation refers to 2023 except for Canada, Colombia, Egypt, Japan, Korea and Mexico (2022), Iceland, Israel and the United States (2021) and the United Kingdom (2020). The earliest observation refers to 2005 except for Bulgaria, France and Romania (2006), Croatia and the United States (2007), and Brazil and Colombia (2008). No data are available for 2005-08 for Canada, Costa Rica, Egypt and Switzerland. The reference period is three months prior to the survey except for the United States (six months in 2021 and no reference period in 2007), and Colombia and Japan (12 months). Data refer to age groups 16-74 years except for Costa Rica (18-74) and Israel (20-74). The OECD observation is based on a simple average of all available OECD countries.
4. Gaps are defined as the difference in uptake rates between men and women, the elderly (aged 55-74) and the young (16-24), individuals with high levels of educational attainment and individuals with low levels of educational attainment, and individuals residing in households in the fifth quintile of the household income distribution and individuals in households in the first quintile.
5. The reference period in the underlying surveys is the last three months preceding the survey. For the United States, the reference period is six months. Observations are for 2023 except for Canada, Egypt, Korea and Mexico (2022), Iceland, Israel and the United States (2021), and the United Kingdom (2020). Data refer to age groups 16-74, 16-24 and 55-74 except for Costa Rica (18-74 and 18-24) and Israel (20-74 and 20-24). The OECD observation is based on a simple average of all available OECD countries.
6. The finding that digital divides decrease in birth year has also been documented elsewhere (Friemel, 2016[86]).
7. This projection is based on a simple logistic model fitted to the pooled data from Istat's *Aspects of Daily Life* surveys for 2015-21 (2023[87]) that includes a linear time trend and fixed effects for different age groups.
8. Uptake among Internet users is estimated by dividing the uptake rate for a given activity by the share of individuals that have used the Internet over the relevant time period (typically 3 months, 12 months in the case of interactions with public authorities' websites and online purchases). Data refer to 2023 except for Canada, Egypt, Korea and Mexico (2022), Iceland and the United States (2021), and the United Kingdom (2020). For Israel, data refer to 2021 except for interacting with public authorities' websites (2020). For telephoning/video calling and Internet banking, the reference period is 3 months prior to the survey, except for Korea (12 months) and the United States (6 months). For online interactions with public authorities, the reference period is 12 months except for Brazil (3 months). For Israel, the data provided correspond to individuals aged 20 to 74 instead of 16-74. For Mexico, data on telephoning/video calling include only "Internet telephone conversations (VoIP)". Data on online interactions with public authorities include the following categories: "communicate with the government", "consult government information", "download government formats", "fill out or send government forms", "perform government procedures" and "comment on government consultations". For the United States, Internet banking also includes investing, paying bills on line and other financial services.
9. The pandemic also affected online labour markets, markets for tasks that can be done remotely on either an hourly or a per-task basis, as well as jobs in the local online gig economy (e.g. delivery or ridesharing app drivers). See, for instance, Stephany et al. (2020[89]) and CGI.br (2021[93]).
10. The finding is based on a set of two logit regressions, which are not reported here, with 814 observations using data collected by Bürger and Grau (2021[36]). In the first, the share of respondents stating that "the Internet is more important today for me than prior to the pandemic" is regressed on gender and age, as well as binary variables capturing income bracket and level of educational attainment. The second regression also controls for self-reported digital skills. The skills question is phrased as follows: "Asked in general terms, how good do you consider your knowledge of digital technologies and the Internet – their areas of application, their risks, but also

their opportunities and benefits for you and society?" and possible answers were "very bad", "rather bad", "rather good" and "very good". Age and gender were found to be statistically significant in both regressions, with women and the young more likely to state that the Internet became more important for them. As expected, those with high levels of self-reported digital skills were significantly more likely to state that the Internet became more important for them during the pandemic. Finally, while the income variables were statistically insignificant in both regressions, the effect of education appeared to be mediated by digital skills, i.e. the education variables were only statistically significant in the first regression.

11. The term "data" refers to either "information, especially facts or number, collected to be examined and considered and used to help decision-making", *or* "information in an electronic form that can be stored and used by a computer" (emphasis added) (Cambridge University Press, 2022[84]). The use of the term in this chapter corresponds to the first definition.
12. An early precursor of cloud computing was time-sharing, the sharing of computing resources among many users, which was popularised in the 1960s and 1970s. However, modern cloud computing became available with the creation of Amazon Web Services (in 2002) and the introduction of *Simple Storage Services* and *Elastic Compute Cloud* (in 2006). IoT technologies also had many precursors (e.g. radio-frequency identification technology) and the first appliance was connected to the ARPANET in the early 1980s. However, today's IoT was "born" sometime between 2008 and 2009 when, for the first time, there were more devices connected to the Internet than individuals (Evans, 2011[85]). Similarly, the systematic and strategic use of data in economic production predates the big data era by decades. However, the high-volume, high-frequency datasets used in big data analytics became available only with increasing Internet use and uptake of online services, with some commentators pointing towards 2012 as the year in which big data entered the mainstream (Lohr, 2012[88]). Finally, the term "artificial intelligence" was coined in the 1950s. However, practical applications such as machine learning arrived more recently (Varian, 2019[92]).
13. The low rate of uptake in Canada of big data analytics may be due to specificities of the survey instrument.
14. It is not clear whether survey respondents are always in a good position to answer questions about the use of AI. In particular, AI applications are often embedded as components of larger systems, which makes it more difficult to recognise them, and cognitive testing tends to indicate that respondents with limited AI knowledge can find it difficult to know whether AI technologies are used (Montagnier and Ek, 2021[94]).
15. While adoption is defined typically as current use, for Japan, adoption refers to use in the three-year period 2019-21. For Australia, observations relate to the fiscal year 2021/22, ending on 30 June 2022. For countries in the European Statistical System, sector coverage consists of all business economy activities except financial services (NACE Rev. 2 Sections B-N except for K). For Canada, the North American Industry Classification System is used instead of ISIC Rev.4. For Switzerland, observations refer to enterprises with five persons employed or more. For cloud computing, data relate to 2023 except for Switzerland (2019), Colombia and Israel (2020), Brazil, Canada, and the United Kingdom (2021), and Australia, Korea and New Zealand (2022). For IoT, data relate 2021 except for Australia, Korea and New Zealand (2022), and Colombia and Israel (2020). For big data analytics, data relate to 2022 for Australia and Korea, to 2021 for Brazil, Canada and Japan, to 2020 for Colombia, Israel and Switzerland, and to 2019 for all other countries. For AI, data relate to 2023 except for Colombia, Israel and the United Kingdom (2020), Brazil, Canada, Japan and Switzerland (2021), and Australia, Korea and New Zealand (2022).
16. M2M SIM cards data are provided to the OECD by communications regulators that collect them directly from network operators according to common definitions. Dongles for mobile data and tablet subscriptions are excluded. The significant growth of M2M in Iceland is due to the provision by Vodafone Iceland of M2M subscriptions for the benefit of international pharmaceutical companies to manage the transport of COVID-19 vaccines.
17. Data refer to enterprises with ten or more employees. Eurostat only started to survey the use of AI and IoT in enterprises in 2020.
18. This assumes that uptake rates eventually reach 100%.
19. The assumption of a common diffusion speed across countries appears justifiable in the case of cloud computing and somewhat less so for big data analytics. The simple logistic model (i.e. controlling only for differences in levels across countries) accounts for 95.8% of the variation in the data in the case of cloud computing and 80.2% in the case of big data analytics (Annex Table 3.A.5). However, of the 20 countries for which data are available for both 2015 and 2019, 6 experienced a decrease in adoption of big data analytics, something that cannot be consistent with an upward-sloping diffusion path.
20. The Eurostat survey questionnaire changed with respect to how respondents were asked about their use of big data analytics between survey year 2018 (which asked about use in 2017) and 2020 (which asked about use in 2019). Using only the 2016 and 2018 data did not affect the estimate (see Annex Table 3.A.5). The adoption rates

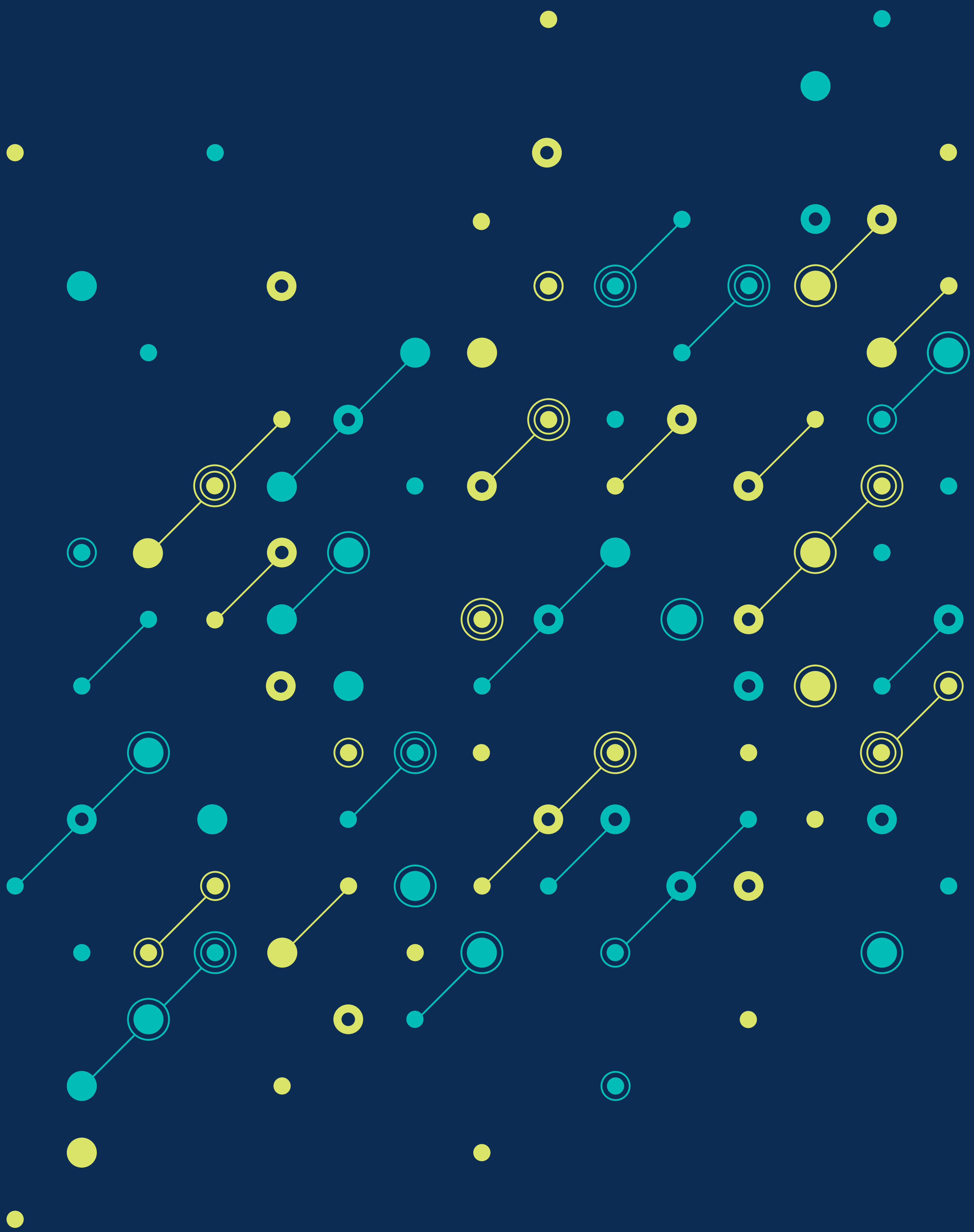
and ratios depicted in Figure 3.11 were computed for the period from 2015 to 2019. Subsequent data are not taken into account, as the perimeter of the definition for “Big data analytics” in the Eurostat survey has been modified (data for the 2023 Eurostat survey do not refer to “big data analysis” but to “data analytics”).

21. ISIC sector codes are as follows: C: manufacturing; D-E: electricity, gas, steam and air conditioning supply, water supply, sewerage, waste management and remediation activities; F: Construction: G46: Wholesale trade (except repair of motor vehicles and motorcycles); G47: retail trade (except repair of motor vehicles and motorcycles); H: transportation and storage; I: accommodation and food service activities; J: information and communication; K: financial and insurance activities; L: real estate activities; M: professional, scientific and technical activities; N: administrative and support service activities. For European countries using the Eurostat Community Survey on ICT Usage and E-commerce in enterprises, data for big data analytics refer to 2019. See also endnote 20.

22. Nolan (2021[60]), for instance, observes that AI adoption in manufacturing remains low – even in most advanced economies – while Calvino et al. (2022[83]) find that a large share of AI adopters are active in the information and communication sectors and professional services.

23. Odds ratios are independent of the level of uptake if the diffusion process follows a logistic map.

24. Differences in odds ratios between different technologies are highly statistically significant jointly (p-value<0.001).



Chapter 4

Virtual reality and its opportunities and risks

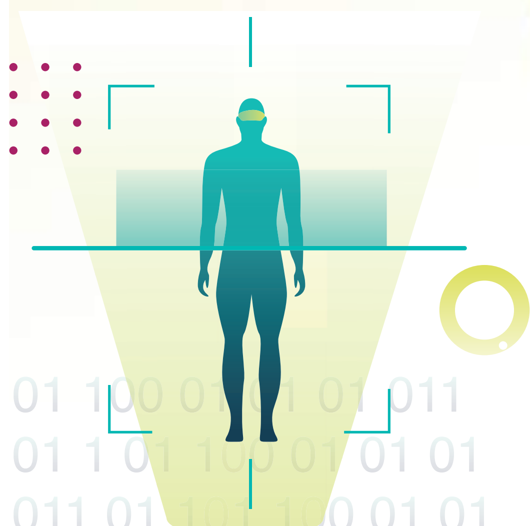
The rise of three-dimensional (3D) technologies is raising questions about the opportunities, risks and impacts of immersive environments on firms, governments, people and society. This chapter disentangles immersive digital environments and focuses on the importance of one immersive medium – virtual reality (VR) – because of its proven ability to scale. It explains the technologies and features of VR, highlighting its benefits and opportunities, as well as its downsides and risks. Concrete use cases help move beyond the buzzwords and hype of VR to a real understanding of when it is exceptionally useful (and when it is not). The chapter also explores the DICE framework, which involves using VR for things that are otherwise dangerous, impossible, counterproductive or expensive, as a useful guide. Key policy issues for VR and immersive technologies include privacy challenges, in particular those associated with tracking data, and safety, especially for children and in moving vehicles.

