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AI research and innovation: Europe paving its own way

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AI research and innovation: Europe paving its own way

Ana Correia and Irina Reyes (DG R&I)

Working paper

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ABSTRACT

Artificial intelligence is often referred to as one of the « game-changing » technologies of our time due to its potential to increase efficiency and productivity across sectors. The optimisation of processes and production could also minimize the consumption of resources such as energy, water and raw materials and hence contribute positively to achieving many of the sustainable development goals. However, the boom in AI applications in recent years has also shown the limitations of the current state of this technology when it comes to ensuring fairness in its algorithms and systems, as well as an ethical governance. The EU ranks among global leaders in AI Science, but its innovation performance in AI could be revamped. At the same time, the EU has been leading in promoting trustworthy, ethical and human-centric AI.

1 Introduction

Artificial Intelligence (AI) as a field of study is already 70 years old. In 1950, Alan Turing put forward the so-called 'Turing test' as a way of determining if a computer is capable of thinking like a human. John McCarthy, a computer scientist, then coined the term 'artificial intelligence' during a conference in 1955. Between 1955 and 1997 – when IBM's Deep Blue defeated Gary Kasparov, world chess champion – there were periods of progress in the field, often restricted to highly specific applications and notably in natural language processing and neural networks. However, there were also periods known as 'AI winters', brought about by overly big expectations, a lack of practical applications of AI and, ultimately, reductions in AI research funding. In 2006, developments in deep learning generated further enthusiasm around AI. Importantly, the rise of big data allied to greater cloud and computing-processing capabilities boosted numerous developments in the field. Nowadays, AI is not only present as a tool in scientific research and industry activities but is also increasingly in everyday life.

Although there is currently no established global definition of AI, a recent definition put forward by the High-Level Expert Group on AI, set up by the European Commission, is presented in Box 1. It includes the subdisciplines described in Figure 1, namely machine learning (and, within this category, deep learning and reinforcement learning), reasoning processes as well as intersections with robotics fields, for example, sensors.

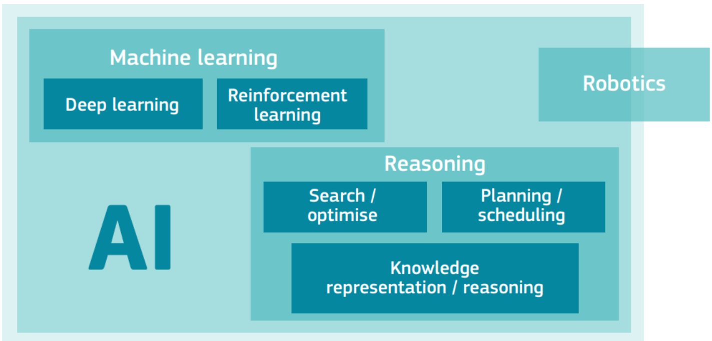
Box 1- Towards an AI definition

Artificial intelligence (AI) systems are software (and possibly also hardware) systems designed by humans that, given a complex goal, act in the physical or digital dimension by perceiving their environment through data acquisition, interpreting the collected structured or unstructured data, reasoning on the knowledge, or processing the information derived from this data and deciding the best action(s) to take to achieve the given goal. AI systems can either use symbolic rules or learn a numeric model, and can also adapt their behaviour by analysing how the environment is affected by their previous actions.

As a scientific discipline, AI includes several approaches and techniques, such as machine learning (of which deep learning and reinforcement learning are specific examples), machine reasoning (which includes planning, scheduling, knowledge representation and reasoning, search, and optimisation), and robotics (which includes control, perception, sensors and actuators, as well as the integration of all other techniques into cyber-physical systems) (see Figure 1).

Source: European Commission (2019), Report by the High-Level Expert Group on AI set up by the European Commission

Figure 1. A simplified overview of AI's sub-disciplines and their relationship



Source: European Commission (2019), Report by the High-Level Independent Expert Group on AI

Building on Chapter 7- "R&I enabling artificial intelligence" of the 2020 'Science, Research and Innovation Performance of the EU' report by the European Commission, this working paper presents an overview of the main trends worldwide when it comes to AI, and attempts to provide a picture of the EU positioning in terms of AI science and innovation. It is complemented by reflections on the main bottlenecks in the field, and the main policy developments that have contributed to creating a robust and human-centric approach for AI to flourish in Europe. The final section puts forward policy considerations and conclusions on the way forward.

2 Artificial intelligence: a potential game-changer for productivity and sustainability

2.1 *The importance of complementary intangibles*

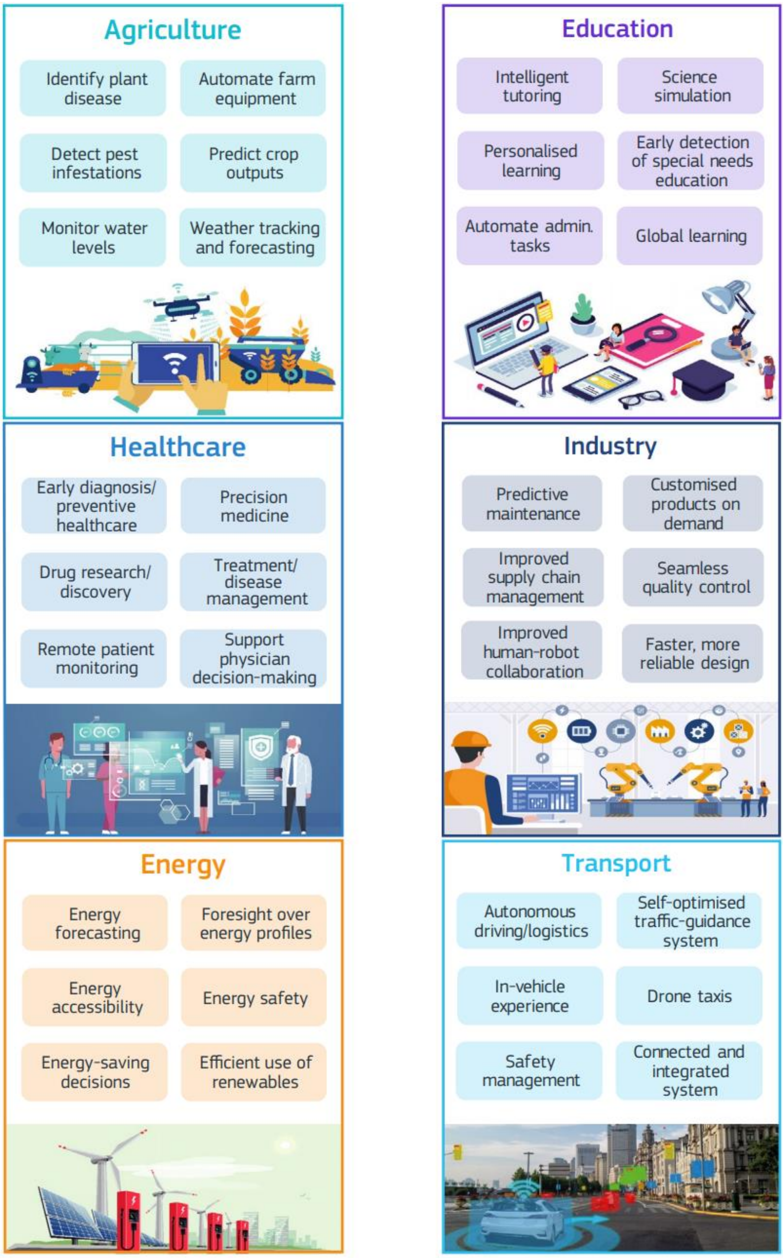
Achieving the full potential of AI for productivity depends on having in place the right complementary skills, infrastructure, and management culture. The fact that AI is seen by many as the ‘new electricity’ relates to its cross-cutting applications that make it a general-purpose technology capable of driving efficiency and productivity in virtually all sectors of the economy. By optimising operations and enabling accurate predictions, AI can also potentially be a powerful tool to help achieve the Sustainable Development Goals. However, while digital technologies such as AI hold a lot of promise for boosting growth and competitiveness, productivity growth remains lackluster. European Commission (2020) highlights potential explanations for this, notably the widening productivity gap between the most and least-productive firms due to insufficient innovation diffusion and the rising market concentration around ‘superstar firms’.

In the specific case of AI, Brynjolfsson et al. (2017) point to the time lag in implementing new technologies such as AI, or potential productivity mismeasurements following a ‘J-curve’ (Brynjolfsson et al., 2018). Moreover, AI investments depend on other complementary efforts and intangible investments that may take some time to materialise. These might include organisational and managerial changes and the need to acquire new skills or retrain staff, among others. The authors refer to the steam engine, electricity, and the internal combustion engine to argue that their impact also took some years (even decades) to be felt. Furthermore, AI can enable faster scientific discovery (OECD, 2018a) especially at a time when research productivity may be falling and new ideas seem harder to find, as highlighted by Bloom et al. (2017). Finally, AI can help increase productivity by helping humans use increased capabilities faster (i.e. towards ‘augmented intelligence’), and enabling more reliable forecasting, more flexibility in operations based on huge amounts of data, more precision, etc. On the other hand, automation entails risks as regards replacing many jobs and tasks as well as other issues related to the future of work (European Commission, 2020).

2.2 Cross-sector applications

As a general-purpose technology, AI applications can boost productivity, improve predictions, and contribute to greater energy efficiency in virtually any sector of the economy. Figure 2 provides some concrete examples of AI applications across different sectors of the economy. For example, in agriculture, AI technologies can better predict crop outputs and detect pest infestations. In healthcare, AI can contribute to drug discovery and early diagnosis. In industry, operations such as supply chain management can be optimised and quality control improved. In energy, powergrid optimisation can rationalise energy supply based on demand. However, AI applications also pose some risks or face certain obstacles. OECD (2019a) stresses that in agriculture the lack of network connections in rural areas may undermine the use of sophisticated systems, and high-tech farms may require costly investments in automation tools and sensors. In addition, in healthcare the data privacy of patients must be duly taken into account.

