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Circular Economy & Industry in 2035

Technology building blocks

S. GAMOURA & J.P. BOOTZ

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1. Definitions

The “Technologies” macro-variable focuses primarily on technologies associated with Industry 4.0: AI, data analytics and big data, blockchain, and IoT. It also considers, to a lesser extent, technologies related to energy and materials, particularly the emergence of bioplastics.

Artificial intelligence (AI): A logical, automated process, generally based on an algorithm, capable of performing clearly defined tasks (CNIL 2022). It encompasses any tool used by a machine to reproduce human behaviors, such as reasoning, planning, and creativity (Parlement Européen 2023).

Data analytics and big data: A broad term encompassing numerous techniques for deriving insights from historical data. Today, the term most often describes the analysis of large volumes of data and/or high-velocity data, which presents challenges for computing and data management. There are four types of data analytics approaches: descriptive, diagnostic, predictive, and prescriptive (IFAC 2018).

Big data consists of information assets characterized by high volume (the first V), high velocity (the second V), and/or high variety (the third V), requiring innovative, cost-effective forms of information processing that enable deeper understanding, better decision-making, and process automation (Gartner 2023). Two additional V’s were subsequently added to these three: veracity and value (Teboul and Thierry 2015).

Blockchain: A ledger or large database whose distinctive feature is that it is shared simultaneously with all its users. Each user holds a copy of the ledger and can also record data in it, in accordance with specific rules established by a computer protocol secured through cryptography (Assemblée nationale 2018). Emerging ten years ago as combinations of older technologies forming the protocol underlying bitcoin, blockchains enable decentralized, secure transactions without a trusted third party (Villani and Longuet 2018).

Internet of Things: Instruments—objects, gadgets, machines, living entities, and so on—that can extend the reach of internet connectivity and thereby transmit information from their surroundings. These instruments may also be activated remotely (Sedkaoui 2018).

Energy mix: The distribution of the different energy sources used to meet the energy needs of a region or country. It encompasses all energy resources, such as fossil fuels, renewable energy sources (solar, wind, hydropower, and biomass), and nuclear energy, together with their respective shares in total energy production. The energy mix is a key indicator for assessing the diversification, sustainability, and security of a region’s energy supply.

Bioplastics: Biodegradable plastics, plastics derived from renewable sources, or both. These include biobased plastics derived predominantly from renewable sources such as corn, sugarcane, and soybeans, but which may contain some petroleum-based plastic and may not be biodegradable. Biodegradable plastics—that is, plastics that microorganisms can assimilate—may sometimes be derived from petrochemicals. Finally, a third category consists of plastics that are both biobased and biodegradable, such as PLA (polylactic acid) or PHAs (polyhydroxyalkanoates). The French definition (Journal officiel, December 22, 2016) reserves the term “bioplastic” for materials that are both biobased and biodegradable.

2. Relevance to the study and key questions for the future

Technologies serving circularity

The technological transition and the transition to a circular economy are two major phenomena profoundly transforming our society in tandem, with the same intensity and social pressure (Geoffron 2017). On the one hand, the technologies brought by the digital transition offer new opportunities for the transition to a circular economy and can therefore have a positive impact on its development in societies (Benkarouba 2022). They can improve the efficiency of production and consumption processes, develop new models, and disseminate information and initiatives supporting the circular economy (Geoffron 2017).

IoT can play an important role in the use of connected sensors to monitor and optimize industrial processes by reducing waste in production lines, optimizing material quality, and monitoring inventory levels (Delpla 2021). Blockchain can also contribute to transparency in supply chains that support product life cycles by improving the traceability and verifiability of recycled materials (Philippossian 2021).

Technologies that can also hinder circularity

On the other hand, the negative impact of these technologies on the development of the circular economy cannot be ignored. It stems primarily from the exponential increase in computing and data storage capacity. This "digital pollution" therefore calls for measures known as "digital sufficiency" (Nicolaï and Peragin 2022). Under Moore's law, the number of transistors on an integrated chip doubles every eighteen to twenty-four months, driving a dramatic expansion in the use of highly energy-intensive algorithms and computations. The web and continuously accessible applications contribute to greenhouse gas emissions.

Technologies are therefore playing a pivotal role in the present, near future, and distant future of the transition to a circular economy.

Links between technological innovation in energy and the CE:

Technological innovation in energy plays a crucial role in the transition to a circular economy. First, advances in renewable energy, such as solar and wind power, reduce dependence on nonrenewable resources, thereby supporting a circular economy based on sustainable energy sources. Technological developments in nuclear power that support low-carbon generation must also be considered. More broadly, the CO_2 emissions associated with the electricity mix are a key component of the transition to a circular economy, particularly with a view to electrifying industrial processes.

Links between bioplastics and the CE:

When they are both "biobased" and "biodegradable," bioplastics considerably limit the environmental impact of this material by preserving natural ecosystems and fossil resources, and thus meet the requirements of the circular economy.