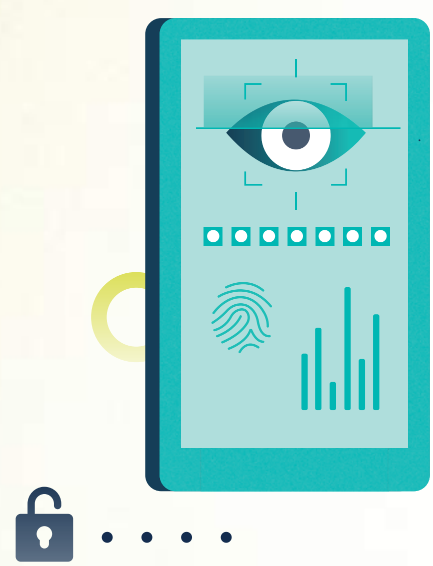
VR opens up new worlds, but user discretion is advised

Mental health and physical safety must be built into VR experiences, especially for children and in moving vehicles.

20 minutes in VR generates almost 2 million unique data points of body language.

Body tracking data makes VR possible, but raises privacy risks.





Key findings

The unique features of virtual reality (VR) involve trade-offs

- VR experiences can be self-contained, social or industrial.
- VR consists of a cycle of tracking, rendering and display, a continuous real-time process. Body tracking whereby scenes respond naturally to body movements facilitates "presence" and sets VR apart from other immersive environments.
- VR involves trade-offs on a range of technological features, including tracking level, field of view, field of regard, update rate, latency and image quality.

VR is best for experiences that are otherwise dangerous, impossible, counterproductive or expensive

- The use of VR – rather than two-dimensional technologies – should focus on areas that fall within the dangerous, impossible, counterproductive or expensive (DICE) framework where research has shown that VR is transformational and clearly the best fit for the job.
- VR applies primarily to experiences that fall within the DICE framework such as training surgeons and firefighters, medical rehabilitation (e.g. stroke victims), and having visceral, perceptual experiences (e.g. space exploration).
- Five areas that epitomise the DICE framework and have a proven ability to scale include: teaching empathy; medical rehabilitation; interventions to improve mental health; corporate training; and digital twins.

Considering the downsides and risks of VR from the outset is critical

- VR experiences can be incredible, but if a virtual experience is powerful enough to alter psychological well-being and empathetic views towards other people and cultures, then it must also have downsides and risks.
- Five downsides and risks are: privacy risks, particularly around the tracking of body movements; cognitive development and behaviour of children; simulator sickness; distracted driving; and overuse and addiction.
- Tracking data – which is key to creating VR experiences – also facilitates the generation and potential sharing of highly detailed user profiles, which creates privacy risks.

A mix of existing digital policy frameworks and new policy approaches will shape a positive immersive future

- Policy action on VR and immersive technologies focuses on promoting the domestic VR industry in countries that participated in the *OECD Digital Economy Outlook (DEO) 2024* Questionnaire, but it is starting to expand into specific sectors (e.g. education).
- Countries are beginning to develop "rights" and "principles" for VR and immersive technologies.
- Given there is no way to "opt out" or "go incognito" in VR, new approaches beyond traditional consent-based models will be needed to protect privacy.
- VR mental and physical safety must be carefully considered, especially for children and in moving vehicles, and safety by design can play an important role in this respect.
- VR businesses have begun to develop guidelines, particularly for social VR experiences.

As digital environments evolve from primarily "flat" formats to 3D environments that respond to users' body movements, questions about the opportunities, risks and impacts of such immersive worlds on firms, governments, people and society become more pressing. Applications of immersive environments span a broad range of sectors, including entertainment, manufacturing, education, health care, construction, government services and defence (Kim, 2021[2]; Marr, 2021[1]). While immersive technologies have existed for many years, the ways in which they are combining, the range of emerging applications and the falling costs create a new sense of urgency for policy makers (MIC, 2022[3]).

A cocktail of terms is used to describe immersive environments – augmented reality (AR), mixed reality, extended reality (XR), the metaverse, Web 3.0 and VR. AR, which is sometimes referred to as mixed reality, allows users to see and hear the real world together with a digital layer. With Google Glass, an early example of AR, a pair of eyeglasses allows light in from the outside world. At the same time, through a small window in a portion of the field of view (FOV) of one eye, users can see images, text or video superimposed on the real world. In more advanced systems, such as Apple's Vision Pro, Microsoft's HoloLens or Magic Leap's headsets, objects can be rendered stereoscopically. In other words, each eye receives an image drawn from the proper viewpoint to create depth, and these objects are registered spatially in a real room (Miller et al., 2019[4]). The most popular use of AR is the camera on a two-dimensional (2D) phone or tablet to look at a real-time video of the world with a 2D image superimposed on it (e.g. the videogame Pokémon Go) (Lee et al., 2022[5]).

XR is a relatively new term used to capture the range of different immersive technologies that exist today – VR, AR and mixed reality – as well as related technologies that may emerge. The term "metaverse" (sometimes called Web 3.0) is the overall architecture that includes XR, blockchain technology and virtual worlds that offer real estate, currency and platforms for events and activities. The term metaverse is broad, not well-defined and overused. The term, which came from science fiction, is a future-oriented concept that has spread to video game developers and academia (Ball, 2022[6]). The concept will evolve as technologies develop and expand.

This chapter focuses on one immersive medium – VR – because it is the only immersive environment with proven ability to scale. In 2022, approximately 9 million VR headsets were sold worldwide (compared to 260 000 AR headsets during the same period) (Ubrani, 2023[7]). Almost all of these headsets were sold by companies whose main source of revenue is social media products and services (80% by Meta, 10% by ByteDance and 10% by other firms). VR comes closer to providing an actual experience than a mediated one, both perceptually and psychologically. It offers "presence", the sensation of an experience feeling "real" to users (Sanchez-Vives and Slater, 2005[8]).

This chapter highlights VR use cases that have already demonstrated their ability to scale and return on investment, while minimising discussion of recently overhyped cases (e.g. cryptocurrency-fuelled VR real estate) (Tangermann, 2023[9]). It begins by explaining VR, including its technological and other features. It identifies the benefits and opportunities of VR, as well as its downsides and risks, and provides concrete use cases in a range of areas. The chapter concludes with a consideration of policy issues raised by VR.

Understanding VR

People often engage in self-contained VR experiences via apps.[1] In self-contained VR, only one live person is in the VR environment at any time, whether to play a game smashing floating boxes with light sabres or to visit Palau to understand how climate change is harming coral reefs. Other examples range from the critically acclaimed blockbuster video combat game "Half Life Alyx" to the smaller-budget experiences that allow users to experience empathy by "walking a mile in the shoes" of an avatar with a different identity. Meta offers VR experiences via the Meta Quest application, while Sony has its own platform for its user group of over 100 million PlayStation console owners (provided they buy the Sony VR headset).

A second type of experience is social VR platforms, which allow people to network as avatars and build and experience VR scenes together. For example, VRChat allows people to create a custom 3D world, embody avatars that can look like them (or not) and share virtual experiences with others who are also wearing headsets. For example, users may play miniature golf or sing Karaoke together. In social VR platforms, users meet new people and form relationships and communities. Horizon Worlds, Meta's current VR social networking app, is estimated to have around 200 000 active monthly users as of the second half of 2022, interacting in more than 10 000 different virtual experiences (Horwitz, Rodriguez and Bobrowsky, 2022[10]).

A third type of experience is the use of VR in industry, including business-to-business use cases that involve immersive solutions. For example, VR technologies can help manufacturers go a step beyond "digital twins" – loosely defined as a dynamic virtual version of a physical place or object (Jones et al., 2020[11]). This allows them to see how a potential product would operate in a realistic setting before physically manufacturing it. The concept of VR digital twins has been used in a range of areas, including the design of complex equipment, highly detailed VR environments of factories and cities, and precision medicine and digital agriculture (Marr, 2021[1]). Use cases exist in a broad range of sectors. To date, however, these applications have been highly customised and only practical for high-value applications (e.g. the design of jet engines, industrial facilities and power plants) (Marr, 2021[1]).

A continuous cycle of tracking, rendering and display enable VR

VR consists ofa cycle of tracking, rendering and display, which takes place continuously in real time (Blascovich and Bailenson, 2011[13]). The cycle starts with tracking, which involves sensors detecting a user's movements and translating them into data that can be used to update the VR content. Historically, tracking used a variety of sensors ranging from mechanical to magnetic, but today's tracking is mostly done with computer vision systems. These systems comprise cameras embedded within a headset that can accurately, quickly (i.e. low latency) and frequently (i.e. high update rate) determine where a user is looking and how their body is moving by constantly filming the room around them. Tracking information is critical because the system needs to know where someone is looking and how their body is situated to display their virtual location properly.

Rendering is how VR creates a virtual representation of the environment based on tracking data. Much in the same way that a GPS system in a car stores a map, a computer powering a VR system stores a 3D digital model of the virtual world. For example, it could store scenes such as a living room and the objects in it or a coral reef and the individual corals. Using the tracking information and data from the digital model, the computer updates the user's viewpoint by rendering the 3D world from that same viewpoint. In an underwater coral reef VR experience, for example, if the user tilts her head and looks down, she may see fish swimming below her. Similarly, in a VR experience in a house, if a user physically turns her head around 180 degrees, she will see the rear wall of the virtual room. Every moment the user moves physically, the tracking equipment detects the movement, causing the computer to render the world appropriately to this new point of view.

In current VR systems on the market, this process repeats itself approximately 100 times per second. When the system is functioning well, everything appears smooth to the user, like moving about in the real world. By dynamically rendering each scene based on the user's position, VR allows a scene to be explored infinitely. In an underwater coral reef VR experience, a user could find a small shell in the periphery, crouch down and look behind it. This contrasts with movies that only offer a single point of view (i.e. when a director films from a particular angle showing the shell). As another example, video games allow users freedom to explore paths and objects but typically only as they relate to the gameplay.

Finally, VR systems display the virtual environment to users in real time, allowing them to experience the environment as if they were physically present. This display is typically achieved through a VR headset, which provides a stereoscopic view of the virtual environment and spatialised sound via multiple speakers synchronised with the user's movements. Other display systems include 3D laptops using lenticular autostereo to show 3D models, or projection systems such as the Cave Automatic Virtual Environment in which all surfaces are screens.

VR has been evolving since the publication of "The Ultimate Display" by Ivan Sullivan in 1965, which explained the concept of VR well but not the manner of implementation (Sutherland, 1965[14]). Indeed, the potential of VR has changed dramatically over the past few decades. In Sutherland's early implementations, headsets could not render scenes stereoscopically or in more than a single colour. Today, headsets can mimic how people see and hear in the real world. However, VR systems vary in quality. A high-end system powered by a costly headset that displays images and a separate (powerful) computer for rendering produces much better sight and sound than less expensive, standalone VR headsets that both display images and render simultaneously.

The technological features of VR

As noted by previous scholars (Cummings and Bailenson, 2016[15]), there is no standard implementation of VR; instead, it combines various features and technologies. These features can be prioritised (or not) to achieve specific goals.

Tracking level refers to the number and types of degrees of freedom by which a user is tracked in VR. One can manipulate the tracking level by adjusting the quality of the input method. For example, more natural movement tracking can simulate how the body moves versus abstract controller input such as buttons or joysticks. Tracking also refers to the number of degrees tracked, such as the position of heads, hands, feet and facial movements.

Head tracking is arguably the most essential feature of VR (Lanier, 2017[16]). Without head tracking, VR is reduced to a 3D movie. Research suggests this active navigation through scenes is what makes VR uniquely effective (Markowitz et al., 2018[17]). Body tracking allows users to manipulate their hands and legs and walk around, and has been shown to significantly increase presence (Zanbaka et al., 2004[18]). Some applications require more tracking than others. For example, VR used for stroke rehabilitation requires an elaborate system to follow arm and leg movements accurately (see subsection on medical rehabilitation).

FOV is typically associated with more presence and engagement in VR (Hendrix and Barfield, 1996[19]). FOV is roughly a proxy for how much of an environment a person can see at once. It is often increased by changing the size of the screens close to a user's eyes. This feature is different from field of regard, which is the total amount of possible area that one can view. For example, the typical FOV of a VR headset is a window about the size of a large piece of paper held at arm's length. By moving one's head around, one can typically move that window, examining objects and spaces in every direction (in which case the field of regard is 360 degrees).

However, the field of regard is often reduced. VR video content creators often shift to 180-degree content by limiting the field of regard to avoid rendering content beyond the user's starting FOV. Some applications do not require a large FOV. For example, in a one-on-one conversation, a person rendered across a desk does not take up much space in a user's visual field. On the other hand, scenes designed to inspire awe, such as a virtual moon landing, benefit immensely from the increase in spatial presence depicted by a large FOV (Brown, Bailenson and Hancock, 2023[20]).

Stereoscopic rendering refers to rendering a scene twice so that each eye receives a slightly different virtual camera location, similar to how humans see in the real world. Most virtual reality designers consider stereoscopic vision – that is, seeing depth – to be one feature that truly sets VR apart from other media. However, people rely on stereoscopic vision primarily for objects nearby (i.e. within a range of about 6 metres) (Ono and Comerford, 1977[21]). Stereoscopic vision is critical for some use cases, like trainee surgeons learning to use scalpels and sharp tools on a body. However, for scenes with critical content in the distance – for example, an educational demonstration of the solar system – seeing depth is not as important.

Update rate (how often a scene is rendered each second) and latency (how long a frame takes to render given one's tracked movement) are different constructs. However, they work similarly to contribute to the overall impact of VR. In general, the ability of a VR system to render objects and scenes quickly increases presence, and this is most readily seen in a high-latency environment (Waltemate et al., 2016[22]). Reducing latency and increasing the update rate are important for reducing simulator sickness, one of the main downsides of VR (see subsection on downsides and risks).

Image quality combines several technological features that contribute to the general quality, realism and fidelity of visuals in VR. There are several ways to improve image quality, including screen resolution, flicker rates, lighting types and texture mapping quality. Improving the general level of detail also increases the number of polygons, which allow objects to have smooth portions and not appear as if they are made of blocks.

The VR ecosystem is complicated as one can only do so much, technologically, on a device worn comfortably on the head. This is especially true with standalone VR that does not link to an external computer or cameras. The features discussed above are necessarily zero sum and so trade-offs are important.

The choice of headset has consequences. A headset with high resolution and a wide FOV could maximise the visual awe or scale of a scene. However, such headsets will usually have high latency. If computers are rendering large and complex scenes, they cannot render as often (i.e. lower update rate) and take longer (i.e. higher latency). Consequently, visual fidelity trades off with the naturalness of navigating through the experience.

Scenes in which users naturally look around frequently are often more effective with headsets that maximise low latency and a high update rate, as opposed to the size and quality of an image (i.e. FOV and resolution). More elaborate tracking – for example, large spaces to walk in and hand and feet tracking for self-avatars – adds value to a scene in terms of presence at the expense of scale and ease of use. Consider a situation in which 30 students are using VR in a classroom. There is no space for all of them to walk around with room-scale VR simultaneously. Instead, teachers tend to use "3DOF" VR, which only tracks and renders head rotations. In this way, the students can sit in their chairs and look around.