Figure 2. Examples of cross-sector applications of AI as a general-purpose technology to optimise operations and increase efficiency



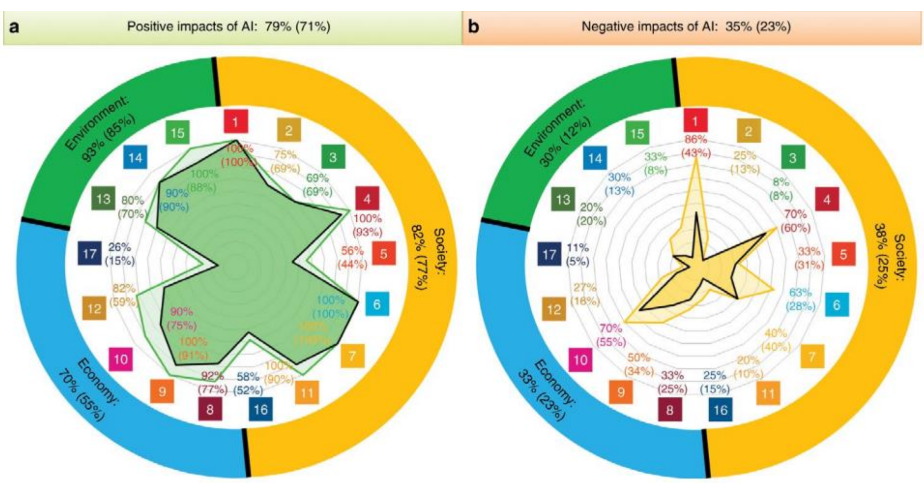
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Statista - AI report (2019), fao.org – State of food nutrition, futurefarming.com, Forbes - How Is AI Used In Education, European Commission (2018), PwC, Forbes with Intel – Sizing Up AI's Predictive Analytics Powers In Healthcare: Top Use Cases, softwebsolutions.com. Images © Ico Maker, #265312009, 2019; © Monopoly919, #188158746, 2019; © Francois Poirier, #209725591; © irinastrel123, #206006119, 2019; © mast3r, #180336886, 2019; © Mykola, #284569356, 2019; © petovarga, #166430109, 2019. Source: stock.adobe.com

2.3 *The role of AI in tackling global challenges*

The role of AI in tackling global challenges should not be underrated. In fact, **AI and other digital technologies can be important channels towards cutting global greenhouse gas emissions. At the same time, AI itself may be a contributor to further emissions,** namely due to greater energy consumption resulting from, for example, data centres and supercomputers. R&I can act as a mitigator by contributing to energy-efficient computing and ‘greener’ solutions. According to the Global Action Summit (2018), AI and digital technologies can contribute to cutting global emissions across sectors. For instance, annual emissions from the energy supply would be reduced via better grid flexibility and storage. Efficient shipping would also be an important channel for reducing the emissions from the transport sector, and precision agriculture could reduce the sector’s footprint.

With growing digitalisation and everlarger data flows, the need for both network capacity and computing power has increased enormously. As a result, energy demand from data centres and data transmission networks could be on the rise. Andrae (2017) estimates that data centres could account for 10% of total electricity use by 2025. Fortunately, the International Energy Agency (2019) argues that to date technological progress in energy efficiency has contributed to limiting the growth of electricity demand and usage. In fact, accordingly, there has been a shift away from small, inefficient data centres towards much larger cloud and hyperscale data centres. Indeed, trade-offs may occur. As discussed in Vinuesa et al. (2020), while AI can act as an enabler in 79% of all SDG targets, the progress of 35% of them may be inhibited by AI, or at least to some extent (Figure 3). As stated by the authors, this requires policies that help direct the vast potential of AI towards the highest benefit for individuals and the environment, as well as towards achieving the SDGs.

Figure 3. Summary of positive and negative impacts of AI on various Sustainable Development Goals (SDGs)



Source: Vinuesa, R., Azizpour, H., Leite, I. et al. (2020)

Thus, R&I can be a powerful ally by generating 'greener' solutions. At the EU level, the EuroHPC Joint Undertaking will develop a 'world-class supercomputing ecosystem in Europe' that will also use R&I to develop a low-power processor, for example. However, concerns over the environmental footprint of AI and data centres will remain in both the short and long run. According to Strubell et al. (2019), training a deep learning model could be equivalent to that of the lifetime of five cars, which calls for the greater mobilisation of R&I efforts to boost the energy efficiency of digital technologies, and eventually replace the most-pollutant technologies with more energy-efficient or even carbon-neutral ones.

2.4 AI-powered solutions in the pandemic times

AI-powered solutions can be important tools to help in the fight against a pandemic such as COVID-19. However, increased surveillance and tracking systems have also reinforced the **need for global ethical governance of AI.**

AI, big data and other digital technologies are vital tools for helping to fight a pandemic such as COVID-19. In just one week, scientists in China were able to recreate the genome sequence of the virus by using AI. The Canadian start-up BlueDot detected an outbreak[1] of pneumonia cases in Wuhan in December and identified the cities that were at the highest risk of facing their own outbreaks.

AI has been used to detect visual signs of COVID-19 on images from lung CT scans, monitoring changes in body temperature in real time, providing an open-source data platform to track and monitor the spread of the disease, and is increasingly being used to help identify potential treatments and cures.

At the same time, the use of AI tracking and surveillance tools in the context of this pandemic has clearly shown the need for a global ethical governance of AI.

All over the world, ambitious R&I projects and collaborations to track, monitor and contain the COVID-19 pandemic are increasingly being carried out, including AI-powered solutions. AI-related applications have enabled population screening, tracking the spread of the infection[2], and the detection and diagnosis of COVID-19. To help quicker contact tracing and complement manual ones, smartphones apps have been launched, causing an international debate about the balance between privacy and human right in the endeavour to monitor and stop the spread of the disease. On April 8, 2020, the European Commission issued a Recommendation[3] "on a common Union toolbox for the use of technology and data to combat and exit from the COVID-19 crisis, in particular concerning mobile applications and the use of anonymised mobility data". The document emphasises that "preference" should be given "for the least intrusive yet effective measures,

1 https://www.cnbc.com/2020/03/03/bluedot-used-artificial-intelligence-to-predict-coronavirus-spread.html

2 https://www.bruegel.org/2020/03/artificial-intelligence-in-the-fight-against-covid-19/

3 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1587153139410&uri=CELEX:32020H0518

including the use of proximity data and the avoidance of processing data on location or movements of individuals, and the use of anonymised and aggregated data where possible".

The European Commission launched an initiative to **collect ideas about deployable AI and robotics solutions as well as information** on other initiatives that could help us to face the ongoing COVID-19 crisis[4]. This inventory has shown that the R&I community and enterprises have been very active in coming up with such solutions. For example, the Lucentia Lab in Spain has developed a platform for big data and AI for handling patients. In Belgium, KU Leuven has deployed therapeutics for the treatment of SARS-CoV infection, and there are many other examples.

Openly accessible, machine-readable, interoperable data is needed to accelerate COVID-19 research. Important datasets include clinical, epidemiological and laboratory data. At the EU level, the European Covid- 19 Data platform [5]was launched in April by the EMBL's European Bioinformatics Institute (EMBL-EBI) and the European Open Science Cloud together with EU Member States and research partners such as ELIXIR[6] to speed up and improve the sharing, storage, processing of and access to research data and metadata on the SARSCoV-2 and COVID-19 diseases. This allows the scientific community to share, analyse and process them rapidly, openly and effectively across the Member States and worldwide in line with the relevant EU data legislation.

AI is also used to further speed up the drug development process by modelling the efficacy of these drugs prior to clinical trials. In this context, AI could also optimise the process of clinical trials to discover new and effective drugs and vaccines. Three powerful **European supercomputing centres** – located in Bologna (Italy), Barcelona (Spain) and Jülich (Germany) – are participating in the EXSCALATE4CoV[7] project, along with a pharmaceutical company and several large biological and biochemical institutes. The consortium is using an EU-backed supercomputing platform, one of the world's most powerful, to check the potential impact of known molecules against the genomic structure of coronavirus.

The project is now processing digital models of the coronavirus' protein and matching them against a database of thousands of existing drugs, aiming to discover which combinations of active molecules could react to the virus. In June, it announced that an already registered generic drug used to treat osteoporosis, could be an effective treatment for COVID-19 and is currently exploring how to advance to clinical trials. The project has received EUR 3 million in funding from the EU's Horizon 2020 for research into COVID-19 vaccine development, treatment and diagnostics.

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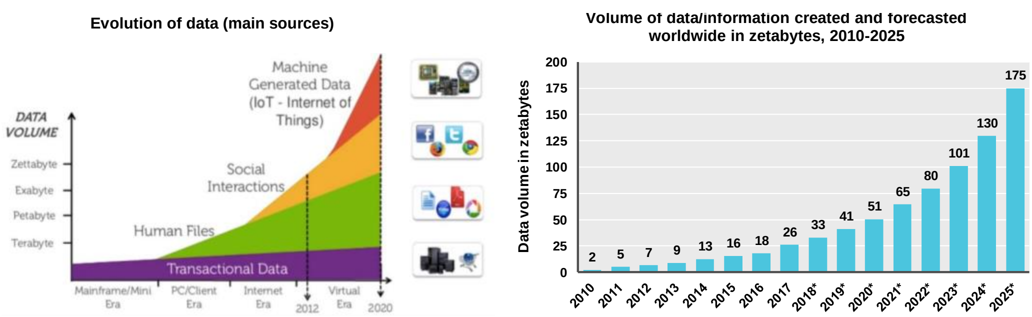
[4] https://ec.europa.eu/digital-single-market/en/news/join-ai-robotics-vs-covid-19-initiative-european-ai-alliance
[5] https://www.covid19dataportal.org/about
[6] https://elixir-europe.org/services/covid-19
[7] https://www.exscalate.eu/en/

3 Global AI trends

Data explosion, stronger computational power, more sophisticated algorithms and open source software have fostered significant developments in AI R&I. The volume of data and information created has increased dramatically from just two zettabytes in 2010 to 26 in 2017 and is expected to reach 175 zettabytes by 2025 (Figure 4). This data explosion has been fuelled by the digital transformation of firms, economies and societies. Nowadays, the sources of data production include not only transactional and personal data, but also social interactions and machine-generated data. Indeed, the use of personal devices such as smart phones has boosted the number of interactions online through, for example, video visualisations and engaging in social media platforms. In addition, greater cloud capacity has enabled the management and storage of big datasets. The connection of different Internet of Things (IoT) devices has also generated large amounts of new data. As a result, the increasing production of data combined with more sophisticated techniques to explore and analyse databases have enabled important developments in AI, notably in deep learning. However, not only huge amounts of data are needed for accurate predictions – the data must also be high quality. Moreover, important privacy and ethical issues related to data should also be taken into account as we will discuss later.

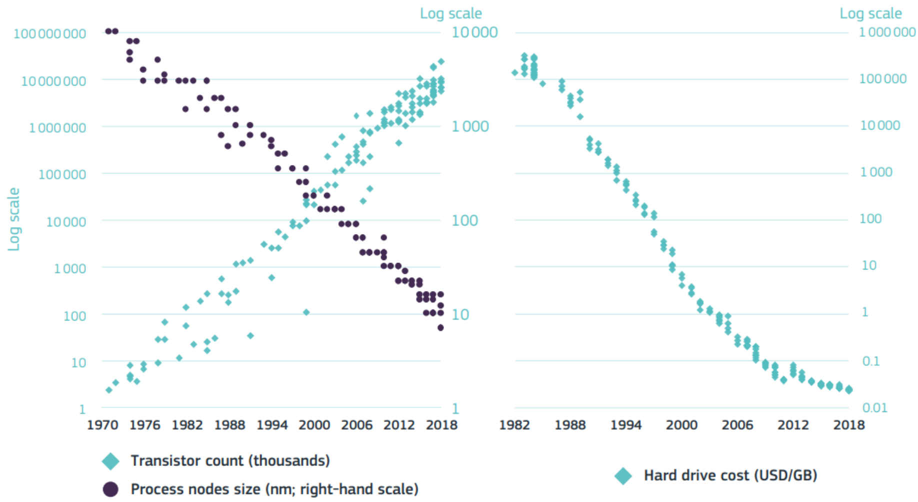
Figure 4. The data explosion: sources and evolution over time



Source:https://medium.com/@melodyucros/ladyboss-heres-why-you-should-study-big-data-721b04b8a0ca, and IDC; Seagate; Statista estimates

Breakthroughs in computing and the decrease in the cost of storage have contributed to greater and cheaper computing capacity to process large volumes of information (Figure 5). Indeed, using the number of transistors per chip as a proxy for computational power, the OECD (2019a) finds that capacity has doubled every two years since the 1970s. Greater speeds and energy efficiency have also been achieved thanks to the continuing miniaturisation of transistors.

Figure 5. Computing power and cost of storage[1], 1970-2018 and 1982-2018

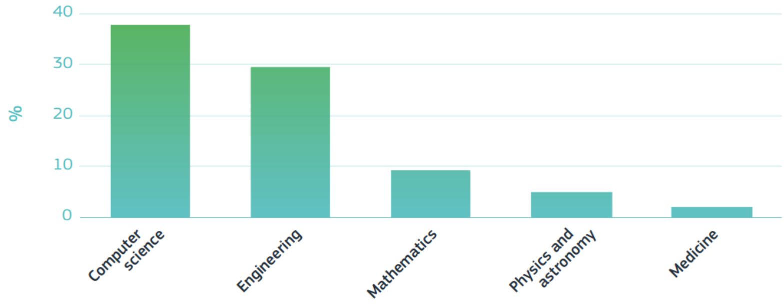


Source: OECD (2019a)
Note: [1] Number of transistors per central processing unit (CPU) microprocessor and process size (left-hand panel), cost of storage per GB (right-hand panel).

Open-source software has enabled developments in AI and, in particular, in deep learning research. In fact, open-source tools have lowered the barriers to entry in the field of AI (CBInsights, 2019a) and are contributing to advancing research (and research productivity) in the AI field by sharing code among a community of users who can build their research upon already-existing code and can potentially improve it. For example, user traffic in one of the most popular open-source software tools – TensorFlow- (a machine-learning library created by Google) – has increased remarkably since it became open and free-of-charge to the world in 2015 (European Commission, 2020).

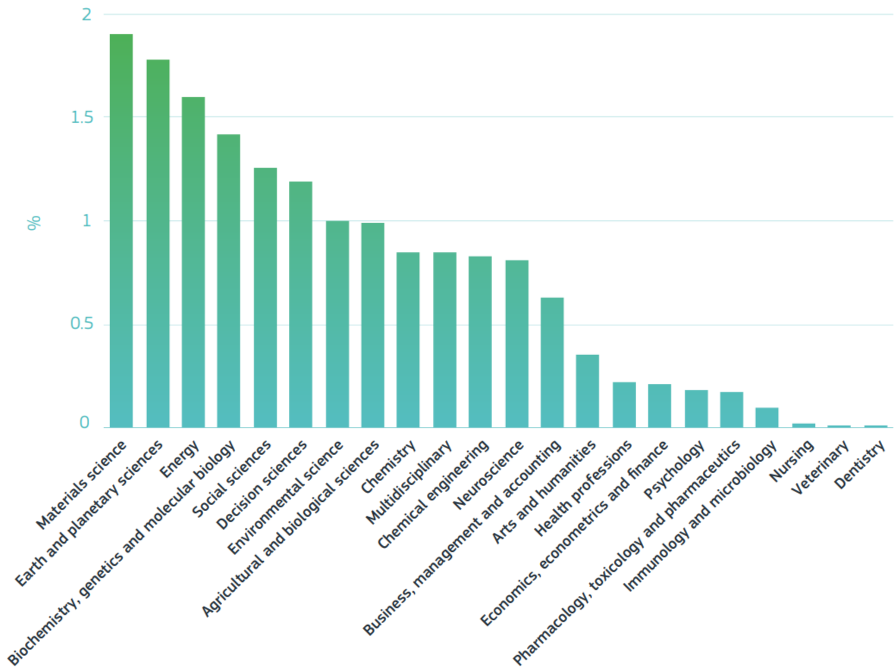
'Deep-tech' and, in particular, AI, are the result of the co-development of hard-core science and technology. AI is increasingly exploring the boundaries of scientific fields beyond computer science. Deep-tech innovations are typically very 'science-intensive' and allied to sophisticated technology. Using text-mining techniques, the OECD (2019) compiled the scientific fields underpinning AI-related documents between 1996 and 2016 (Figure 6). Although computer science has (as expected) made a major contribution to AI science, of almost 40 % to AI publications, 60 % of which actually refer to other scientific fields: engineering corresponds to 30 %, followed by mathematics (9 %), physics and astronomy (5 %) and medicine (2 %). The remaining 13 % are spread across a wide diversity of fields (Figure 7).

Figure 6. Top 5 scientific fields for AI-related scientific documents as a percentage of all AI-related documents, 1996-2016



Source: OECD (2019a), Measuring the Digital transformation
Note: Calculations based on Scopus Custom data, Elsevier, Version 1.2018, January 2019.

Figure 7. Other scientific fields for AI-related scientific documents as a percentage of all AI-related documents, 1996-2016



Source: OECD (2019a), Measuring the Digital transformation
Note: Calculations based on Scopus Custom data, Elsevier, Version 1.2018, January 2019.

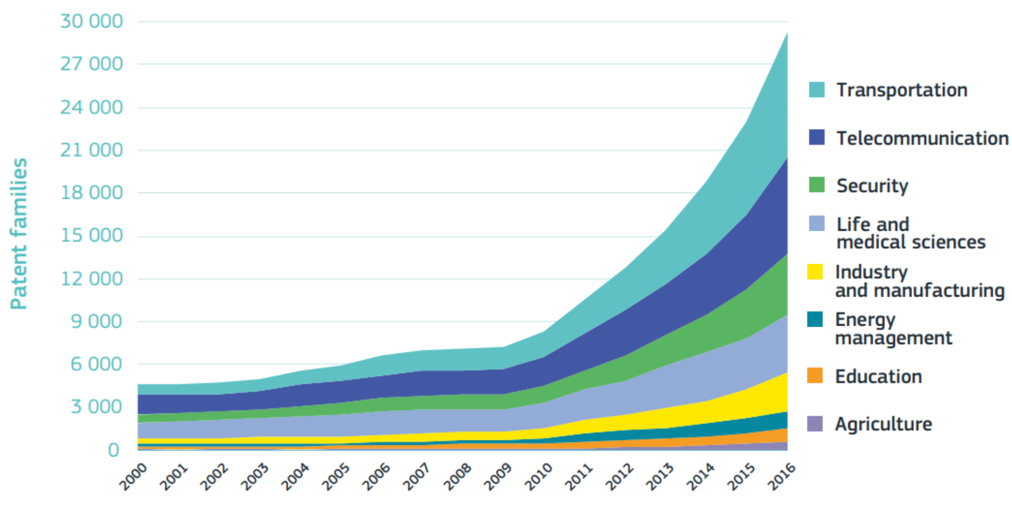
In the case of AI, **Motohashi (2018) found that the co-development of science (proxied by research articles) and technology (proxied by patents) in AI has been fostered by the intersectoral mobility between academia and firms**, i.e.