Many believe that VR has not become more mainstream due to hardware limitations. However, most VR headsets cost about half as much as a typical smartphone. Researchers point instead to the lack of engaging content specific to VR (as opposed to a 2D screen) as the reason for low adoption rates (Mado et al., 2022[23]). Unlike typing a social media post or recording a video, which anyone can do relatively quickly, building a successful VR scene is difficult. Moreover, as the hardware system increases in complexity, it becomes more challenging for users to learn the system and for physical spaces to support multiple users concurrently.

Touch and smell are complex to render in VR

For sight and sound, the cycle of tracking and rendering is straightforward – objects are rendered bigger and louder when one approaches them. However, touch and smell are more complex. The tactile output of a user's VR experience is typically rendered by simple vibrations in a user's hand controllers. In a VR experience in a coral reef, for example, users receive a slight vibration in their hand when they reach out in the physical world to "touch" the place where a piece of coral is rendered spatially. In this sense, touch in virtual reality can contribute to the overall realism of a VR experience (Kreimeier et al., 2019[24]).

Scholars have also studied interpersonal virtual touch, which is enabled by the networking of multiple haptic devices[2] to allow two people to touch each other (Bailenson and Yee, 2008[25]). For example, when two avatars touch hands, each hand controller can vibrate simultaneously to provide a haptic representation of the mutual grasp. Studies have shown when people can touch one another – like shaking hands virtually – they like one another more than in social interactions without touch (Bailenson and Yee, 2007[26]).

The sense of smell is compelling when rendered in VR. One of the most researched use cases of smell is exposure therapy for soldiers with post-traumatic stress disorder (PTSD) (Herz, 2021[27]) (see subsection on mental health). Specific smells, such as diesel fuel, can act as a trigger for traumatic events. Therapists can use those triggers to help patients develop skills and strategies to undo the associations between particular smells and trauma (Mozgai et al., 2021[28]). Over the past few years, olfactory devices have become portable. They are now light enough to attach to the bottom of a head-mounted display.

The benefits and opportunities of VR

VR is most often associated with the entertainment industry where it has achieved modest success.[3] However, VR has more potential if developed and used responsibly. This section presents a framework, based on decades of research, that guides people for when to choose VR over 2D technologies. The DICE framework helps identify experiences for VR that would be "dangerous", "impossible", "counterproductive" or "expensive" in the real world. Training firefighters, rehabilitating stroke victims, learning art history via sculpture museums, and having a visceral, perceptual experience of the Earth's future to understand climate change, for example, all fit squarely in DICE. Alternatively, checking e-mail, watching television and general office work do not earn their keep in a VR headset. Such applications work far better on 2D screens. By not putting such use cases needlessly in VR, society can avoid some of its challenges (see subsection on downsides and risks). Instead, research should focus on areas where VR is transformational and clearly the best fit for the job.

This section focuses on five areas that epitomise the DICE framework: Teaching empathy; using VR as a tool for medical rehabilitation; interventions to improve mental health; corporate training; and VR digital twins. These use cases are chosen for two reasons. First, they all use VR to solve hard problems in the real world, as opposed to simply doing something "cool" with technology. Second, they have already demonstrated their ability to scale. These five areas have all demonstrated how VR can be used in an applied context and extended that application to thousands of people around the world.

Teaching empathy

Doing something in VR that is impossible in the real world – to occupy another body – is a classic DICE use case. VR allows people to experience the body of another person from a perceptual standpoint. Perspective-taking tasks can more effectively promote empathy, improve attitudes and increase prosocial behaviours than less immersive tasks such as watching a video or reading a story. For example, previous studies have asked participants to take the perspective of people with schizophrenia (Kalyanaraman et al., 2010[29]) and the elderly (Yee and Bailenson, 2006[30]) through VR. Other studies have had people transform virtually into animals to understand where beef comes from (Ahn et al., 2016[31]) or cut down virtual trees to feel the consequences of not recycling (Ahn, Bailenson and Park, 2014[32]). VR is uniquely able to enhance understanding of marginalised groups and produce changes in attitudes and behaviour that can last months after the VR experience (Herrera et al., 2018[33]). Such experiences can facilitate the sense of ownership and identification with an avatar even if the avatar does not look like a user's body.

Academic studies of VR and empathy are gaining a foothold in corporations. Sprouts Farmers Market, a US retail chain with about 35 000 employees, created a set of VR experiences to exemplify their core values, some of which were related to empathy. For example, an employee might teach an anxious mother how to buy gluten-free food for her child or deliver a watermelon to an elderly sick customer who cannot drive to pick up his favourite food.

Instead of teaching rules about empathetic behaviour, Sprouts Farmers Market implemented an "Exemplar Model" (Smith and Medin, 2002[34]). Such a model highlights salient experiences that are different on the surface but which all show empathy. These work in tandem to build a particular view of the world organically. In one study, a subset of about 300 employees was tested on its conceptual understanding of the firm's core values. Half were trained through VR, while the other half took PowerPoint training (Bailenson, 2020[35]). Of those trained through VR, 48% learnt all six concepts perfectly, compared to only 3% of the trainees who learnt through PowerPoint.

Another example of VR empathy at scale is the film "Clouds over Sidra". Produced in part by the United Nations, "Clouds over Sidra" is an 8.5-minute, 360-degree immersive film. It takes viewers inside the Za'atari refugee camp in northern Jordan, which was then home to over 80 000 Syrians displaced by civil war. The user hears a young girl named Sidra describing the camp, where she explains that her family lives in a small, converted shipping container. The film has been heralded as one of the most effective pieces of VR content ever made. According to the United Nations, the film doubled the number of people who donated to relief efforts for Syrian refugees (Gaudiosi, 2016[36]).

Medical rehabilitation

Medical rehabilitation can be expensive, and a home VR system can often replace a visit to a physical therapist, improving both comfort and efficacy. Therapeutic VR applications already exist to rehabilitate patients suffering from stroke, traumatic brain injury, cerebral palsy and more (Weiss et al., 2021[37]). Repetition and practice are important for the motor learning component of rehabilitation, and patients need feedback about the success of such repetitions. Additionally, participants must be motivated to practise movements, which are often painful or boring.

An early study used VR to rehabilitate motor performance in stroke patients (Holden, 2005[38]). This VR system trained patients how to perform a variety of arm movements to overcome stroke-induced deficits. A patient would practise activities to elicit movements, such as placing a letter in a mailbox. Motion trackers captured the patient's movements and provided feedback within the virtual simulation on how to improve the trajectory. The system outperformed other types of rehabilitation in terms of the patient's experience, leading to improved motion in the real world (Holden, 2005[38]). A recent systematic review that describes 27 quantitative studies using VR in similar ways highlights consistently positive outcomes (Khan, Podlasek and Somaa, 2021[39]).

One promising area for medical rehabilitation involves transforming the virtual representation of physical movements. Scholars have researched how much effort is needed to act virtually by increasing the gain between participants' movements in real life and their avatars' movements in the virtual world (Won et al., 2017[40]). In other words, if patients bend a knee 20 degrees in the real world, they see their virtual avatar bend its knee 40 degrees in VR. The aim was to give the patients a "can do" visualisation, to let them see the gain in mobility that could be possible.

Psychologists call this "self-efficacy" – the idea that believing in a goal is essential to achieving it. Positive visualisation can be a powerful aid to healing. However, when a patient is suffering, it can be hard to overcome agonising pain to visualise good form in physical therapy. Still, early clinical results are promising (Won et al., 2015[41]), and using VR to show movements that are currently impossible for patients remains a unique benefit of VR.

Over the past few years, VR stroke rehabilitation has scaled beyond academia. For example, Penumbra medical devices implement a full body tracking system used by thousands of war veterans across the United States for rehabilitation (i.e. the REAL System) at scale (Bailey, 2023[42]). This use case epitomises the DICE guidelines, and patients are reaping huge benefits from just a few short sessions each week.

Mental health

Negative behaviours in digital environments are associated with mental health risks (e.g. cyberbullying and harassment), and they become potentially even more dangerous in immersive environments (Danaher, 2018[43]) (see also the Spotlight "Mental health in digital environments"). Phenomena such as presence, emotion and immersion mean that emotionally charged content, including violent threats, can make users feel the effects more deeply because VR goes beyond abstract words to present content in three dimensions (Cummings and Bailenson, 2016[15]; Cadet and Chainay, 2020[45]).

However, there is also evidence that VR can play a positive role in mental health. For example, clinical studies across the globe have examined the impact of VR in domains ranging from anxiety reduction and treating phobias to connecting people and decreasing social isolation. Over the past few years, a number of systematic reviews analysed the state of the field of research in mental health in VR (Cieślik et al., 2020[48]; Hatta et al., 2022[47]).

Exposure therapy is one of the most validated VR treatments for mental health. It has been defined as a scientifically proven psychological treatment developed to help patients confront their fears, decreasing avoidance to feared objects, situations or activities through desensitisation (APA, 2023[49]). There are many forms of exposure therapy. In vivo exposure refers to direct interaction with fears in the real world. Imaginal exposure refers to the vivid imagining of feared objects or situations. Today, the American Psychological Association explicitly lists VR exposure therapy as an evidenced-based form of this therapy to treat anxiety disorders.

Rothbaum et al. (1995[50]) produced the first evidence that VR was an efficacious treatment, demonstrating that VR exposure therapy could help patients overcome their fear of heights. In some ways, VR works like traditional in vivo exposure therapy because it elicits presence. If a patient is afraid of heights in the real world, then standing on the edge of a virtual building is scary in VR. Hence, it can be used to help treat this phobia.

VR in this context has four unique advantages. First, it drastically reduces costs. Treatment for fear of flying, for example, commonly involves a physical trip to an airport, spending time in a boarding area and eventually boarding the plane. Given today's airport security protocols, patients often need to purchase plane tickets for treatment, which is expensive. Second, VR allows the therapist to simulate extremely rare events, such as bad weather and turbulence, at the touch of a button. In so doing, the therapist can use VR to evoke the patient's fears in a way that is not possible in an actual flight. Third, with VR, the therapist can reduce a patient's exposure to experiences that are psychologically dangerous or potentially re-traumatising. If a patient fears driving across gorges, for example, the clinician can alter the height of the gorge, the speed of the car or the weather conditions. Finally, VR protects the patient against any risk of physical harm. In VR, for example, spiders do not actually bite and a flying object unleashed by turbulence on a flight cannot actually hit a patient.

In the years since Rothbaum's first study, a large body of work has focused on treating PTSD. In 2002, scholars used VR therapy to treat a first responder of the 9/11 World Trade Center attack who subsequently developed PTSD (Difede and Hoffman, 2002[51]). Traditional therapies relying on guided imagery techniques did not work for him. Through VR, he was gradually exposed to a virtual environment in which planes flew overhead and crashed into buildings, explosions occurred and skyscrapers collapsed. Following treatment, the patient reported a reduction in acute PTSD symptoms. This case illustrates how VR safely immersed a user in simulations of traumatic environments.

In the decades since, there have been hundreds of studies in this area. One meta-analysis, for example, examined the efficacy of VR for PTSD. It concluded VR outperformed conditions of controlled trials, and that positive effects remained after treatment (Wenrui et al., 2019[52]).

As with other uses of VR discussed in this chapter, academic work on PTSD shows it can successfully scale to the world at large. In 2007, Rizzo, Rothbaum and Graap (2007[53]) developed a VR exposure therapy system for veterans with PTSD that incorporated feedback from returning soldiers from the Iraq War Studies. Over the next few years, the treatment showed clinical efficacy. Today, a commercial system called Bravemind features exposure scenarios, including cities and villages modelled after actual ones in Iraq and Afghanistan (Rizzo et al., 2010[54]). Bravemind is in use at scale in clinics and veterans' hospitals across the United States.

Training

Training can be dangerous, expensive and the rare events that are often teachable moments are hard to replicate. Consequently, soldiers, surgeons and astronauts have trained for decades in VR (Bailenson, 2018[55]). People learn best by doing, and by getting feedback when they make mistakes. Thus, training for high-stake activities is a natural application of VR. For example, research shows that VR increases the confidence of trainee surgeons, improves their understanding of anatomy and gives them a low-risk arena to practise difficult surgical techniques (Paro, Hersh and Bulsara, 2022[56]). Today, thousands of surgeons are training in VR. Even consumer-grade VR helps them become more skilled and efficient at their jobs (McKinney et al., 2022[57]).

There are also academic studies on procedural training, with the literature mature enough to include several meta-analyses. One such analysis, for example, compares VR surgical training to other techniques (Su et al., 2023[58]). Findings generally support the advantage (or equivalence) of VR training to face-to-face training, the economic savings of VR and the decreased time needed to train with VR compared to traditional techniques.

Over the past decade, VR has expanded into corporate training (Bailenson, 2018[55]). "The Pickup Tower", one of the most frequently used corporate modules, is basically a large kiosk that lets customers pick up online orders. Walmart has trained over a million of its associates in this module. Trainees receive step-by-step instructions on how to operate the machine with immediate feedback when they make mistakes. Before the VR training module was developed, every employee spent an entire day training inside special stores. VR reduced training time to 15 minutes, as well as eliminating the time and expense of travel. Given that all Walmart associates in the United States need to train on The Pickup Tower, VR has saved over a million full days of work, while maintaining efficacy (Bailenson, 2020[35]).

Within the training realm, human resources have also adopted use of VR. A recent study examined methods of training bystanders to intervene properly in situations involving sexual harassment (Rawski, Foster and Bailenson, 2022[59]). The study demonstrated that practice scenarios for bystander intervention training were more effective with VR than with 2D video; VR allowed trainees to develop skills in a more realistic environment.

Since the development of the flight simulator in 1929 by Edmund Link, flight training has proven a perfect use case of VR. It checks all the factors in the DICE model, and continues to be the driving force for VR as a medium, both for businesses and consumers. Indeed, personal training is one of the most popular use cases of standalone VR (Eakin, 2018[60]). In one case, Walmart associates had been trained in emergency response to an active shooter. The training used a digital twin of the store and enabled associates to rehearse critical survival skills, such as how to hide, what to say to the shooter and to practise nonverbal behaviour. Some of these trainees were on the job during the 2019 mass shooting at a Walmart store in El Paso, Texas. According to Walmart CEO Doug McMillon, "lives were saved and seconds were gained" because of the training (Jenkins, 2019[61]). Those associates were not daily VR users, but the intense experience of training in VR had stayed with them.

VR digital twins

Some companies are focusing on VR digital twins to save time and resources. They use digital twins to model complex systems, often in urban planning, architectural design, manufacturing and training (Botín-Sanabria et al., 2022[62]). In a factory that never closes and where employees work continuous, alternating shifts, any real-world training of new workers would require shutting down operations. Digital twins allow for training without disrupting workflow.

There are two types of building techniques – modelling and capture. Modelling involves building a VR world, one asset at a time. For example, construction of a specific factory would require 3D modelling software or photogrammetry to build machinery, parts, workers and the accompanying sounds. These elements would then be assembled as if building a diorama.