'those who had published AI-related publications in public research organisations later became involved in patenting activities at a private company (either through a joint appointment or by moving job)'. Hence, academia and public research organisations have an increasingly important role in AI-driven innovations which has been intensified by greater mobility.

The role of intellectual property (IP) in AI spin-offs also needs to be better understood. For example, it has been suggested that the standard technological discovery model does not apply in spin-outs based on machine learning that may rely instead on know-how on the part of the academic founders, which is central to the new business (Royal Society, 2017).

Since 2009, there has been a boom in AI patenting, notably in the fields of transportation, telecommunications, security, and life and medical sciences. Figure 8 depicts the evolution of patent families for the top selected AI application categories between 2000 and 2016. It can be seen that, since 2009, patenting activity has grown across all sectors identified in the graph, with the most pronounced increases in transportation, telecommunications, security, and life and medical sciences.

Figure 8. Patent families for top selected AI application patent field categories, by earliest priority year, 2000-2016

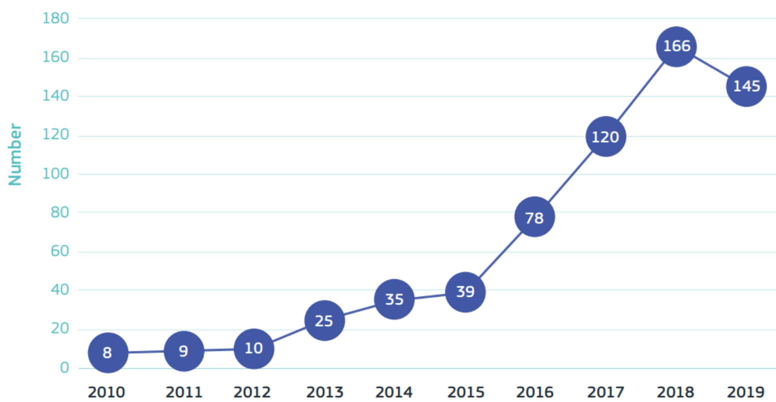


Source: WIPO Technology Trends 2019: Artificial Intelligence, based on Questel Orbit Intelligence, Fampat Database, March 2018
Note: A patent may refer to more than one category.

Acquisition of AI startups is increasingly regarded as a strategic move by acquirer companies to acquire data and absorb new AI knowledge and capacities. Cumulatively, CBInsights reports that between 2010 and 2019 (August) there were 635 acquisitions of AI companies. According to the WIPO (2019), most of the companies acquired are young start-ups with a median age of three years old.

Accordingly, these companies tend to specialise in virtual assistants, big data analytics for recommendation systems, and image recognition, using machine learning as the main technology. From Figure 9 it is possible to conclude that acquisitions have become more common in recent years – in particular, around two thirds of all AI acquisitions occurred between 2017 and 2019. This is also in line with the general trend in the growing number of acquisitions worldwide (European Commission, 2020). Moreover, the WIPO (2019) highlights that acquisitions in the AI sector can complement IP and development efforts since they may reduce the need for the acquirer to patent. The authors illustrate this argument with the example of Alphabet which has acquired a substantial number of AI companies 'while at the same time reducing its patent filing activity over the last several years'.

Figure 9. Number of AI acquisitions by acquisition year, 2010-2019[(1)]

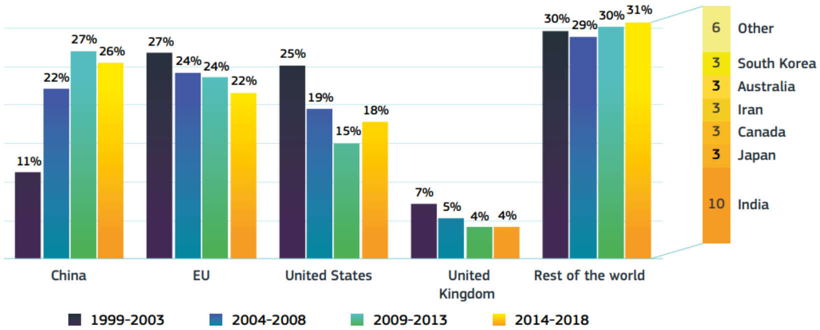


Source: CBInsights (2019), 'The Race For AI: Here Are The Tech Giants Rushing To Snap Up Artificial Intelligence Startups'
Note: [(1)]Data as of 31/08/2019 hence not covering the whole year.

4 EU positioning in AI science

Although the EU ranks among global leaders in AI scientific production and excellence, its position has been deteriorating over time, while China has risen quickly. Globally, the weight of EU publications in AI has been on the decline since 2003, although it still ranks among the global leaders in AI scientific production (Figure 10). Indeed, between 2013 and 2017, the EU accounted for 22% of world publications in AI, down from 27% over 1999-2003. This compares with 26% in China (up from only 11%), and 18% in the United States (down from 25%). Thus, China has been emerging quickly as the global leader in scientific production in the AI domain. Other players, such as India (with a 10% share) and the United Kingdom (with a 4% share) have also been quite active in AI publishing.

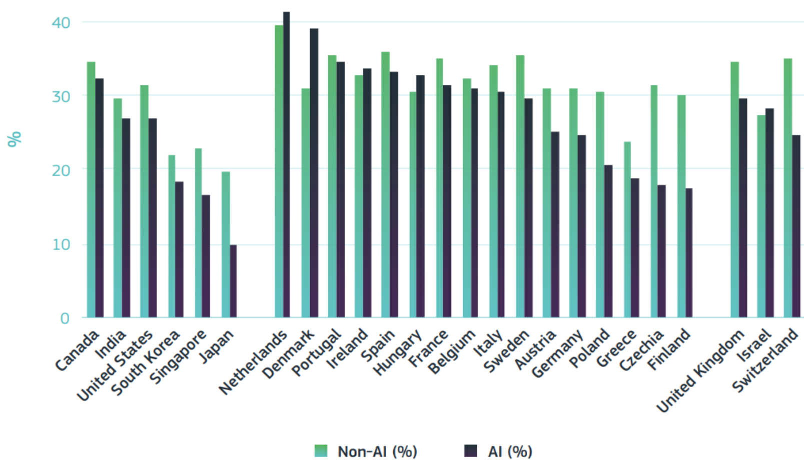
Figure 10. Share of world publications in artificial intelligence in selected regions (%), 1999 - 2018



Source: Elsevier (2018)

The lack of gender diversity in AI research persists, although there has been progress over time, notably in certain European countries. As reported by NESTA (2019), a gender diversity gap in AI research (using the arXiv repository) continues to be prominent (Figure 11). Within the EU, in 2018, the share of papers with at least one female author was highest in the Netherlands (42%), Denmark (39%) and Portugal (35%). Moreover, in most EU Member States represented in the study, gender diversity was higher than in non-EU countries such as Canada, the United States, South Korea and Japan. It is also interesting to note that in the Netherlands, Denmark, Ireland and Hungary, the share of female authors in AI papers actually appears higher than in nonAI papers, contrary to the global picture. When looking at trends over time, the AI Index 2019 highlights the growth of female authorship between 2000 and 2018, with the most visible increases overall taking place in European countries, namely in the Netherlands, Ireland, Hungary, France and Belgium. On the contrary, international economies, such as the United States and Japan, reported a decline over time in female authorship in AI.

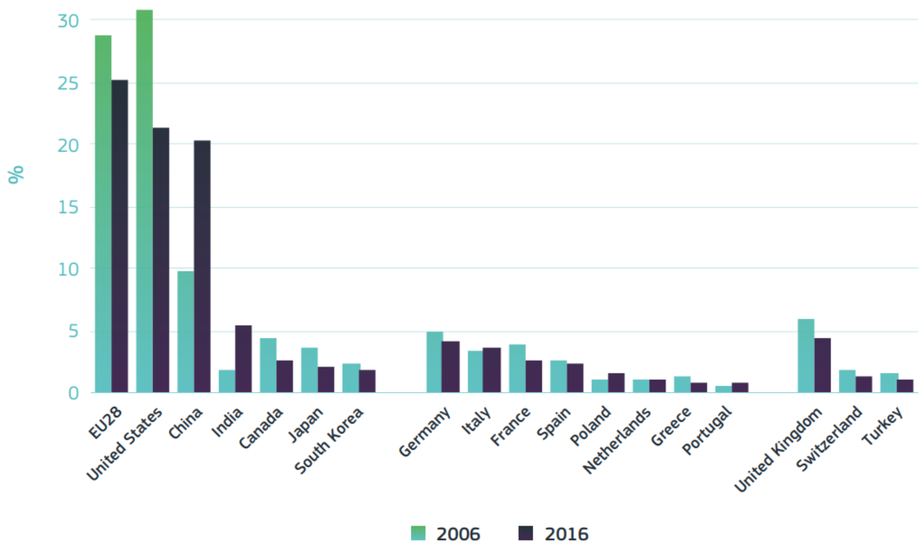
Figure 11. Percentage of AI and non-AI papers with at least one female author by country, 2018



Source: AI Index 2019, based on NESTA, arXiv, 2019

The EU28 is a leader in scientific excellence in the AI field, as measured by the share of AI-related documents in the top 10% most-cited publications worldwide (Figure 12). In 2016, the EU represented 25% of the top most-cited AI publications, closely followed by the United States (21%), and China (20%). Both the EU and the United States saw a decline in their relative importance in AI excellence between 2006 and 2016, the EU down from 29% and the United States down from 31%. China, on the other hand, registered a remarkable increase in scientific excellence in the AI field, doubling its relative weight in just a decade. Within the EU, the German, Italian and French economies are the highest ranking in AI scientific excellence.

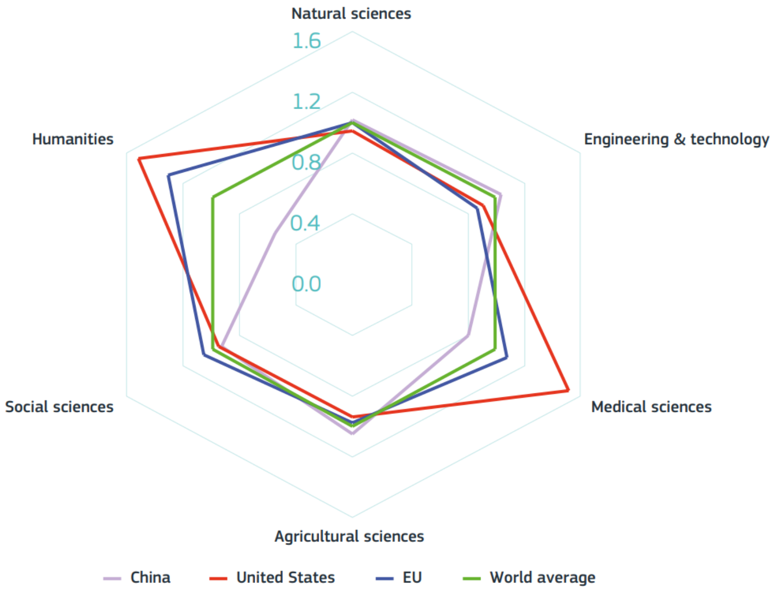
Figure 12. Top-cited scientific publications related to AI [1], 2006-2016



Source: OECD (2019), Measuring the Digital Transformation: a Roadmap for the Future
Note: [1] Selected countries with the largest number of AI-related documents among the 10% most-cited publications (%). OECD calculations based on Scopus Custom Data, Elsevier, Version 1.2018 and 2018 Scimago Journal Rank from the Scopus journal title list (accessed March 2018), January 2019. Fractional counting used.

Global AI specialisation profiles show that the EU's AI research is more oriented towards humanities and to a lesser extent also in medical sciences. China is more specialised in agricultural sciences and engineering and technology, and the United States in medical and health sciences as well as humanities. Figure 13 displays the specialisation profiles of AI publications by field and major economy relative to the world average. The EU's top specialisation appears to be in humanities, and the United States in both humanities, and medical and health sciences, and to a greater extent than in the EU. China exhibits a different orientation of AI research activity from both the EU and the United States, with AI publications more oriented towards agricultural sciences and engineering and technology. Elsevier (2018) explains that the apparent focus of the EU and the United States on the humanities could be driven by a 'very low number of publications and may be influenced by language'.

Figure 13. Relative Activity Index[1] of AI publications (all document types) per FORD category per region, 2018



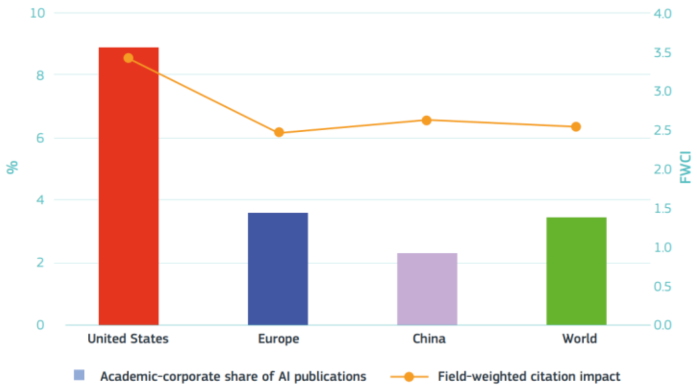
Source: Elsevier (2018)
Note: OECD Fields of Research and Development (FORD) categories show R&D expenditure and personnel by fields of research and development. A value of 1.0 indicates that a country's research activity in AI corresponds exactly with the global activity in AI; higher than 1.0 implies a greater emphasis, while lower than 1.0 suggests a lesser focus.

5 AI technological collaboration over time

Co-publications between academia and the private sector in the AI field are more common in the United States than in Europe. They also have a higher citation impact. Academic-corporate collaboration in AI is increasingly driving AI developments. It seems more apparent in the United States, where 9% of the AI publications involve academia and the private sector. It also has inherently a higher citation impact than in Europe or in China (Figure 14). In Europe, AI co-publications account for close to 4% of AI publications, which is similar to the share of scientific output resulting from public-private co-publications in the EU28[8]. This compares with only around 2% in China. However, Chinese AI co-publications appear to have a higher citation impact than Europeans.

8 The share of scientific public-private co-publications in scientific output was of 4.5% from 2000-2018 in the EU28 (full count). Data: Science-Metrix using data from the Scopus database

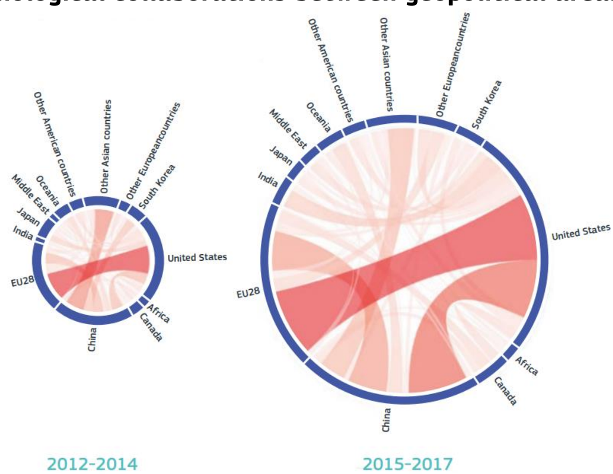
Figure 14. Academic-corporate share of AI publications (% total AI publications by region) and related field-weighted citation impact, 1998-2017



Source: Elsevier (2018)

In recent years, international collaborations on AI technology around the world have intensified. In particular, EU28 players have significantly increased their collaboration with the United States and China in the AI domain. Science is increasingly 'open to the world' in order to tackle global challenges and contribute to scientific advances/discoveries (European Commission, 2020). In this context, international collaboration on AI between R&D players all over the world can also be beneficial to AI science and innovation. Figure 15 represents the evolution of the intensity of bilateral AI technological collaborations (namely co-publications and co-patents) across the globe, in three different periods. A bigger radius in the diagram means that collaboration was higher over that period. More recently, the level of international collaboration in AI has expanded remarkably. Furthermore, EU28 R&D players are not only collaborating more with the United States but with China, too.

Figure 15. AI technological collaborations between geopolitical areas[1], 2012-2017



Source: De Prato et al. (2019)
Note: [1]Number of bilateral collaborations (i.e. co-publications and co-patenting) between players active in R&D in the AI domains and located in different countries, in the indicated periods. The radius of the diagrams is proportional to the amount of external collaborations in the corresponding period of time.

Countries, international organizations, civil society and research centres are also collaborating at the EU and global level to agree on common principles governing AI. To date, the EU has taken the lead here.

Box 2- Towards trustworthy, ethical and innovative AI in the EU

In itself, AI is neither good nor bad; nor is it neutral (Kranzberg, 1986). As with any impactful new technology, the way in which it is further developed and applied will determine either a positive or negative outcome. AI powered cameras with facial recognition capabilities can make your neighbourhood safer but may also help oppressive regimes to identify and silence dissidents. Receiving targeted advertising based on the contents of your e-mails may be acceptable but having similar AI systems use your data for manipulating your voting behaviour is not. Certain AI programmes for facial analysis display gender and racial bias, demonstrating low errors for determining the gender of lighter-skinned men but high errors in determining gender for darker-skinned women. Biased decision-making is not unique to AI, but as many researchers have noted, face recognition algorithms and decision algorithms can be alarmingly biased or inaccurate reflecting historical patterns of discrimination based on gender, ethnicity, race and other identities.

For AI to have the positive impact we want, we should carefully reflect on the choices we make while developing and applying it. '**AI ethics**' is about identifying the core principles to guide us in our quest to maximise the technology's benefits while minimising its risks. Companies working with AI could use such principles to self-regulate their developments; governments could go a step further and enforce compliance through regulation.

For the Commission, **seven key requirements define trustworthy and human-centric artificial intelligence**:

1. Human agency and oversight
2. Technical robustness and safety
3. Privacy and data governance
4. Transparency
5. Diversity, non-discrimination and fairness
6. Societal and environmental well-being
7. Accountability

To operationalise these requirements, the High Level Expert Group on AI presented also an assessment list to check compliance with each of these requirements, also tested by a large range of sectors and types of organisations.

The '**ethics-by-design**' approach will play a key role in ensuring that ethical and legal principles are embedded at the very outset of system development. The European Commission has thus committed to exploring the opportunities for introducing the ethics-by-design principle in relevant calls for proposals under the EU-funded research programme.