Capture involves using special cameras to produce spherical video. Volumetric capture – which uses passive and active cameras to produce point clouds of scenes – allows for movement within a scene and renders realistic models. However, this is expensive, requiring dedicated rooms, stereoscopic video and other forms of video that can capture a scene "as is". For example, a spherical video creates a seamless 360-degree vista that can be seen by turning one's head around. While it has high resolution, and is easy to record with a single camera, it only allows for a single viewpoint. For example, if a 360-degree video were shot from a factory assembly line, the viewer would never be able to look underneath a nearby table. Photogrammetry, which infers 3D structure by instantiating many different still images of the same object from alternate angles, is a robust technique. However, it does not work well in scenes with movement, such as a conveyer belt that has many people working around it.

Elizabeth Baron's work at Ford Motor company (Baron, 2009[63]) offers one of the best examples of digital twins. Baron's lab used VR to test how drivers of various ages responded to digital twin car prototypes. Their test results guided car designs to make entry and exit easier for older drivers. Additionally, Ford wanted to understand how the shape of windshields affects driving distractions. For example, how does the shape of the windshield affect how drivers react to attention-grabbing views? Using VR, Baron's team designed windshields that minimised distraction and improved driving performance. Because VR testing does not produce actual physical damage, it allowed Ford to run experiments that would be impossible otherwise. For example, it tested a life-saving system that detects when one's car is drifting into another lane. Such a test in the real world obviously presents safety risks. However, using a digital twin, scientists captured "naturalistic" driving behaviours without risk.

The downsides and risks of VR

A virtual experience powerful enough to alter psychological well-being and empathetic views towards other people and cultures must also have downsides and risks. This section reviews five unique concerns associated with VR that go beyond those involving 2D digital environments: privacy, particularly around the tracking of body movements; cognitive development of children; simulator sickness; distracted driving; and overuse and addiction. They were chosen for two reasons. First, they all have academic research behind them to help guide policy makers. Second, they are unique to the technological features of VR discussed above.

Privacy risks

VR magnifies privacy risks associated with Internet-connected devices, including the Internet of Things (IoT), and extends them in new ways. VR technologies and their applications are developing at a fast pace. The unprecedented collection of data directly related both to users' environment and their bodies creates even higher risks for the fundamental rights and freedoms of individuals. This is exacerbated by the need for sensors such as cameras (see above) in VR. In other words, blocking cameras – as one might do on a laptop – is impossible in VR.

As a key negative impact, privacy and data protection regulators foresee the constant surveillance of users' interactions, where privacy invasion becomes the norm, including for both direct users and bystanders (European Data Protection Supervisor, 2022[64]). Another impact is the risk of ever deeper profiling that enables the targeting of individuals at a granular level. This is coupled with the unprecedented monitoring of real-time sensitive data like physiological responses, emotions and biometric data (Kim, 2022[65]).

VR technologies routinely record personal data regarding people's location, social ties, search queries and product preferences which, combined, can identify people in detail. Such combined data can already be considered sensitive because of inferences that can be drawn about people (e.g. their health, sexual preferences or religious beliefs).

In VR, the collection of data generated by the person's environment or bodily behaviour amplifies the risks associated with creating detailed profiles of people. Such data relate to the functioning of the body, including verbal communication. However, they also relate to emotions (e.g. inferred from facial expressions and vocal inflections).

Data are collected about nonverbal behaviour, such as a user's posture, eye gaze, gestures, facial expressions and interpersonal distance. Some of the most popular VR systems in use track body movements 90 times per second to display a scene appropriately. High-end VR systems record 18 types of movements across the head and hands. Consequently, spending 20 minutes in a VR system generates just under 2 million unique recordings of body language.

Nonverbal behaviour is largely automatic, and can be used to infer medical conditions, emotions and a person's identity (Miller et al., 2020[66]). Although people can regulate images and text posted on social media, few can consistently regulate their body size, as well as subtle micromovements and gestures such as sidelong glances or genuine smiles. In this sense, nonverbal data are uniquely telling about an individual (Ekman and Friesen, 1969[67]). A VR service provider arguably knows users more intimately than they know themselves.

Box 4.1. Tracking data: Actions speak louder than words

As VR has evolved, tracking data have grown exponentially. The computer vision sensors of leading standalone headsets rely on cameras on the outside of the headset, which film the physical room users are in and the people they are with. Many privacy policies (Meta, 2023[68]) associated with these headsets clearly state that headset manufacturers may use the imagery from the cameras, in part because tracking data are an essential part of VR.

Scholars have used VR tracking data for research for more than a decade. Early on, Rizzo and colleagues built a virtual classroom with students, a teacher delivering a lesson and distractions throughout the room (Rizzo et al., 2004[69]). There were more head movements tracked in children with attention-deficit/hyperactivity disorder (ADHD) than those who did not have ADHD.

Using a similar assessment paradigm, Jarrold and colleagues demonstrated that students with high-functioning autism spectrum disorder looked less frequently at other people in a VR experience than other students (Jarrold et al., 2013[70]). Won and colleagues used VR tracking data from students during a lesson to accurately predict test scores (Won, Bailenson and Janssen, 2014[71]). The body language of teachers and students during a lesson in VR accurately determined the subsequent test score of the student.

While aggregating and anonymising data generally help protect privacy, they work less well in the case of tracking data. Miller and colleagues tested the identifiability of users under typical VR viewing circumstances, with no specially designed identifying task (Miller et al., 2020[66]). In other words, they examined the tracking data of people doing standard VR activities such as watching 360-degree videos. They then removed the tracking files and used machine-learning algorithms to identify individuals from the set. Out of 511 participants, the system identified 95% of users correctly when trained on less than five minutes of tracking data per person. More recent work shows that length of time in a VR experience, and the frequency of VR experiences, are key elements to help identify users (Miller et al., 2023[72]).

Research on more than 55 000 users of the "Beat Saber" game showed that VR tracking data allowed individual identification of just over 94% of users (Nair et al., 2023[73]). This work also compared the identification accuracy of various biometric technologies (iris scans, motion data from VR and AR systems, fingerprints, face scans and speech). While iris scans were the most accurate at individual identification, motion data from VR and AR systems were rated in second place.

VR also raises issues around protection of biometric health data and other health-related data that are not managed through traditional patient-care channels such as hospitals and health care providers. New questions are emerging about whether and how entities offering immersive experiences should be prohibited from creating behavioural or emotional profiles of users and/or sharing them with others. Do such entities require limits on targeted advertising to minors or to recipients who may be vulnerable because of their gender, race or ethnic origin, or disability?

Simulator sickness

In the real world, the brain constantly assimilates perceptual cues. These include sights, sounds, vestibular cues (i.e. when people walk or move their head, the inner ear vibrates in particular ways) and somatosensory cues (i.e. the muscles in people's feet feel the floor as they walk forward). Humans have evolved by relying on these precise and unwavering perceptual patterns for hundreds of thousands of years. These cues work together in a specific way, and it is only in the last few decades that immersive technologies have presented the brain with a new perceptual challenge.

Simulator sickness occurs when the brain receives these cues in ways that are unnatural, often described as "sensory rearrangement" or "perceptual cue conflict". This phenomenon has been studied since the 1950s, beginning with early flight simulators (NATO, 2021[74]). Given the recent rise of immersive technologies that can trigger simulator sickness (e.g. VR, IMAX or four-dimensional rides), scientific work proliferated in the area. Simulator sickness is a subset of what most people understand as motion sickness. For example, seasickness happens typically because the brain is getting vestibular cues, but the eyes are not receiving changes in optic flow, especially when one is sitting inside of a boat. In VR, the eyes are often receiving optic flow, but there are no corresponding vestibular cues since viewers are stationary in their seats.

Symptoms of simulator sickness are typically measured by about 20 different physiological and psychological markers, including difficulty focusing, nausea, blurred vision, fullness of head, dizziness, vertigo, general discomfort, eye strain, sweating and burping. About one-third of all VR users experience some symptoms, and about 5% experience severe symptoms (NATO, 2021[74]). Individual differences such as age, gender and medical history can influence whether people will have simulator sickness. These symptoms are fleeting, but they are unpleasant. Removing the VR headset every half hour, good hardware (i.e. low latency and high update rate) and content that avoids the perceptual cue conflict described above can be an effective approach to minimise simulator sickness. At the same time, even in short durations, some people – like those who get nauseous in the passenger seat of a car – simply cannot handle VR at all.

Cognitive development and behaviour of children

The effects of long-term exposure of VR and other immersive technologies on the cognitive development of children is an important concern (Allcoat and von Mühlenen, 2018[75]). Others include whether VR differs from other media in how and whether it changes the perspectives and behaviour of children.

While academic research in this area is limited, the literature generally shows that VR experiences are stronger for young children than for adults (Bailey and Bailenson, 2017[76]). In addition, the effects of VR tend to be magnified compared to traditional media such as television. Young children are, for instance, notoriously susceptible to acquiring false memories when exposed to everything from verbal narratives to mental images to altered photographs. In a 2008 study, scholars tested how well children in preschool and early primary school could differentiate virtual experiences from real ones, both directly after exposure and one week after exposure to a VR experience (Segovia and Bailenson, 2008[77]). For instance, after giving children in elementary school a VR experience of swimming with whales, many formed "false memories". They believed they had physically been to SeaWorld to see an Orca as opposed to just seeing it in VR.

Another study examined the potential effects of VR on children's behavioural and cognitive responses (Bailey et al., 2019[78]). The researchers compared the effects of interaction with a virtual character on either a television screen or in VR. In a programmed simulation, 55 children ranging from four to six years of age could interact with a virtual character – in this case the loveable, furry blue monster Grover from *Sesame Street*. When compared to the non-immersive experience (i.e. watching Grover on a television screen), children in the VR experience showed significantly less inhibitory control. This was measured by their success in playing a game of "Simon Says" with Grover. At the same time, children who experienced VR were more likely to interact with, and give away real stickers to, the character in VR. This study suggests that VR elicits different behavioural responses from children than experiences with similar content on 2D screens, and that children may process VR content differently.

Given that more research on the effects of VR on children is needed, moderation in children's use of VR should prevail. Instead of hours of use, which might apply to other digital devices, usage could be measured in minutes. As far as content goes, a good rule: if parents do not want children to live with the memory of the event in the real world, they should not allow it in VR. Travelling to the moon is fine, but scary experiences will stay with them. Physical safety is another important factor for everyone but especially children. By definition, VR blocks out the real world. Therefore, children should be watched around sharp edges, pets, stairs, etc. Studies show that most children are delighted to play with VR and do not report sickness or injury. However, in these studies, children were meeting Grover from *Sesame Street* and were supervised in VR sessions that lasted only about five minutes.

Distracted driving

The notion that someone would drive an automobile while wearing a VR headset may sound extraordinary, but a number of companies are pushing towards this direction. The motivations range from entertaining passengers, who often read books or use other media for entertainment, to creating an "add-on" to a self-driving car similar to a car radio. Sometimes companies also promote the use of VR headsets for drivers.

In a recent collaboration, the car company BMW and Varjo, a VR headset producer, touted the ability of drivers to use VR headsets in automobiles in the same way that fighter pilots use virtual cockpits. In this way, drivers would see a computer rendering of their surroundings as opposed to light through a glass windshield. Consequently, information about traffic, temperature and speed could be projected onto the driver's FOV (XR Today, 2022[79]).

Faccio and McConnell (2018[80]) studied the impact of the AR video game Pokémon GO, where players navigate the real world by looking at a real-time camera feed that layers virtual objects onto the scene. While this is not technically a VR or AR headset, it is an important precursor to how people may use VR in cars. The authors show that Pokémon GO was downloaded 100 million times in the 148 days after the game was introduced. They then analysed just under 12 000 police reports of accidents in a single city to identify those caused by playing Pokémon GO, and projected the impact nationally. The authors concluded that playing Pokémon GO was associated with just under 150 000 car crashes during the study period, including just over 250 fatalities (Faccio and McConnell, 2018[80]). Since completion of the study, the popularity of this AR location-based game has remained steady. More than a third of all people who regularly play video games in the United States play Pokémon GO (Statistica, 2023[81]).

Overuse and addiction

VR is special because it is immersive, responds to natural body movements and blocks out the physical world to make the illusion that much more compelling. Yet these same qualities also make virtual temptations hard to resist. In the novel *Ready: Player One*, by Ernest Cline, the only refuge from a dystopian world is a massive virtual universe into which people retreat whenever they have a chance. VR is depicted in these and other stories as a place of ultimate escape, with disturbing consequences for the physical world. Based on contemporary media use patterns, retreat into a self-curated fantasy world no longer seems like science fiction (Steinicke and Bruder, 2014[82]). Imagine a world in which social media resembles the best party ever, and online gambling puts the player into the most exclusive room in Monaco. The constant availability of perfection in the virtual world could change how people engage with the real world.

There is a lack of research on the health consequences of prolonged VR use. In one study, a scholar spent 24 hours in a VR headset under carefully monitored conditions (Steinicke and Bruder, 2014[82]). In their paper, the authors indicate that, "Several times during the experiment the participant was confused about being in the virtual environment or in the real world, and mixed certain artefacts and events between both worlds." Of all the pressing needs within the research community, studying how prolonged VR use over months affects people physiologically and psychologically is paramount (Han et al., 2023[83]).

Experimental research has sought to quantify the effects of exchanging a desktop-based work environment with a VR-based environment (Biener et al., 2022[84]). In this study, participants worked either in a traditional office environment or in a VR environment for eight hours per day for five days straight. The results showed that people in the VR environment had lower ratings of usability in addition to non-trivial amounts of simulator sickness compared to the traditional office environment. Moreover, two participants in the study had to quit the experiment on the first day because of physical discomfort, including nausea and migraine headaches. However, those who continued in the VR condition showed a slight increase in their usability ratings over the week.

Governing VR

Fast-paced technological developments often race ahead of regulatory frameworks. Digital transformation is multi-faceted and complex, and a comprehensive and co-ordinated digital policy framework, such as the Going Digital Integrated Policy Framework (OECD, 2020[85]), is essential. Such a framework helps ensure that digital technologies are on balance a positive force for people and society. As VR becomes more widespread, policy makers need to consider if VR has unique characteristics. Does it require specific policy action or are existing rules governing digital transformation (e.g. privacy, digital security or competition) sufficient?

VR and other immersive technologies are at a tipping point. They are developed enough to clarify opportunities and risks, but policy can still shape their future development. Many countries increasingly recognise the need for a unified policy for VR and other immersive technologies, including the metaverse. G7 leaders have underscored that governance of digital transformation should reflect shared democratic values (G7, 2023[86]). While a technology-neutral approach to digital policy is important, this section considers how policy frameworks may need to be adapted – or complemented – to support a positive immersive future.