6 EU positioning in AI innovation

Despite ranking among global leaders on AI scientific excellence, the EU trails when it comes to AI innovation performance, both in the number of companies and patenting. However, the EU's performance is in line with its share in global R&D investments. Nearly one third of the world's AI firms can be found in the United States. China ranks second, with close to one quarter of AI companies. Hence, the two countries together account for slightly more than half of all AI startups. The EU28 represents 19% of firms active in AI worldwide (in accordance with the EU's approximate 20% share in global R&D investments), followed by India, Canada, South Korea and Japan (Figure 16). Today, AI applications are widespread across different industries. CBInsights' 2019 list of 'the most promising 100 AI startups' points precisely to the sectoral diversity of AI startups with 'high-potential' including in healthcare, finance, retail, cybersecurity, marketing and agriculture, among others (CBInsights, 2019c).

The EU's gap in AI innovation relative to the United States and China can also be observed in terms of the number of firms active in patenting in AI in each region. Indeed, Chinese AI companies account for almost 60% of all AI firms' patenting applicants. This compares with 14% in the United States but only around 7% in both South Korea and the EU28 (Figure 17) between 2009 and 2018.

Figure 16. Share of AI firms worldwide (%), 2009-2018

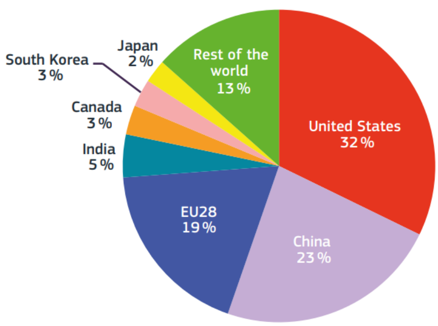
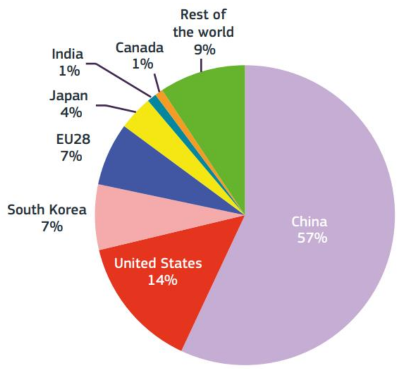


Figure 17. Share of firms' patenting applicants in AI, 2009-2018

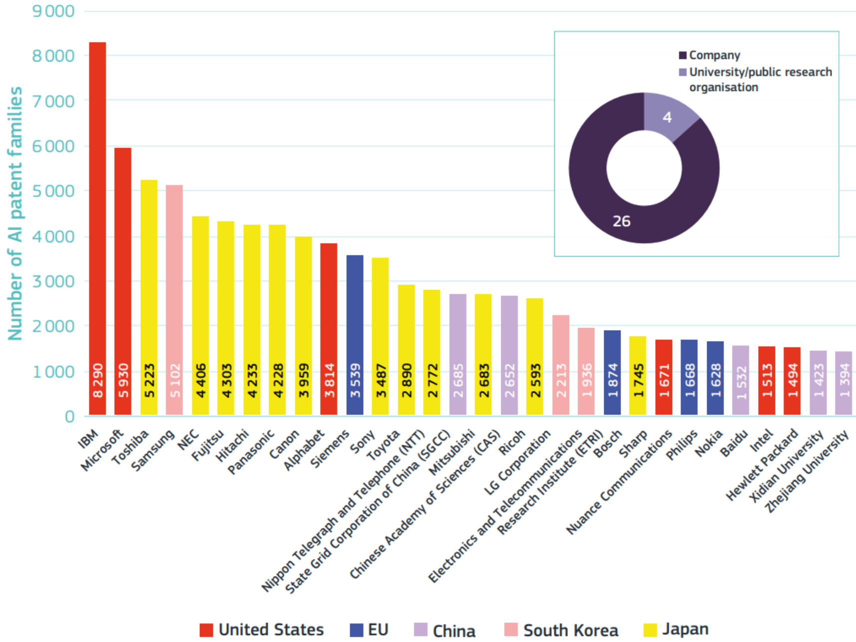


Source: De Prato et al. (2019)
Notes: Percentage over total number of firms active and firms´ patenting applicants in AI.

The majority of the world's top AI patent applicants are companies in IT, consumer electronics, electric power and automobile manufacturing. Almost **half of the top patent applicants in the AI field are Japanese**. The EU is represented by four companies – Siemens, Bosch, Philips and Nokia. Looking into patent applications in the AI field can provide an indication of who the global AI innovators are. Figure 18 shows that 26 of the top 30 applicants are companies, while only four are universities and public research organisations from China (three) and South Korea (one). Japan stands out as the nation with the largest number of companies (12) represented in the top 30, with Toshiba leading the Japanese group.

The United States come next with six companies. In fact, IBM is the clear leader in AI patenting with a number of patent applications almost equivalent to the total sum of patents from Zhejiang University, Xidian University, Hewlett Packard, Intel, Baidu and Nokia. The EU has four companies in the list, namely Siemens, Bosch, Philips and Nokia, although none of them feature in the top 10. Finally, China has five companies, universities and public research organisations in the global top 30, while South Korea is represented by three entities.

Figure 18. Top 30 world patent applicants by number of AI patent families, region and type of organisation, 2018



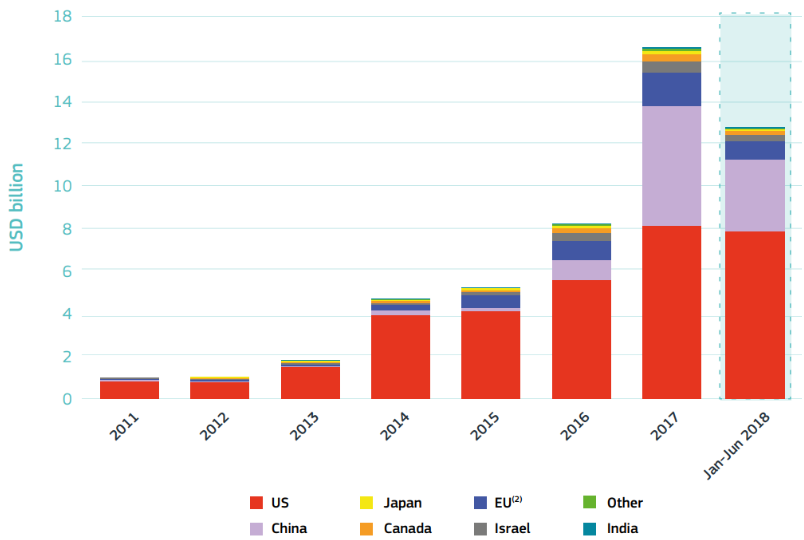
Source: WIPO Technology Trends 2019: Artificial Intelligence, based on Questel Orbit Intelligence, Fampat Database, March 2018.
Note: Fujitsu includes PFU; Panasonic includes Sanyo; Alphabet includes Google, Deepmind Technologies, Waymo and X Development; Toyota includes Denso; Nokia includes Alcatel.

7 Enabling AI: capital and people investments

With the unlocking of the potential of AI, private investments in AI startups are on the rise. The United States leads, followed by China. Although the EU has also made some progress in recent years to attract private capital, investments remain well below that of its main global competitors. Since 2016, private investments in AI startups have registered a significant boost worldwide, having doubled between 2016 and 2017 alone. Developments and breakthroughs in the AI field have attracted growing interest from private investors who are aware of the high potential of AI applications to disrupt several sectors. Indeed, OECD (2018) found that in the first half of 2018, 'AI startups attracted around 12% of all worldwide private equity investments, a steep increase from just 3% in 2011'.

Figure 19 provides evidence of the United States' global leadership in terms of equity investments in AI startups. According to the OECD (2018), US startups have attracted around two thirds of total private investments since 2011. However, more recently, China has rapidly increased its rate of private investments in AI companies, climbing from just 3% in 2015 to 36% of all AI private-equity investments worldwide in 2017. EU28 startups seem to be less attractive to private investors compared to US and Chinese AI startups, although it is important to note the substantial progress made in recent years – from only 1% in 2013 to 8% of global AI private investments in 2017. OECD (2018) also shows that within Europe, UK-based AI startups are the top recipients of more than half of all private equity investments targeted towards AI startups in the EU28, attracting 55% of all AI equity investments in the EU28 German AI startups rank second and account for 14% of AI private investments, followed by France (13%), Spain (3%) and Ireland (2%).

Figure 19. Total estimated equity investments in AI startups[(1)] (USD bn) by startup location, 2011-2017 and first half of 2018



Source: OECD estimates based on Crunchbase (July 2018)
Notes: [(1)]AI startups are companies founded after the year 2000 and categorised in the 'artificial intelligence' technological area of Crunchbase, as well as companies that use AI keywords in the description of their activity. The sample is restricted to companies located in OECD and BRICS countries and for which sufficient information is reported. Numbers for 2018 are likely conservative due to possible delays in the input of new deals in the database. [(2)] EU includes United Kingdom.

It is likely that the recent upsurge in AI capital has enabled the growth of more AI startups into the next unicorns. This is particularly the case in the United States and China. Figure 20 shows that the number of new AI startups becoming the next unicorns has increased remarkably especially since 2017, having more than doubled between 2017 and 2018 alone. Between 2015 and 2019, 46 new AI-related unicorns came into the picture (11% of the current total number of private unicorns), with half (or 23) being US-based. China accounts for slightly more than a quarter of all AI unicorns, followed by the United Kingdom with four, Israel with two, and France, Japan, Canada and Singapore with one each. Hence, only one unicorn in the AI field was found in the EU over the period 2015-2019 (Figure 21). However, UiPath, an 'AI unicorn' with headquarters in the United States, has 'EU DNA' as the company's founders are Romanian and the headquarters were initially based in Bucharest. Considering that the amount of funding received is a key component of private valuations, this increase could be partly explained by greater interest on the part of private investors in AI technologies due to their potential to boost innovation and productivity.