Policy action on VR and immersive technologies is focused on promoting the domestic VR industry

Policy initiatives on VR and immersive technologies more broadly are limited. Data from the *DEO 2024* Questionnaire suggest that any policy action is primarily focused on supporting development of immersive technologies domestically. For example, the "Digital Luxembourg" strategy includes a VR financing initiative.[4] Spain provides grants to promote projects using immersive technologies,[5] Germany funds immersive technologies programmes[6] and Korea has a "Metaverse Industry Promotion Strategy".[7] Meanwhile, Singapore's PIXEL Innovation Hub[8] includes a focus on VR and immersive technologies, and Finland promotes these technologies with its "National Metaverse Strategy".[9] The US CHIPS and Science Act, signed into law in 2022, directs the federal government to carry out a programme of measurement research in communications technologies, including VR and other "immersive technologies" (US Government, 2022[87]).

Belgium stands out as a country that has taken policy action in a particular sector – the education sector. Its "Action Plan Extended Reality" aims to integrate XR into technical and vocational secondary education. To that end, it promotes training on the use of XR and further development of XR in education. The plan involves co-operation with Belgian universities of applied science, which will help analyse the nature and effectiveness of the plan.[10] Pilot projects in certain Spanish provinces under "InnoVET XR" will encourage creation of new software and apps for technical and vocational education.[11] In the United States, a similar trend is emerging. In December 2022, US House Representative Lisa Blunt introduced the draft "Immersive Technology for the American Workforce Act". The proposed legislation aimed to fund use of immersive technology to train workers at community colleges and other educational centres, but it did not pass Congress (Davalos, 2023[88]).

Data from the *DEO 2024* Questionnaire also indicate that some countries are adopting VR and other immersive technologies to enhance public services. Austria is testing an application that uses AR to streamline customs inspections by overlaying digital information over a vehicle. Türkiye is leveraging immersive technologies within the cultural sector to promote interactive virtual tours of cultural sites and boost tourism. The United States has taken steps towards integrating AR to help screen passengers at airports, enhancing security while ensuring a smoother screening (Deloitte, 2021[89]). Furthermore, the regional government of Korea introduced the "Metaverse Seoul". The platform allows citizens to access various public services, such as filing complaints and talking to officials through avatars.[12] Finally, Luxembourg launched a "Luxembourg Megaverse" and the European Commission funds the development of "Citiverses", immersive environments that provide engaging experiences of policy processes (Hupont Torres et al., 2023[90]).

Spain actively promotes the integration of underprivileged groups, particularly women, in financing initiatives involving immersive technologies.[13] This is important considering studies that indicate women are more likely than men to experience discomfort while wearing VR (Stanney et al., 2003[92]; Munafo, Diedrick and Stoffregen, 2017[91]) and are less inclined to purchase VR headsets (Kommando Tech, 2022[93]). Australia also recognises the importance of designing immersive hardware with inclusive access in mind (Australian eSafety Commissioner, 2020[94]). Other policy makers are also indicating an interest in specific legislation on immersive technologies. For example, the European Commission has announced it will propose legislation "on virtual worlds, including the metaverse" (European Commission, 2022[95]).

Towards the development of "rights" or "principles" for VR and immersive technologies

Given the limitations of regulatory approaches to address issues arising in VR experiences (Dick, 2021[96]), scholars and policy makers have turned their attention to developing "rights" or "principles" for VR and immersive environments. In a July 2023 report, Japan advocates for fostering international common recognition of the metaverse and encourages the trustworthy use of metaverse technologies based on democratic values (MIC, 2022[3]). Researchers also argue that safeguarding equitable access and authenticity is crucial for VR and immersive experiences.

If VR and immersive environments will become the place where people will work, learn and interact, they should be accessible to all. The adaptability of VR hardware to diverse people and body types should be prioritised. As noted, many VR displays in the market do not provide a comfortable fit for women, leading to discomfort and nausea (Stanney, Fidopiastis and Foster, 2020[98]). This may partially explain why most intended VR headset purchasers are men (Kommando Tech, 2022[93]). Failing to make VR more accessible may widen digital divides. As a result, it is important to ensure equal and effective access to immersive environments, including women, people with disabilities and cultural minorities (Dick, 2021[100]; Heller, 2022[99]).

Some also argue that users should have "rights" in immersive environments that are protected (i.e. the right to "authentic" experiences). Most adults can recognise advertisements in the physical and digital realms as paid messages. However, in VR and other immersive environments, advertisers can undermine context by seamlessly blurring the lines between authentic experiences and those engineered for marketing (Rosenberg, 2022[101]). The "self-endorsement" possible in VR represents a new and powerful advertising strategy (Ahn and Bailenson, 2011[102]). As one approach, engineered marketing artefacts and people could be required to be visually and audibly different in immersive environments. This would enable users to perceive promotionally altered experiences as different from authentic ones.

Korea is at the forefront of developing principles for VR, announcing a set of non-binding ethical guidelines for the use and development of metaverse services in 2022.[14] The "Metaverse Ethical Principles" aim to provide guidance for developers and consumers based on three core values: self-identity, safe experiences and sustainable prosperity. These values advocate for individuals to have the autonomy to authentically embody their chosen identities (self-identity) and to enjoy immersive environments in a safe manner (safe experiences). Furthermore, the principles state every individual should have the right to benefit from immersive environments without being intentionally excluded, with these rights extended to future generations (sustainable prosperity).

To implement these core values, Korea proposes eight practical principles: authenticity, autonomy, reciprocity, respect for privacy, fairness, protection of personal information, inclusiveness and responsibility for the future. The authenticity principle, for example, encourages users to sincerely define their virtual identities and act truthfully towards them, recognising the impact of the virtual self on the real self. Similarly, developers are urged to enable users to present themselves as closely as possible to their real selves.

Data from VR applications bring new challenges to existing privacy frameworks

VR and immersive environments magnify privacy issues and extend them in new ways. Policy makers and relevant stakeholders, including privacy enforcement authorities, thus look to clarify the application of relevant privacy regulations to these new realities. To that end, they want to identify suitable mitigation measures, including technological solutions integrated into VR applications.

How do data sources, contexts and activities help identify and support the building of algorithms, privacy enhancing technologies (PETs) (OECD, 2023[103]) and policies that can protect privacy? By understanding what influences the accuracy of de-anonymisation techniques, researchers can develop more effective ways to limit risks to end-users. This can further enable development of privacy-by-design VR products, including PETs such as federated analytics and trusted execution environments (TEE)[15] (OECD, 2023[103]). TEE ensure data remain shielded from third-party applications by processing them within a secure environment on the device.

No policies target the unique data collected from VR applications and how they are used or shared. However, a growing number of privacy legal frameworks such as the EU General Data Protection Regulation (European Union, 2016[104]) already address biometric data and thereby apply to VR directly. Processing of biometric data in VR is commonly subject to reinforced obligations (e.g. user explicit consent or legal authorisation) depending on their purpose.

How can such definitions remain relevant over time? Certain provisions may prove to be too specific as technological developments overtake the law. For example, the Illinois Biometric Information Privacy Act in the United States applies to information based on "scans" of hand or face geometry, retinas or irises, and voiceprints. This definition of "biometric identifiers" does not explicitly cover the collection of behavioural characteristics or eye tracking, making its application to VR data uncertain (Berrick and Spivack, 17 November 2022[105]).

VR further creates a new dynamic for legislation that revolves primarily around consent. For example, a user cannot have a VR experience without consenting to the terms and conditions of the VR system. This, in turn, requires processing such data to ensure a realistic immersive experience. Given there is no way to "opt out" or "go incognito" in VR, new approaches will be needed to adequately protect the privacy of VR users.

Moreover, users may not fully understand how their highly personal data may be monetised. They may also not know about subliminal techniques or automated decisions that may cause harm (Barros Vale and Berrick, 2023[106]). This leads to questions about the relevance of consent-centric legislation that places an unfair burden of choice on individuals.

As another challenge, consent requirements commonly add to additional baseline requirements that include transparency, fairness, purpose limitation, data minimisation or storage limitation. Some of these principles may significantly constrain development of VR and other immersive technologies. In particular, the "data minimisation" principle (i.e. only strictly necessary data should be collected for the purpose to be achieved) embeds consent into the design of VR and other immersive technologies.

VR developers must also pass the test of "purpose compatibility". Biometric and tracking data, for example, can be used effectively for authentication (e.g. facial recognition data can make accessing password-protected websites easier). This can help protect young children by automatically detecting if they are using their parents' VR headsets. It can also improve medical care and rehabilitation (see above). At the same time, biometric and tracking data can identify people in a way that is not transparent (e.g. creation of a user profile for targeted advertisements) (Miller et al., 2020[66]).

User behaviour captured by tracking data has also been associated with medical problems (e.g. dementia or ADHD) (Cherniack, 2011[107]), raising questions about discrimination (e.g. by prospective employers and insurance companies). As VR moves from tracking via headsets to full body tracking, motion data will become even more predictive of a user's identity. Such risks of "function creep" raise new questions about whether and how entities offering immersive experiences should be prohibited from creating behavioural or emotional profiles of users and/or sharing them with others.

Another privacy issue emerging with VR is how to treat the "personal" data from avatars – a new type of actor in VR. In some VR applications, a user can create multiple avatars or personalities (so-called alts) with different identities. To whom do such "personal data" belong? How will identity theft of avatars be addressed (Madiega, Car and Niestadt, 2022[108])? At first blush, avatars might appear to engage in VR experiences anonymously. However, once a VR system correctly maps a user's name with tracking data, it becomes extremely difficult to re-anonymise a user (Bailenson, 2018[109]).

Defining who is a data controller and a data processor may also be difficult in VR and immersive environments (Madiega, Car and Niestadt, 2022[108]). A governance challenge shared with the IoT thus consists in clarifying the chain of responsibilities in VR among stakeholders ranging from device manufacturers and VR service providers to app developers, owners of the underlying algorithms and network providers. When will data be produced, collected and shared based on choices by such stakeholders and at what moments in the operation of the VR system? It can be challenging to demonstrate accountability, and the legal and ethical responsibilities in the case of errors, hackings or accidents may be far from clear. This chain of responsibilities can also be blurred by the applicability of other statutes, including consumer protection, non-discrimination, privacy, data protection and effective judicial remedies.

VR mental and physical safety must be carefully considered

While this chapter documents the positive effects of VR on mental health, negative behaviours in digital environments are associated with mental health risks (e.g. cyberbullying, harassment, overuse and addiction). Such risks may become even more dangerous in immersive environments (Danaher, 2018[43]) (see also the Spotlight "Mental health in digital environments"). Phenomena such as presence, emotion and immersion mean that emotionally charged content, including violent threats, can make users feel effects more deeply since such content is less abstract and more visceral. VR applications should include safety by design features that allow users to protect themselves from bad actors. For example, Meta's Personal Boundary prevents avatars in Horizon Worlds and Horizon Venues from getting within about four feet of each other (Tabahriti, 2022[110]).

In addition to possible mental health risks, careful consideration of physical harms from VR and immersive environments is also important. Policy makers may want to prioritise use of VR in cars and other moving vehicles. The safety challenges of moving vehicles have already become clear with the Pokémon GO game (see above), as well as the significant number of deaths due to smartphone use in moving vehicles. In 2021, distracted driving resulted in 3 522 deaths in the United States, and many individual states in the country have laws against texting and using a mobile phone while driving (US DOT, 2022[111]). With respect to drivers wearing VR or AR headsets that block out or otherwise impede drivers' ability to see the "real world", it is unclear whether advantages outweigh the risks.

Safety by design principles are likewise important in VR and other immersive experiences, including parental controls, age verification and content moderation (OECD, forthcoming[112]). Some immersive applications incorporate human and automated image review, automated chat filtering and rules, special chat restrictions, community reporting, and user and parental controls.[16]

More research on the effects of VR on children is needed, but in the meantime moderation should prevail. Frightening experiences in VR could scar children. Instead of hours of use, which might apply to other digital devices, usage for children should be measured in minutes. Physical safety is another factor especially important for children. As VR blocks out the real world, children should be supervised when using VR.

VR businesses have been self-regulating

In the vacuum of comprehensive policy by governments, VR businesses have developed their own guidelines. Valve, one of the largest marketplaces for VR games and experiences, has a minimalist approach to self-contained content moderation. It allows anyone to upload content to its Steam Store except for things that are identified as "illegal" or "trolling" (Steam, 2018[113]). As of April 2023, more than 4 500 VR applications were available for download on the Steam Store.

Meta is an especially salient example given its large market share – 80% in 2022 – of VR headsets. Its code of conduct (Meta, 2022[114]) condemns sexualising minors, cyberbullying, harassing, stalking, hateful behaviour, advocating violence, human trafficking, supporting terrorism, hate-based organisations and/or criminal groups, promoting or co-ordinating acts of suicide, and sharing intimate images of others without consent. Primary responsibility for enforcing these policies rests with VR creators and app developers.

Self-regulation matters depending on whether users are in a self-contained VR experience or a social VR experience. Meta's code of conduct applies to self-contained VR; content regulation in its social VR app Horizon Worlds is more robust. Meta enforces its code of conduct by temporarily or permanently suspending accounts primarily on the basis of human content moderation (Meta, 2022[114]). In some cases, Community Guides, who are humans paid to don headsets, maintain order and remove malicious users. In other cases, community members report unruly behaviour directly to the platform or remove players by vote.

VRChat – a company that began dedicated to VR (as opposed to 2D screens) – is another example of social VR moderation. However, it did not attempt to retrofit social media legacy standards. From its inception, VRChat focused on allowing people in a scene to eject bad actors from the virtual world by community vote. However, this is a cumbersome process that requires both identification of malicious intent and consensus from multiple parties in the environment. In practice, it is difficult to eject a bad actor via community vote (Freeman et al., 2022[115]). Exacerbating this situation, current social VR platforms are rife with underage children who circumvent the minimum age limit of platforms (Nix, 2023[116]).

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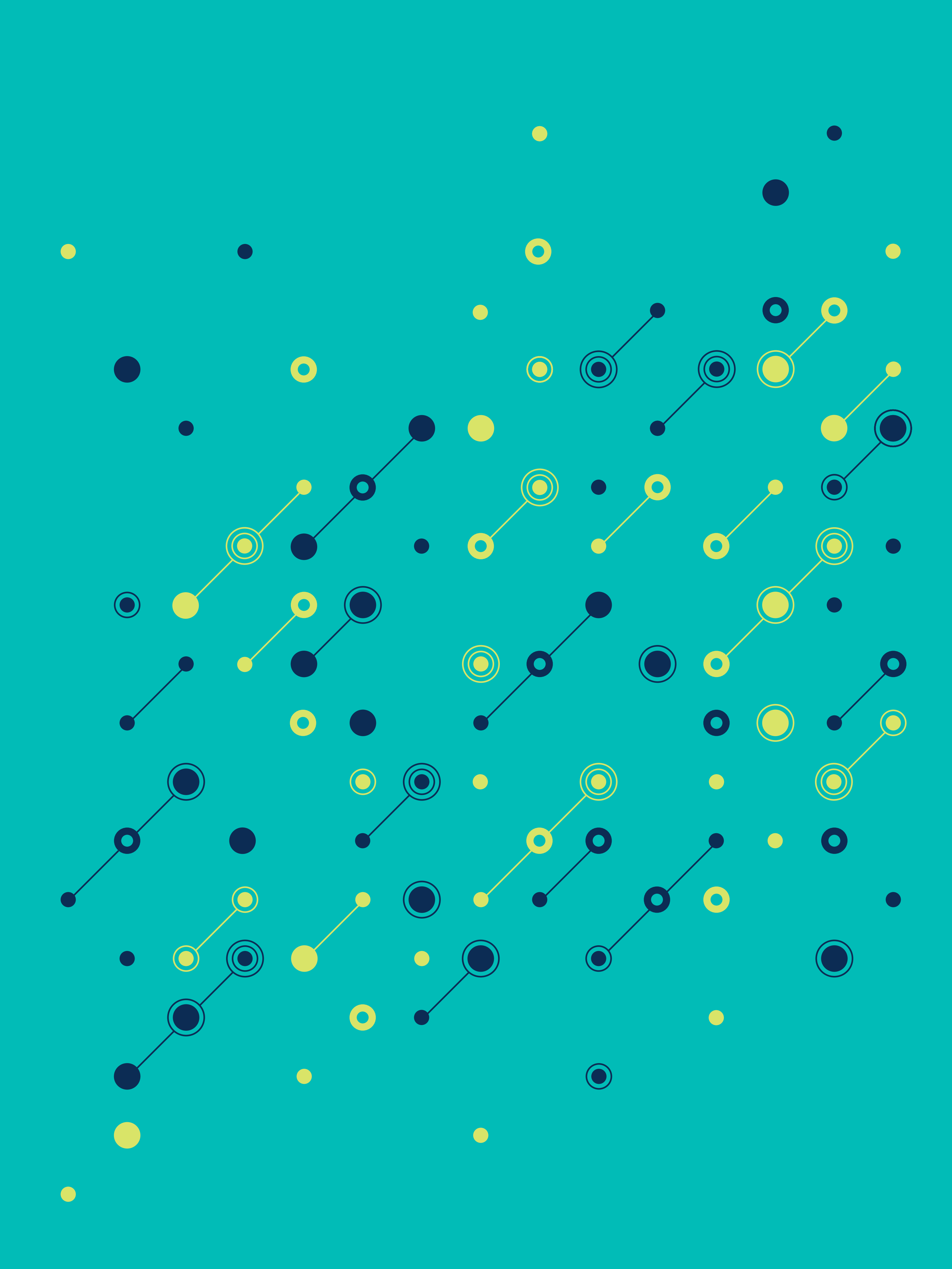
Notes

1. The Steam Store is a popular VR app seller.
2. Haptic devices simulate the experience of touch through vibrations or motion.
3. While some VR video games have achieved broad popularity, VR video games considerably lag 2D video games in terms of revenue. Overall total consumer spending on video games in the United States amounted to USD 56.6 billion in 2022 (ESA, 2023[121]). Conversely, Beat Saber, the best-selling VR video game in 2022, earned USD 255 million as of October 2022 (Bezmalinovic, 2023[122]).
4. For more information, see: *https://digital-skills-jobs.europa.eu/en/actions/national-initiatives/national-strategies/luxembourg-digital-luxembourg-initiative#:~:text=Digital%20Luxembourg%20is%20an%20ongoing,within%20the%20national%20tech%20sphere*.
5. For more information, see: *https://spainaudiovisualhub.mineco.gob.es/en/actualidad/publicada-convocatoria-metaverso-web3*, *www.red.es/es/actualidad/noticias/la-incubadora-de-empresas-del-sector-tecnologico-sobre-realidad-virtual-y* and *www.boe.es/boe/dias/2021/12/22/pdfs/BOE-A-2021-21192.pdf*.
6. For more information, see: *https://bmdv.bund.de/SharedDocs/EN/Articles/DG/mFund-overview.html*.
7. For more information, see: *www.msit.go.kr/bbs/view.do?sCode=user&mId=113&mPid=238&pageIndex=2&bbsSeqNo=94&nttSeqNo=3181303&searchOpt=ALL&searchTxt=%EB%A9%94%ED%83%80%EB%B2%84%EC%8A%A4*.
8. For more information, see: *https://pixel.imda.gov.sg*.
9. For more information, see: *www.businessfinland.fi/en/whats-new/blogs/2022/what-is-the-metaverse--humanitys-digital-future*.
10. For more information, see: *www.vlaanderen.be/kenniscentrum-digisprong/nieuws/ga-jij-binnenkort-aan-de-slag-met-xr-in-je-school*.
11. For more information, see: *https://onderwijs.vlaanderen.be/nl/onderwijspersoneel/van-basis-tot-volwassenenonderwijs/lespraktijk/extended-reality-in-de-klas*.
12. For more information, see: *www.seoul.go.kr/news/news_report.do#view/378498*.
13. For more information, see: *https://spainaudiovisualhub.mineco.gob.es/en/actualidad/publicada-convocatoria-metaverso-web3*.
14. The set of principles is the result of a research group to identify public awareness, experiences and concerns about the metaverse through a survey of 2 626 people aged 20-69 nationwide. Among the issues raised by the survey are unethical and anti-social behaviour, the digital divide, invasion of privacy and personal information, and potential restrictions on creative activities. More information about Korea's Metaverse Ethical Principles is available in *www.msit.go.kr/bbs/view.do?sCode=user&mId=113&mPid=238&pageIndex=1&bbsSeqNo=94&nttSeqNo=3182405&searchOpt=ALL&searchTxt=%EB%A9%94%ED%83%80%EB%B2%84%EC%8A%A4*.
15. An example is Apple's Vision Pro, where Apple affirms that federated Optic ID data remains encrypted, never leaving the user's device while being solely accessible to the device's TEE (the Secure Enclave processor). Furthermore, the system-level processing of data from cameras and sensors would eliminate the need for individual apps to access the users' surroundings, while still enabling spatial experiences.
16. An example is Roblox platform's safety features. For more information, see: *https://en.help.roblox.com/hc/en-us/articles/203313120-Safety-Features-Chat-Privacy-Filtering*.



Spotlight

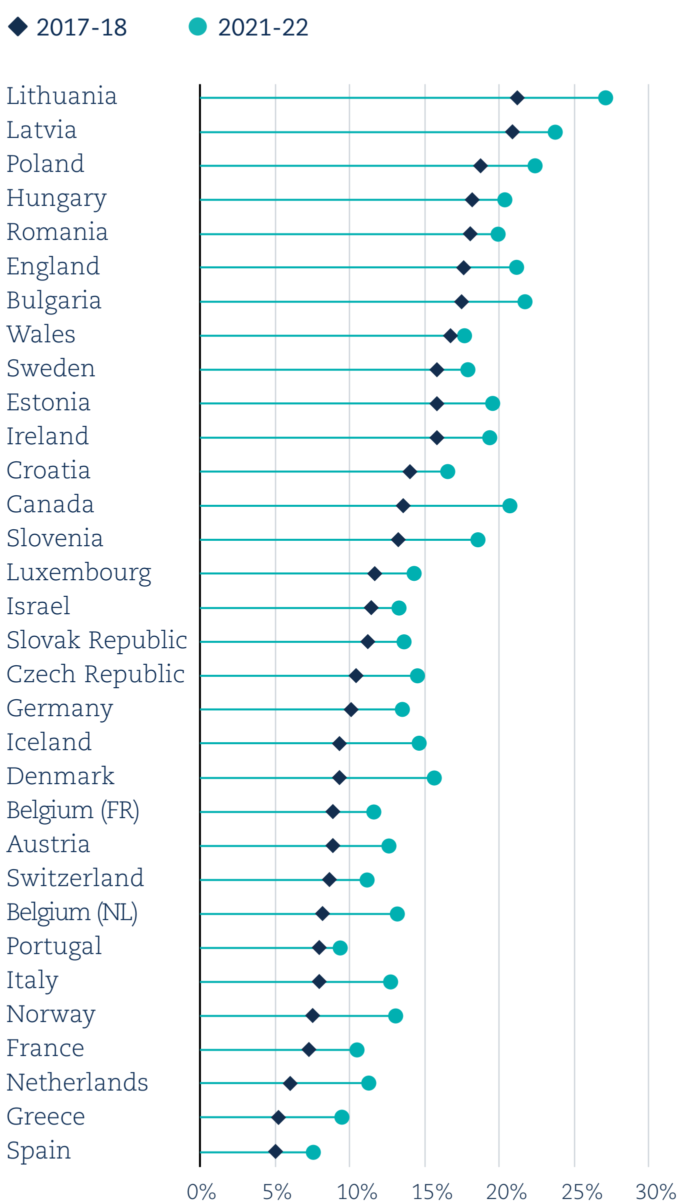
Mental health and digital environments

Digital technologies have dramatically changed how people live and communicate, bringing benefits and opportunities, as well as new risks, including for mental health. This Spotlight discusses features of digital environments that help explain why people communicate and interact differently on line, including anonymity, disembodiment and disinhibition. It reviews negative behaviours associated with mental health problems, focusing on cyberbullying, excessive or problematic Internet use (PIU), and problematic social media use (PSMU), and how immersive technologies may magnify their effects. It shows that negative behaviours in digital environments are on the rise and they disproportionally affect girls. The Spotlight concludes with an emerging policy agenda to harness the opportunities and minimise the risks of digital and immersive environments for mental health.

Negativity online is rising and affects girls more

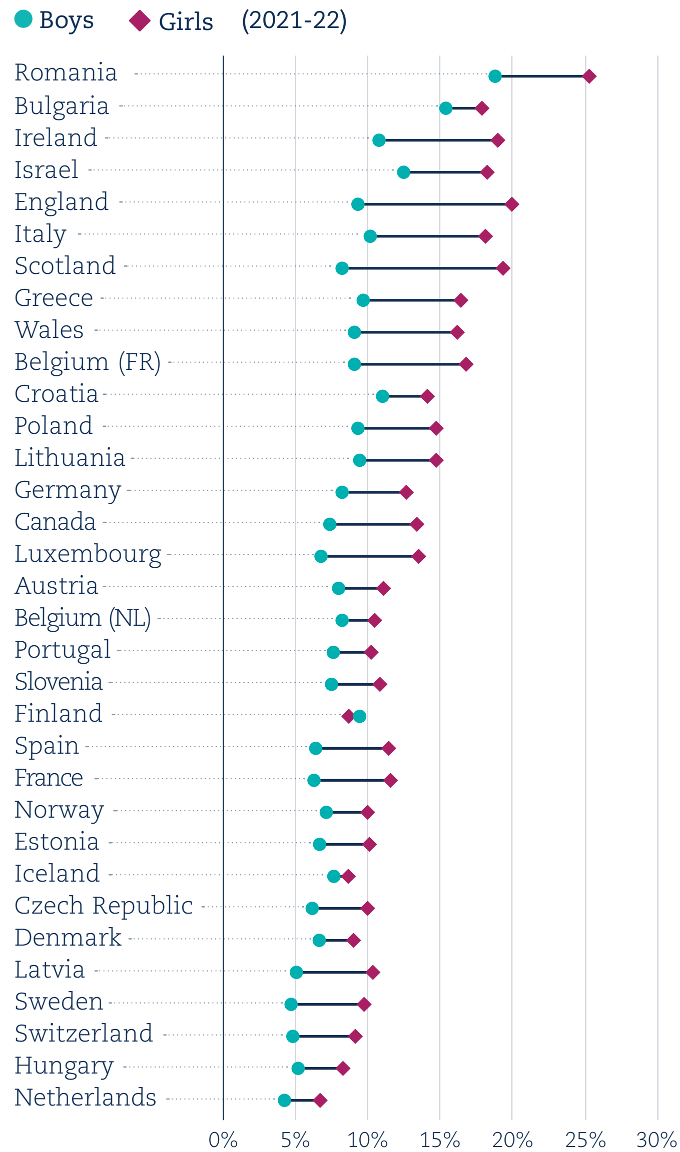
Cyberbullying of young people is increasing.

(11-15 years of age)



Girls are more often problematic social media users than boys.

(11-15 years of age)



Across 37 countries and regions, young people reported an increase of

49%

in problematic social media use between

2017 ⋯ 2022

Source: OECD based on the WHO's HBSC study.

As the use of digital technologies intensifies, the way people communicate and behave changes. Advancements in artificial intelligence (AI), big data analytics and immersive technologies, coupled with the COVID-19 pandemic, have accelerated digitalisation worldwide. While the evolving digital environment brings important benefits and opportunities for developing healthy, productive and fulfilling lives, it also creates new risks and potential dangers to mental health (Büchi, 2021[1]).

While disentangling cause and effect is challenging, the risks of digital and immersive environments for mental health raise important questions. Public health authorities and the international policy community have identified concerns about online victimisation and cyberbullying, particularly for youth, as a significant risk by (OECD, 2021[2]). Recently, both the United States Surgeon General and the American Psychological Association have warned about the risks of social media for mental health, including cyberbullying and PSMU (APA, 2023[3]; OSG, 2023[4]).

This Spotlight discusses the features of digital environments that help explain how people communicate and interact on line. It reviews some of the related negative behaviours associated with mental health problems, focusing on cyberbullying, PIU and PSMU. It considers the unique features of immersive environments and how they may affect mental health, and it explores data available on the prevalence of cyberbullying and PSMU. It concludes with a policy agenda to harness the opportunities and minimise the risks of digital environments for mental health.

Anonymity, disembodiment and disinhibition help explain why people communicate and interact differently on line

Digital environments provide new ways to communicate and interact, allowing people to establish relationships and have experiences that would be impossible off line. However, societal norms and physical constraints are different in digital and physical environments. Three features that help explain why people communicate and interact differently on line are anonymity, disembodiment and disinhibition (Suler, 2004[6]; Whitty and Young, 2017[5]). These features of digital environments can lead to feelings of happiness and strengthen mental health. Yet they can also enable negative behaviours like cyberbullying, PIU and PSMU that are associated with mental health problems.

Anonymity is a common feature of many online activities and interactions. Anonymity may positively affect mental health by creating a free and safe space for people to express their opinions and explore different aspects of their identity without fear of judgement or criticism. In the same vein, allowing people to choose what aspects of themselves to keep anonymous has been shown to help some people share personal feelings they otherwise would not. It also allows connection to others with similar feelings or experiences, leading to greater perceived social support (Naslung et al., 2016[8]; Holtz and Kanthawala, 2020[7]). In addition, it can help marginalised people benefit from social and emotional support while remaining relatively anonymous (Ybarra et al., 2015[10]; Hawkins and Haimson, 2018[9]).

At the same time, anonymity poses risks. Feeling unidentifiable in digital environments can lead people to feel unaccountable and unresponsible for their actions, leading to impulsiveness, hastiness and carelessness (Terry and Cain, 2016[11]). The anonymity of interactions in many digital environments can also lead to feelings of moral disengagement (Kowalski et al., 2014[12]). Thus, anonymity can make it easier for people to engage in aggressive behaviours, such as cyberbullying (Wachs, Wright and Vazsonyi, 2019[13]) and trolling – the act of deliberately “baiting” people on line to provoke a strong reaction (Australian eSafety Commission, 2023[14]). These behaviours can enable conflict, emotional distress and anger.