Figure 20. Number of new AI unicorns, 2015-2019

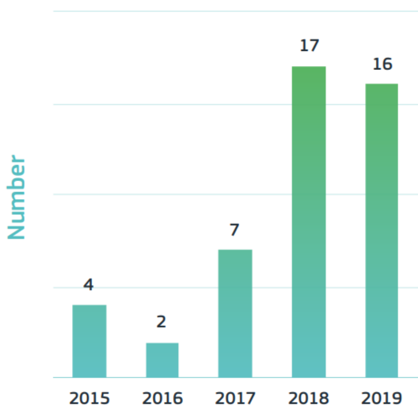
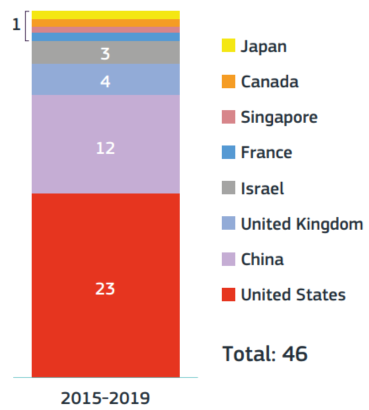


Figure 21. Number of AI unicorns by country, 2015-2019

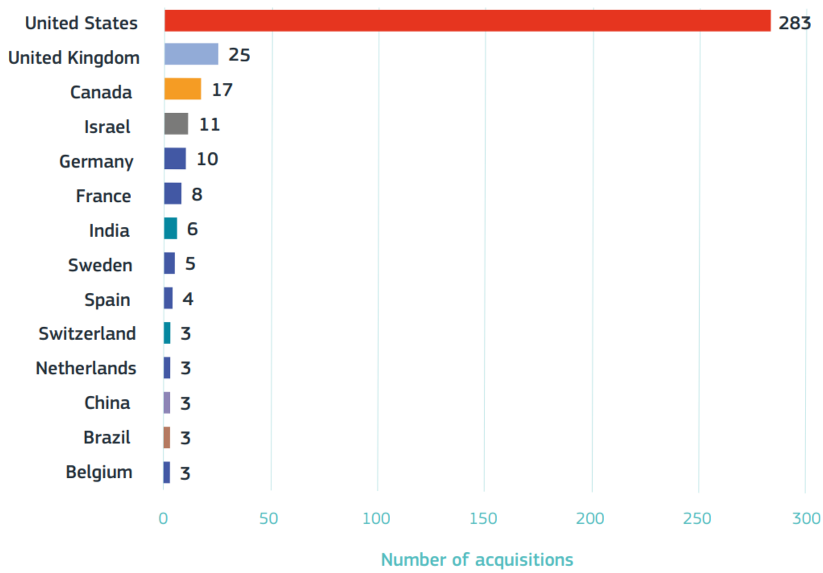


Source: CBInsights Unicorn Tracker, accessed on 11/12/2019

Acquisitions are on the rise. Around two thirds of acquisitions in the AI sector were in the United States, where one third of all AI firms are located, too. The United Kingdom comes next with 25 British startups acquired over the same period. In the EU, there were AI-related acquisitions of by 10 German, 8 French, 5 Swedish, 4 Spanish, 3 Dutch and 3 Belgian AI companies (Figure 22).

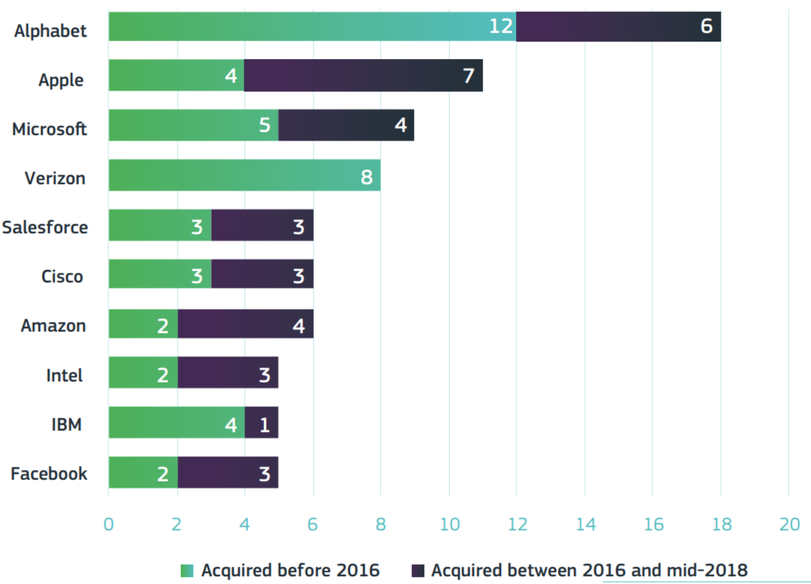
The top 10 acquirers of AI companies are mainly 'tech' or 'digital giants' from the United States. Together they account for almost 20% of all AI-related acquisitions, and their pace of acquisitions has accelerated since 2016. Figure 23 shows the number of AI-related companies acquired by a top acquirer, both before and after 2016 (up to May 2018). Most of the top 10 acquiring companies are US multinationals in tech, which also have high market capitalisation. Alphabet leads the list with 18 acquisitions, Apple ranks second with 11 and Microsoft comes third with nine. Cumulatively, up to mid-2018, the top 10 acquirers made 79 AI acquisitions. Furthermore, the number of acquisitions has accelerated since 2016 as companies increasingly perceive AI as a technology to boost their R&D and innovation capacities, productivity and competitiveness. Besides acquisitions, 'tech giants' are also adopting a set of different strategies to lead in AI development, from investing heavily in R&D labs for AI to programmes designed to attract overseas talent.

Figure 22. Acquisitions in the AI sector by country of acquired company, 1998-2018



Source: WIPO 2019 report, based on CrunchBase database, May 2018

Figure 23. Number of AI companies acquired by top acquiring companies, before and after 2016 up to mid-2018

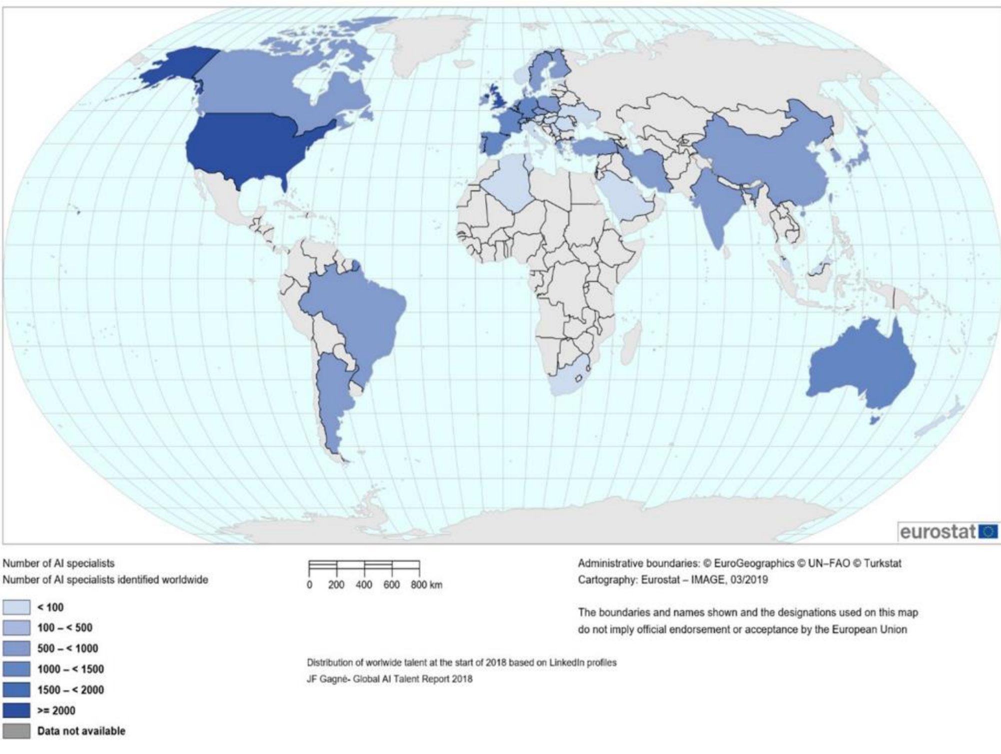


Source: WIPO 2019 report, based on CrunchBase database, May 2018

The race for AI talent is on. Currently, AI talent is relatively scarce worldwide but appears more predominant in the United States. The EU faces a shortage in AI professionals which could undermine its ambition to galvanise its AI innovation landscape. AI-related jobs seem harder to fill compared to the 'average job'[9], which hints at a limited pool of AI talent worldwide. In particular, the profiles of computer scientists, algorithmic engineers and principal scientists are proving to be the hardest AI-related vacancies to be filled. For example, in the Indeed portal – a job-search portal – 64% of the computer scientist vacancies were still open after 60 days of being published on the portal.

Official statistics on the existence and production of AI talent are still lacking. However, certain external efforts have provided some indication of the **geographical distribution of AI specialists worldwide**. J.F. Gagné (2018) used the LinkedIn job platform to identify AI specialists all over the world (Figure 24). One caveat of the analysis is that the use of LinkedIn is more common in the West, so there may be a bias in the data collected which may underestimate the presence of AI specialists, for example, in China. The United States appears to have more AI talent available than, for example, the EU or China. In addition, most tech giants are based in the United States. In light of the scarcity of AI talent, these multinationals offer highly competitive salaries and alluring benefits to attract and retain top talent.