Disembodiment is another important feature of digital environments. Disembodiment allows people to create identities and have experiences without being held back by physical appearance, age, occupation, location, ethnic origin or other factors influencing face-to-face interactions. The possibilities brought by the “disembodiment of the self” – the ability to create an online identity independent of physical features (Bessière, Seay and Kiesler, 2007[15]) – allow people to play with different identities in digital environments. This, in turn, raises concerns about the risk of the dissociation of identities (Whitty and Young, 2017[5]). A related question involves the creation of unrealistic beauty standards and how they affect mental health. The possibility to construct hyper-realistic bodies in the virtual world through avatars and filters have been associated with dissatisfaction with, and the distortion of, one’s body image, negatively affecting self-esteem (Park and Ogle, 2021[16]).

A third distinctive feature of digital environments is disinhibition, which refers to a lack of restraint in social interactions. While disinhibition may lead to benevolence and generosity, it is often linked to acts of psychological aggression, such as the use of hostile and derogatory language and the defamation of others’ reputations (Lapidot-Lefler and Barak, 2012[17]). The feeling of anonymity may contribute to disinhibition because it can lead to disregard for traditional social norms and rules. Reduced eye contact and personal visibility in digital environments can exacerbate disinhibition (Whitty and Young, 2017[5]), as well as the perception of reduced accountability for behaviours in digital environments. Online disinhibition is often linked to problems of cyberbullying, trolling and cyberstalking. Studies have shown that people in digital environments feel less constrained to express themselves and act differently than they would face-to-face (Wachs and Wright, 2019[19]; Wachs and Wright, 2018[20]; Wang et al., 2022[18]).

Cyberbullying, PIU and PSMU are associated with mental health problems

Since the early days of the Internet, parents, doctors and researchers have worried about the psychological impacts of computer-mediated communications and the potential risks they create for people's mental health (Kiesler, Siegel and McGuire, 1984[21]). Public health authorities and the international policy community have identified online victimisation and cyberbullying, particularly for youth, as a significant risk (OECD, 2021[22]). The literature does not use one consistent definition of cyberbullying. However, cyberbullying is generally associated with three main features: repeated, intentional aggressive behaviour; a power imbalance between perpetrator and victim; and use of online media. Early studies argued that cyberbullying was simply bullying in a digital environment, but researchers have noted that some features manifest themselves differently in digital environments. Repetition, for example, takes on a different meaning because cyberbullying acts can be disseminated widely. As a result, even if the perpetrator does not cyberbully again, the exponential effect of sharing creates a sense of repetition for the victim (Campbell and Bauman, 2018[24]; Gottschalk, 2022[23]).

Cyberbullying is related to decreased life satisfaction and several mental health problems, including depression and psychological distress (Hamm et al., 2015[27]; Brailovskaia, Teismann and Margraf, 2018[26]; Giumetti and Kowalski, 2022[25]). Notably, research suggests that cyberbullying may have a more pronounced association with mental health problems than face-to-face bullying (Baier et al., 2019[28]). Recent research indicates that engagement in digital self-harm, including self-cyberbullying, significantly raises the likelihood of suicidal thoughts and suicide attempts. Adolescents who engage in anonymous self-cyberbullying are 15 times more likely to attempt suicide (Patchin, Hinduja and Meldrum, 2023[29]).

Cyberbullying is mainly measured through self-assessments (Chun et al., 2020[30]). However, some alternative sources of data, such as victims' complaints, have become accessible and valuable in understanding the prevalence and impact of cyberbullying.[1] Some surveys ask people to indicate if or how often they have experienced cyberbullying within a specified time (e.g. during the past couple of months). While the results of such surveys are easy to understand, these measures have limitations. For example, they presume that people fully understand the components of cyberbullying and bias, such as response tendencies like acquiescence and social desirability.

Other surveys ask people to indicate if or how often they were involved in specific behaviours associated with cyberbullying. These surveys also make certain assumptions. They presume that people, when asked to indicate if and how often they have experienced cyberbullying, may be less willing to respond honestly because they do not want to identify themselves as a bully or a victim. They also assume people may indicate their involvement in specific behaviours associated with cyberbullying (Ybarra et al., 2012[31]).

PIU has also received growing attention. While there is no common agreement about PIU, most definitions point to difficulties in everyday functioning, interpersonal relationships and emotional well-being because of Internet use (Aboujaoude, 2010[33]; Spada, 2014[34]; Aboujaoude and Starcevic, 2015[32]). The notion of PIU is often associated with a variety of terms, including Internet addiction, excessive Internet use and compulsive Internet use. Numerous studies indicate that PIU is associated with hostility and mental health disorders. These include depression, anxiety, attention deficit hyperactivity disorder (ADHD) symptoms and obsessive-compulsive symptoms in adults and youth (Carli et al., 2013[37]; Masi et al., 2021[35]; Nguyen et al., 2022[36]).

The measures most frequently used to assess PIU are based on self-reported questionnaires. These include aspects such as loss of control, withdrawal symptoms, neglect of other activities, conflicts in interpersonal relationships and reduced sleep associated with using the Internet. Each measure has different criteria and cut-off points that determine whether a user is a problematic Internet user (Laconi, Rodgers and Chabrol, 2014[38]; Aboujaoude and Starcevic, 2015[32]). In practice, though, it is often difficult to disentangle PIU and underlying disorders (e.g. anxiety).

Since online communication through social media has become central in the lives of adults and adolescents, scholars have also proposed measures of PSMU. As definitions of PIU are broad and consider all uses of the Internet, including gaming and social media use, PSMU and PIU measures correspond. Thus, the same set of diagnostic criteria and self-reported questionnaires are used when measuring PIU and PSMU. A problematic social media user is identified when people report feelings including preoccupation, the wish to escape, deception, displacement and conflict because of social media use (Van Den Eijnden, Lemmens and Valkenburg, 2016[40]).

PSMU is consistently associated with attention deficits, sleep problems and feelings of exclusion in young people (Van Rooij et al., 2018[42]; Boer et al., 2020[41]; Dekkers and van Hoorn, 2022[43]). Studies also indicate that PSMU is associated with serious mental health problems, including depression, anxiety and stress (Raudsepp and Kais, 2019[46]; Malaeb et al., 2021[45]; Shannon et al., 2022[44]). One study suggests that fear of missing out, i.e. "concern that others are having rewarding experiences from which one is absent", is a factor that induces PSMU (Fioravanti et al., 2021[47]).

Immersive technologies bring new opportunities for mental health but can also exacerbate the risks

Immersive technologies have characteristics that enable hyper-realistic experiences, and make users feel like they are in another environment, transcending distance, time and scale. For example, "presence" – or the sense of communicating without mediation in virtual realities – is unique to immersive digital environments. In other words, someone experiencing presence no longer feels like part of an artificially constructed environment but rather part of the physical world (Tjostheim and Waterworth, 2022[48]). Another unique feature is the sense of embodiment – experiences with avatars or virtual bodies may feel like real bodily experiences. These unique characteristics of immersive technologies bring new opportunities for mental health (see Chapter 4 on virtual reality) but can also exacerbate the risks.

The hyper-realistic experiences made possible by immersive technologies have opened up promising opportunities for improving mental health. Health interventions using virtual reality (VR) have been successful as a supportive treatment for anxiety, phobias and other psychiatric disorders (Rus-Calafell et al., 2018[50]; Cieślik et al., 2020[51]; Segawa et al., 2020[52]; Hatta et al., 2022[53]).[2] For example, exposure therapy – which allows people to confront their fears in a safe space – has been shown to be effective at overcoming mental health problems (Carl et al., 2019[54]). In addition, these technologies allow for a real-time assessment of physiological indicators like heart rate, skin responses and eye movements. In so doing, they enhance the efficiency of health interventions by relating them to features of the virtual environment (Bell et al., 2020[55]).

The psychological and physical sensations produced by hyper-realistic experiences in immersive environments may also make the feelings they evoke more intense, amplifying the effects of negative behaviours in digital environments (Heller, 2020[56]). As with other types of digital environments, immersive environments enable people to communicate and interact. Thus, people face many of the same types of challenges, such as harassment, bullying and other negative behaviours. In immersive environments, users interact through avatars, which can both lead to new forms of harassment such as "embodied harassment", or harassment that occurs as users experience embodiment in social VR (Freeman et al., 2022[57]).

Research on negative behaviours in immersive environments is still at an early stage. One study found that hugging and cuddling between avatar bodies without consent is perceived as harassment in immersive environments, while they are considered to be positive behaviour in traditional online gaming (Freeman et al., 2022[57]). Another study found that users of one popular VR social app are exposed to negative behaviour, including cyberbullying, every seven minutes (Center for Countering Digital Hate, 2021[58]).

One concern from the emerging literature in this area is that gender-based, racial, ethnic, religious and homophobic targeting are common. Furthermore, the integration of generative AI and immersive technologies will speed up content creation. This facilitates the development of experiences that may encourage negative behaviour (Lorenz, Perset and Berryhill, 2023[60]; DataHub YouTube channel, 20 July 2023[59]). One study found that nearly half of female VR users (49%) reported experiencing at least one incident of sexual harassment, while 28% of men reported facing racist or homophobic comments (Outlaw, 2018[61]).

Evidence suggests that negative behaviours in digital environments are on the rise and they disproportionally affect girls

The associations between negative behaviours in digital environments and mental health are a growing concern. Numerous studies highlight their prevalence across countries and regions (Livingstone, 2013[65]; Hamm et al., 2015[27]; Inchley et al., 2020[63]; Smahel et al., 2020[64]; OECD, 2021[62]). While internationally comparable data on negative behaviours in digital environments are limited, evidence suggests that some demographic groups experience the Internet and social media differently.[3] This Spotlight analyses recent data from the Health Behaviour in School-aged Children: WHO Collaborative Cross-National Study (HBSC),[4] currently the most comprehensive cross-national study reporting indicators on cyberbullying and PSMU in youth.[5]

The latest HBSC data cover 44 countries and regions, including 28 OECD countries in 2021-22.[6] The data show an increase in the prevalence of PSMU and cyberbullying from 2017-22. Average rates of PSMU increased by 49%,[7] while victimisation (26%) and perpetration of cyberbullying (25%) also rose.[8] The data also show significant variation in the prevalence of cyberbullying and PSMU across countries and regions. In 2021-22, the prevalence of cyberbullying victims among boys was as low as 6% in Spain, while it reached 32% in Lithuania, Similarly, the prevalence of PSMU ranged from 4% among boys in the Netherlands to 25% among girls in Romania (Inchley et al., 2023[66]).

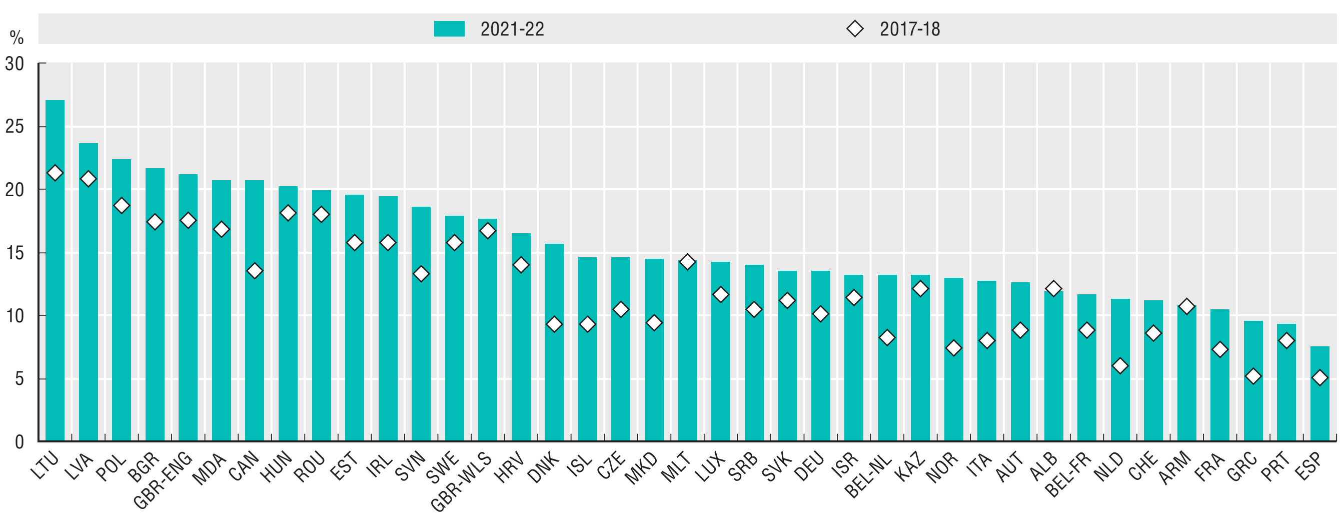
Cyberbullying is becoming more prevalent across countries, with girls experiencing higher rates than boys

Online and offline risks are interrelated. Negative behaviours off line, such as aggression, bullying and harassment, seem to carry over into digital environments. HBSC data from the 2017-18 for 11-, 13-, and 15-year-olds show that countries with the highest rates of bullying, such as Lithuania, Latvia and Türkiye, also emerged as countries with relatively high rates of cyberbullying. In most countries and regions, bullying victimisation rates were higher than cyberbullying rates, and boys were on average slightly more bullied than girls.

In the countries and regions analysed, the data suggest that, on average, cyberbullying is becoming more prevalent (Figure 2.S.1) and that girls are more cyberbullied than boys. The percentage of girls who reported being victims of cyberbullying at least once in the past couple of months was significantly greater than boys in more than half of the countries and regions analysed in 2021-22. Among OECD countries where girls were cyberbullied more than boys, the gap between cyberbullied girls and boys ranged from almost 1 percentage point in Norway to just over 6 percentage points in France.

Figure 2.S.1. Cyberbullying rates have increased in nearly all countries

Share of youth (11-, 13- and 15-year-olds) who report being victims of cyberbullying at least once in the last couple of months, 2017-18 and 2021-22



Note: Regional codes: BEL-FR: Belgium (French speaking); BEL-NL: Belgium (Flemish speaking); GBR-ENG: England; GBR-SCT: Scotland; GBR-WLS: Wales.

Source: Authors' calculation based on the Health Behaviour in School-aged Children: World Health Organization Collaborative Cross-National (HBSC) Study, 2017-18 and 2021-22.

StatLink https://stat.link/74jc3p

Boys are more likely than girls to cyberbully others. On average, 14% of boys aged 11, 13, and 15 years in 2021-22 said they had cyberbullied others at least once in the last couple of months,[8] compared with 9% of girls. Furthermore, in almost all of the countries and regions analysed, the rate of boys who reported cyberbullying others was greater than girls.