Figure 24. Global AI talent pool based on AI Specialist LinkedIn profiles, 2018



Source: J.F. Gagné - Global AI Talent Report 2018

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9 Priceoconomics data studio – Which Industries are investing in Artificial inteligence (18 November 2018) based on Indeed data.

For the EU, this means that, on the one hand, it is important to **increase the number of students and professionals with an AI-related academic background and/or AI technical competences and skills acquired**, for instance, in trainings that also reflect the potential risks of AI technologies. On the other hand, the EU should **enable the right environment for them to work in the EU (i.e. to retain AI talent) and attract more talent from abroad**, as highlighted in the 2018 European Commission Communication on 'Artificial Intelligence for Europe', for example through the 'Blue Card scheme'. This is important because the Global AI Talent Tracker[10] found that around 60% of top-tier AI researchers worldwide work at US universities and companies, with two thirds having obtained degrees in other countries (11% are "affiliated" to Europe). The European Commission adopted on 30 September 2020 a Communication on a new European Research Area for Research and Innovation that established the need to make Europe more attractive for talent from the EU and abroad. This requires improving researchers´ careers and skill sets, strengthening the mobility of researchers, and providing access to more sophisticated research and technology infrastructures. On the same day, the Commission also put forward its Digital Education Action Plan to foster a true digital education system, learning from the Covid-19 pandemic where online learning and digital technologies are used at a scale never seen before. Actions on AI include the update of the European Digital Competence Framework to include AI and data-related skills, the development of **AI learning resources** for schools and VET organisations, and training programmes for researchers and students on the ethical aspects of AI with a target of 45% of female participation.

8 Building trust and social acceptance around AI

While the use of AI can do much good, some of its applications may also cause harm, as well as immaterial harm for example, **unlawful discrimination** (such as in the case of recruitment tools that display a bias against certain groups of the population) or limited **free right of expression** (caused by invasive monitoring systems).

Also, some characteristics of AI, including its opacity ('black box-effect'), may **impede the enforcement of existing EU law meant to protect fundamental rights**. For example, **biased and discriminatory outcomes** resulting from decisions taken or supported by AI systems might remain fully or difficult to contest without appropriate documentation about how the system is designed or the goals it pursues. AI may also cause **new safety risks** for third parties and users, which are not necessarily covered clearly by the product safety legislation.[11]

Building trust and broad social acceptance around AI is key for its success. For instance, most Europeans agree that robots and AI require careful management (Centre for the Governance of AI and Eurobarometer), while the same applies to the

10 https://macropolo.org/digital-projects/the-global-ai-talent-tracker/

11 https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12527-Requirements-for-Artificial-Intelligence

United States. As a result, policies to foster AI should follow a human-centric, transparent and trustworthy approach in order to promote public trust in this field.

On 19 February 2020, the Commission published a White Paper and two Communications pertaining to the Digital Single Market, together referred to as the **'Digital Package'**. In 'Shaping Europe's digital future'[12], the Commission presents its overall vision and goals for the development and use of digital technologies in Europe, as well as a roadmap for future actions, Communications and regulatory initiatives. The aim of '**A European strategy for data'**[13] is for Europe to have a genuine single market for data so that the EU's share of the data economy could correspond to its economic weight. The strategy includes setting up a governance framework (including regulatory action), increasing investment, and creating sector-specific common European data spaces. Data spaces for industry (manufacturing), the Green Deal and health data, are among those being proposed, as well as the European Open Science Cloud. The **'White Paper on Artificial Intelligence – A European approach to excellence and trust'**[14] outlines the Commission's vision for a European approach to AI, building on its existing strengths (research, robotics, manufacturing, EU research funding, coordinated plan with the MS), respecting European values (ethics, privacy protection) and presenting the main challenges. In order to overcome these challenges, the White Paper describes actions to **build an 'ecosystem of excellence' to encourage investment**, on the one hand, and an **'ecosystem of trust' through a regulatory framework**, on the other.

The ecosystem of trust would consist of an appropriate regulatory framework providing legal certainty and trust in AI and addressing its significant risks. The Commission held an open public consultation on the **White Paper's vision for AI in Europe**, which was closed mid-June. A majority of participants (95%) responded to the section on the regulatory options for AI where their main concerns related to the possibility of AI breaching fundamental rights and the use of AI that may lead to discriminatory outcomes. The possibility that AI endangers safety or takes actions that cannot be explained were also considered as important by respectively 82% and 78% of respondents, as well as concerns about lack of compensations following harm caused by AI (68%) and possible lack of accuracy of AI systems (70%). To address such concerns, 42% of respondents request the introduction of a new regulatory framework on AI, 33% think that the current legislation needs to be modified in order to address the gaps identified and only 3% think that current legislation is sufficient.

The Commission is currently assessing a multiple set of options ranging from an exclusively "soft law" approach to comprehensive EU-level legislation complemented by other initiatives concerning product safety and civil liability to come forward with a proposal for a legal act laying down requirements for Artificial Intelligence.

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12 https://ec.europa.eu/info/sites/info/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf

13 https://ec.europa.eu/info/sites/info/files/communication-european-strategy-data-19feb2020_en.pdf

14 https://ec.europa.eu/info/sites/info/files/commission-white-paper-artificial-intelligence-feb2020_en

9 Conclusions

The EU ranks among global leaders when it comes to AI science. However, the evidence shows there is an AI innovation gap when compared to the United States and China. This includes, for instance, the number of AI firms and the share of firms active in AI patenting. Most unicorn companies in the AI field are also based in the United States and China.

Worldwide, major economies have put forward ambitious AI strategies. China was first to launch a comprehensive AI strategy in 2017 with the 'Next Generation Artificial Intelligence Development Plan' followed by the industry-targeted 'Three-Year Action Plan for Promoting Development of a New Generation Artificial Intelligence Industry (2017)'[15] with the aim of becoming the global AI leading nation by 2030. With the Declaration on Cooperation on Artificial Intelligence (2018) and the Coordinated Plan on Artificial Intelligence 'Made in Europe' (2018), the EU and the Member States demonstrated their ambition to align priorities and maximise the impact of public and private investments in AI to enable innovation and collectively ensure that the EU as a whole can compete globally. The EU Digital Strategy[16] wants to ensure not only that Europe is a global digital player but also that the EU leads in making sure that technology works for all, and that we live in an open, democratic and sustainable digital society. The United States followed with a national strategy for AI, the American AI Initiative (2019)[17] which identifies R&D as a top priority for maintaining global leadership in AI.

AI can play a big role in the economic, social and ecological transition that Europe is undergoing. In the context of the current productivity slowdown, AI can be a powerful tool to improve the efficiency of operations throughout the economy. As a result, the EU should capitalise on its industrial strengths to lead in AI development. This includes, for instance, manufacturing as well as new areas of early application such as material science. In order to achieve technology sovereignty in the field of AI as well as to diffuse it across sectors and regions, the combination of efforts at the EU and Member State level is paramount.

AI also requires investing in a set of complementary assets. These include fostering talent production and retention in the EU (while attracting foreign talent from other parts of the globe), investments and capacity building in related digital technologies, such as high-performance computing, European cloud and micro-electronics, and research and digital infrastructure, notably 5G networks, for Europe to remain competitive and ensure technological sovereignty. Both the EC's Horizon Europe and Digital Europe Programmes will be instrumental in achieving this. Furthermore, advancing market integration in Europe with a complete Digital Single

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15 http://www.gov.cn/zhengce/content/2017-07/20/content_5211996.htm

16 https://ec.europa.eu/digital-single-market/en/content/european-digital-strategy

17 https://www.whitehouse.gov/ai/

Market is vital for AI startups and scale-ups to succeed, including simpler and quicker patent rights.

AI and other digital technologies have reached a stage of technological maturity that makes them important tools to help in the fight against a pandemic such as COVID-19. All over the world, ambitious R&I projects and collaborations to track, monitor and contain the COVID-19 pandemic are increasingly being carried out, including AI-powered solutions. At the same time, the use of AI tracking and surveillance tools in the context of this pandemic has clearly shown the need for the global ethical governance of AI.

One of the most important considerations is to ensure that the economic and social benefits of AI are broadly shared across society. Thus, **building 'trust in tech' and social acceptance around AI** is essential. For example, open source and open data have important implications for boosting innovation, although there are also concerns relating to privacy and cybersecurity. AI predictions and decision-making capabilities are only as good as the quality of the underlying data. Its excellence depends on how sound its creators programmed it to decide, learn an act. Concerns over amplified **AI bias** based on gender, race and other factors due to 'inherited' bias in historical data or missing observations are real.

All in all, Europe is currently carving out a position to lead in a more thoughtful, ethical approach to AI with a clear and adequate legal and ethical framework to build an AI ecosystem that spurs innovation: Europe is designing its own way. By seeking out opportunities in the business-to-business market, investing in the development of privacy-preserving and transparent AI, rethinking existing paradigms (e.g. edge vs. cloud-based AI), putting an emphasis on the environmental impact of information technologies, and by introducing regulation, **Europe is positioning itself for a self-designed, AI-infused future**.

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Artificial intelligence is often referred to as one of the « game-changing » technologies of our time due to its potential to increase efficiency and productivity across sectors. The optimisation of processes and production could also minimize the consumption of resources such as energy, water and raw materials and hence contribute positively to achieving many of the sustainable development goals. However, the boom in AI applications in recent years has also shown the limitations of the current state of this technology when it comes to ensuring fairness in its algorithms and systems, as well as an ethical governance. The EU ranks among global leaders in AI Science, but its innovation performance in AI could be revamped. At the same time, the EU has been leading in promoting trustworthy, ethical and human-centric AI.

Studies and reports

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