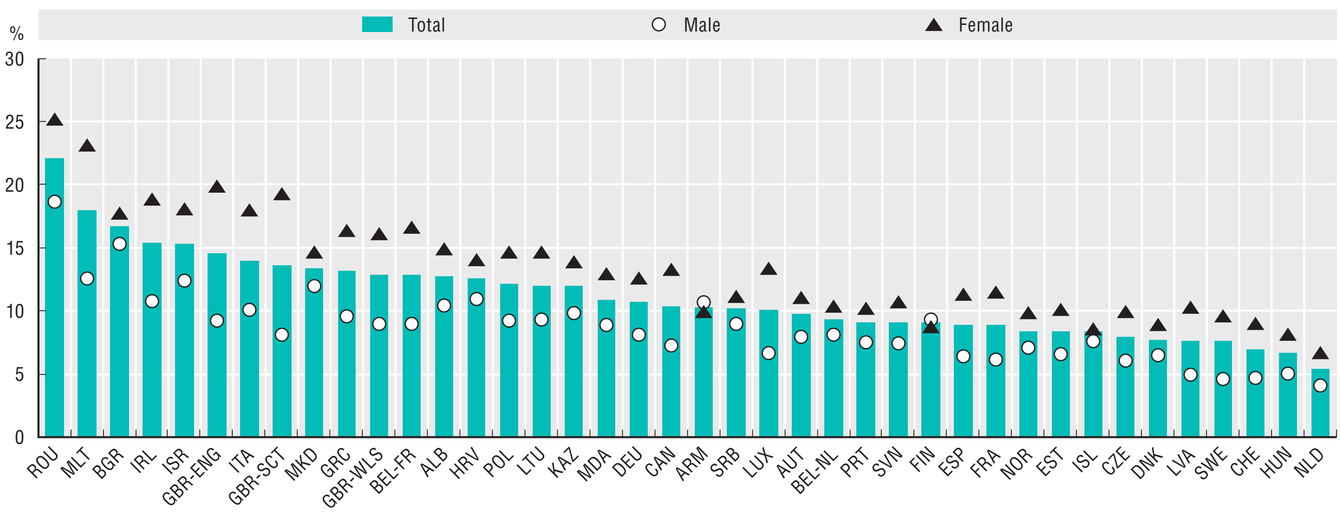
National safety centres that receive cyberbullying complaints may provide a complementary source of cyberbullying data. In Australia, for example, data from 2021-22 showed more complaints received about girls being cyberbullying victims (63.1%) than boys (31.8%) (eSafety Commissioner and ACMA, 2022[67]).

Girls are more likely than boys to be problematic users of social media and the gap is widening

Girls are more likely to communicate intensively with friends and others through instant messaging, social networks, e-mail and other forms of online communication than boys (Inchley et al., 2020[63]).[9] They are also more likely to be problematic social media users[10] than boys. In 2021-22, the rate of girls identified as problematic social media users was significantly higher than boys in almost 80% of the countries and regions analysed (Figure 2.S.2) and the gender gap is widening. In 2017-18, the average gap between girls and boys identified as problematic users of social media stood at 1.5 percentage points, and in 2021-22 this gap expanded to 5 percentage points. Among the OECD countries analysed in 2021-22, Ireland had the highest overall PSMU rate with a notable gender difference.

Figure 2.S.2. Girls are problematic social media users more often than boys

Share of youth (11-, 13- and 15-year-olds) identified as PSMU, 2021-22



Notes: PSMU = problematic social media use. PSMU was assessed through the Social Media Disorder Scale (Van Den Eijnden, Lemmens and Valkenburg, 2016[40]). Regional codes: BEL-FR: Belgium (French speaking); BEL-NL: Belgium (Flemish speaking); GBR-ENG: England; GBR-SCT: Scotland; GBR-WLS: Wales.

Source: Authors' calculation based on the Health Behaviour in School-aged Children: World Health Organization Collaborative Cross-National Study (HBSC) 2021-22.

StatLink *https://stat.link/6u1fmv*

Age may also affect how girls and boys experience social media. Girls are more likely to be problematic social media users as they become teens. Prevalence of PSMU rose from 5% at age 11 to 10% at age 15 among girls, while among boys, the overall percentage remained relatively constant (6% and 7%, respectively) (Inchley et al., 2020[63]).

Moderate use of digital technologies tends to be beneficial, but "overuse" may be detrimental

Time spent on line has increased, especially among youth, and sparked concerns about mental health and well-being (Bell, Bishop and Przybylski, 2015[68]; Twigg, Duncan and Weich, 2020[69]). One in three young people aged 11, 13, and 15 years are intensive users of online communications – that is, they communicate with friends and others on line via instant messaging, social networking or e-mail almost all of the time throughout the day (Inchley et al., 2020[63]).[11] Early theories suggested that exposure to technology was directly proportional to harm, referred to as the '"displacement hypothesis" (Neuman, 1988[71]). This is now seen as an overly simplistic view, given that online communication offers many benefits for mental health and well-being. For example, it provides opportunities to create positive communities around similar identities and interests, and enables social-emotional support from peers, especially for marginalised people (Kardefelt-Winther, 2017[72]; Ito et al., 2020[73]; Charmaraman, Hernandez and Hodes, 2022[74]).

More recently, the "Goldilocks hypothesis" (Przybylski and Weinstein, 2017[75]) has gained support. This hypothesis indicates a curved association between the use of digital technologies, mental health and well-being (OECD, 2018[76]). It suggests that a moderate use of digital technologies tends to be beneficial whereas "overuse" may be detrimental.

The relationship between the pervasive exposure to digital technologies, mental health and well-being is complex and bidirectional. To date, most evidence is correlational. Reviews of studies have found a mix of conflicting positive, negative and null associations (Seabrook, Kern and Rickard, 2016[79]; Odgers and Jensen, 2020[77]; Orben, 2020[80]; Alonzo et al., 2021[78]).[12] On average across OECD countries, 45% of students reported feeling nervous or anxious when they did not have their digital devices nearby. These students were also more likely to report lower satisfaction with life (OECD, 2023[81]). Recent data from Canada indicate that increased smartphone use is linked to worse mental health (Asselin, Bilodeau and Khalid, 2024[82]), and the frequency of social media use is positively associated with eating disorder symptoms as well as suicidal tendencies (Kerr and Kingsbury, 2023[83]).

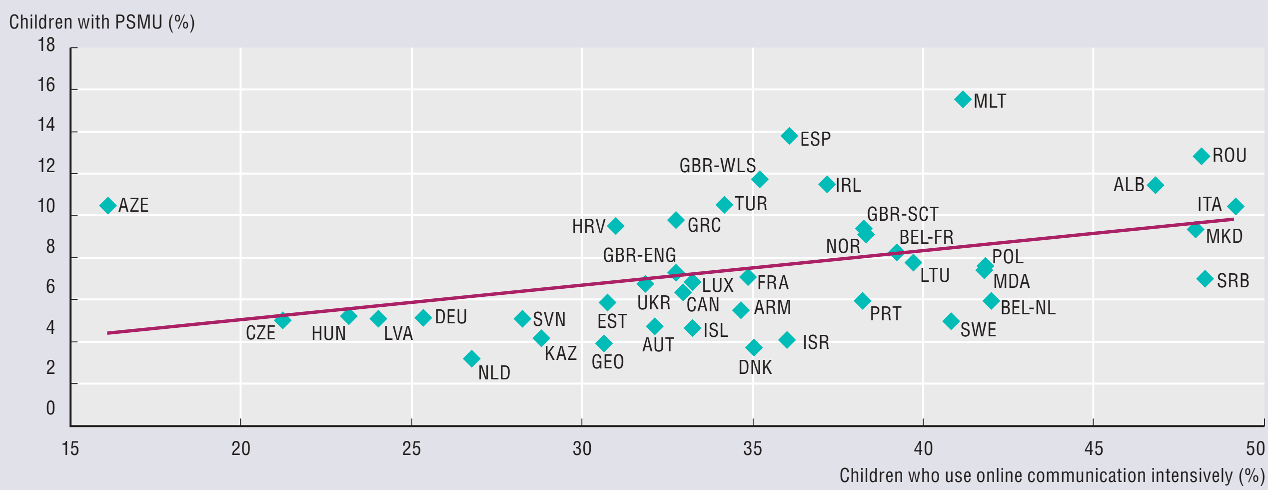
The use of digital technologies is not inherently harmful or beneficial as their impacts on mental health and well-being are likely to depend on many factors. These factors include the amount of time spent on line, the content consumed, the user's pre-existing vulnerabilities, and the cultural and socio-economic context (Hollis, Livingstone and Sonuga-Barke, 2020[85]; Prinstein, Nesi and Telzer, 2020[84]; Büchi, 2021[1]; Valkenburg et al., 2022[86]; APA, 2023[3]; OSG, 2023[4]). This complex and heterogeneous relationship is illustrated below (Box 2.S.1). The large variation in PSMU prevalence across countries at the same level of communication intensity suggests that other factors beyond time spent on line are at play.

Box 2.S.1. Is time spent on line associated with problematic behaviour?

Data from HBSC 2017-18 suggest that intensive users of online communication are more likely to experience PSMU, which is consistent with the "Goldilocks hypothesis". However, it is unclear whether the intensive use of online communication is a cause or a consequence of PSMU. Of youth who use online media intensively, 11% were classified as problematic social media users. Meanwhile, the prevalence of PSMU among those who use online media less frequently hovered around 5% (Inchley et al., 2020[63]). Countries with higher average rates of problematic social media users, such as Spain, also have higher percentages of users that use online communication intensively (Figure 2.S.3).

Figure 2.S.3. Evidence suggests that intensive use of online communication is associated with PSMU

Share of youth (11-, 13- and 15-year-olds) identified as PSMU vs. share of intensive users of online communication



Notes: PSMU = problematic social media use. Regional codes: BEL-FR: Belgium (French speaking); BEL-NL: Belgium (Flemish speaking); GBR-ENG: England; GBR-SCT: Scotland; GBR-WLS: Wales. The fitted line is based on an ordinary least squares (OLS) regression. The correlation coefficient between the share of youth identified as PSMU and who use online communication intensively is 0.16 (p-value<0.001, 222 865 observations). The R-squared value is 0.7.

Source: Authors' calculation based on the Health Behaviour in School-aged Children: World Health Organization Collaborative Cross-National Study (HBSC) 2017-18.

StatLink https://stat.link/k63pfr

This indicates insights can be gained from the experiences of countries with low prevalence rates of PSMU. It also confirms the need to collect longitudinal, more granular and beyond time-based data (e.g. activity or content-based) on digital technology use (Kardefelt-Winther, 2017[72]). Several authors recognise variation around average relationships. Embracing heterogeneity approaches is an important avenue to improve understanding in this domain (Parry et al., 2022[88]; Valkenburg et al., 2022[86]; Valkenburg, Meier and Beyens, 2022[87]).

Towards a policy agenda for fostering mental health in the digital age

As people spend an increasing amount of time on line, and digital environments become more immersive and "real", policy makers need to address the risks of digital technologies for mental health. Groups that may be disproportionally affected by negative behaviours in digital environments, such as girls, should be supported. As this is an emerging area, governments may lack formal initiatives to prevent and address mental health problems in the digital age. Thus, a policy agenda to foster mental health should be mapped. In this respect, several areas seem especially promising.

Raise awareness about negative behaviours in digital environments and promote media literacy

Public policies on awareness raising and promotion of media literacy are crucial to prevent and manage cyberbullying (Gottschalk, 2022[23]) and protect children in digital environments more generally (OECD, 2021[22]). Victims need to know that how they are being treated is wrong, and that they can safely report perpetrators of cyberbullying and other forms of online aggression. Awareness-raising campaigns can help victims and bystanders (e.g. family members, friends and teachers) recognise negative behaviours. They can then report cyberbullying or develop coping strategies, such as blocking unwanted contacts (McDaid, Hewlett and Park, 2017[89]). Promoting media literacy also has an important function in tackling PIU and PSMU (OSG, 2023[4]). Media literacy skills are needed to understand how to safely navigate the Internet and immersive digital environments.

Promote safety by design

Governments can foster safety by design for youth by encouraging development and use of technologies that protect privacy, safety and security, and that limit contact with and access to age-inappropriate content (OECD, 2022[90]). Firms increasingly embed user protections in their products and services to prevent and manage risks associated with negative behaviours in digital environments. Examples include mechanisms that block access to digital platforms after excessive use and AI-based filtering systems that flag negative messages. Immersive technologies can help develop mitigation mechanisms by preventing harassment. For example, some platforms allow for creation of invisible barriers around users, making it impossible to get within someone else's "personal boundary". Companies are also enabling parental control tools to limit content seen on line. Companies should analyse the impact of the design and functioning of their services, including their algorithmic systems, and be transparent about them. Public initiatives that support safety-by-design technologies can also promote mental health in digital ecosystems by minimising and addressing abusive behaviour.

Identify specificities of immersive environments that present risks for mental health

As immersive environments become common at home, school and work, policy makers must anticipate the potential benefits and challenges of these technologies to mental health. They must pay special attention to emerging debates about the need to adapt or develop new rules, regulations and approaches to deal with negative behaviours in immersive environments and the associated mental health risks. Public policies should consider gender differences in how bullying plays out in digital environments. They should focus on equipping vulnerable groups such as children, who are more susceptible to the influence of immersive experiences, with the skills to cope and adapt. Because immersive technologies are in the early stages of commercial adoption, this is a good opportunity to work constructively on the adaptation or development of regulations that allow positive and healthy online experiences. Public-private dialogue can help define rules that protect users, while also helping industry build trust in immersive environments.

Improve the evidence base on mental health and digital environments

The lack of a robust, cross-country comparable evidence base on mental health and digital environments is a challenge for researchers and policy makers. Establishing standard definitions is an important step forward. Many researchers have underlined, for example, the lack of consensus regarding definitions and measurement criteria for phenomena such as cyberbullying, PIU and PSMU (Laconi, Rodgers and Chabrol, 2014[38]; Chun et al., 2020[30]; Shannon et al., 2022[44]) and the associated mental health problems. Researchers could determine the prevalence of cyberbullying and PSMU with respect to gender, age and geographical region. This would help policy makers design and implement related policies and programmes, such as integrating cyberbullying and PSMU prevention measures, in educational systems and other relevant domains.

Engage in partnerships with a range of stakeholders to prevent and address negative behaviours in digital environments

Collaboration on mental health in general is a priority (McDaid, Hewlett and Park, 2017[89]; OECD, 2023[91], 2022[92]) and this is likewise true in digital environments. Responses to mental health issues associated with negative behaviours in digital environments depend on partnerships between governments, firms and non-governmental organisations. By exchanging insights on programmes and policies that have (and have not) worked to address negative behaviours in digital environments, policy makers can tailor their activities to best support mental health in digital environments. Sharing information on the effectiveness of programmes and policies can help inform development of well-targeted policies. It may also help increase public willingness to invest in mental health promotion and prevention. The European Union and Australia are already taking innovative approaches in this area; they have national and subnational bodies that co-ordinate initiatives to tackle negative behaviours in digital environments associated with mental health risks.[13]