3. Retrospective analysis

The explosion in AI use:

In 2000, Honda unveiled ASIMO, the first AI-based humanoid robot. In 2005, DARPA, an autonomous vehicle race, stimulated research in robotics and computer vision (Grand Challenge). In 2011, the IBM Watson chatbot won the television game show *Jeopardy!* In 2012, AlexNet, a convolutional neural network (CNN), revolutionized image recognition. In 2016, DeepMind's AlphaGo program defeated world Go champion Lee Sedol, demonstrating AI's ability to perform complex strategic and tactical tasks. In 2017, conversational AI gained momentum with Amazon's Alexa and Google Assistant. In 2020, generative text AI through GPT-3 began to revolutionize the world by producing realistic, creative text. In 2022, generative visual AI (DALL-E 2, Midjourney, and others) expanded creativity in images and video.

Today, AI is becoming widely accessible in France and reaching every sector, including craft trades. The ecosystem is growing rapidly: In 2022, AI startups raised twice as much funding as in 2021, reaching a total of €3.2 billion (BDM 2023).

Big data: A history of the power of data:

Coined in 1990, the term "big data" began to gain traction in industry in 2000. In 2004, Google became the first to launch its big data platform (Google Maps). In 2005, Hadoop, the open-source framework for analyzing massive datasets, was launched. In 2008, Amazon Web Services (AWS) entered the big data race

with its S3 service. By 2010, Facebook had reached 500 million active users migrated to big data platforms. In 2020–2021, the COVID-19 pandemic accelerated the adoption of big data infrastructure across various sectors. Between 2011 and 2017, the big data market grew from $7.3 billion to $50.1 billion (CoMarketing 2014). Storing 1 GB of data cost businesses more than US$500 in 2000; it cost less than US$0.02 in 2022 (McKinsey 2022).

Blockchain, or digital democracy:

In 2008, Satoshi Nakamoto invented blockchain for the first cryptocurrency, bitcoin. In 2011, the first public Bitcoin blockchain was launched, followed three years later by Ethereum, a programmable blockchain platform. In 2015, a group of major banks (the R3 consortium) came together to explore blockchain applications in the financial sector. In 2016, the first smart contract was executed on the Ethereum blockchain. In 2017, bitcoin's price surged, drawing the general public to blockchain. In 2018, supply chain management companies began to take an interest in blockchain for product traceability. In 2019, Facebook announced its blockchain-based cryptocurrency, Libra. In numerical terms, the total market value of blockchain-based cryptocurrencies reached $3 trillion in 2022.

The rise of IoT:

Limited to specific applications in 2000, IoT use became widespread, reaching twenty-five billion connected objects for 7.2 billion people in 2015, or an average of more than three objects per person. The average unit price of an IoT sensor exceeded US$1.30 in 2000; twenty-two years later, in 2022, it had fallen to US$0.50 (McKinsey 2022). According to the same study, 2G networks operated at approximately 50 kbps/s in 2000; Wi-Fi and short-range connectivity (Bluetooth) were only beginning to emerge. By contrast, in 2022, the power of the 5G mobile network was becoming available, with speeds of up to 20 GB/s—a 400,000-fold increase over 2000—alongside the expansion of Wi-Fi and short-range networks (Bluetooth), which had become standard technologies.

Links between technologies and the CE: From hope to reality:

Increasing regulatory pressure for the ecological transition, coinciding with the massive expansion of technologies, prompted businesses to establish a potential link between the two phenomena by placing technological tools at the heart of sustainable development and circularity. In 2010, the International Energy Agency (IEA) reinforced this "belief" by discussing a low-carbon technological revolution. In its report *Energy Technology Perspectives (2010)*, the IEA stated that technologies would help achieve a 50% reduction in CO_2 emissions by 2050.

After 2020, there was a growing realization that the long-awaited savings technologies promised for the CE had often been canceled out by rebound effects from those same technologies—for example, more energy-intensive data for AI.

4. Current developments

The advent of ubiquitous computing:

"Ubiquitous" or "diffuse" computing is described as a system enabling access to relevant information and the ability to act on it at any time and from any location (Banâtre 2007). It relies on interaction between users and physical objects, combining intelligent interfaces through mobile technologies: IoT, IIoT, smartphones, M2M devices, 3G, 4G (LTE), and 5G wireless networks, GPS navigation devices, and so on.

Ubiquitous computing is closely linked to the growing accessibility of AI. It supplies AI with large quantities of real-time contextual and spatial data needed to develop more powerful, accurate, and effective algorithms. AI, in turn, makes ubiquitous computing smarter, more adaptive, and more closely aligned with

consumers' needs wherever they are (Sajous 2023). The growth of ubiquitous computing can be understood through the growth of mobility. The fastest-growing category of mobile devices is M2M devices, which are widely used in businesses. This category of mobility, M2M, experienced an average annual growth rate of 30% from 2018 to 2023. Applications related to ubiquitous computing are also expanding rapidly, particularly in companies such as JCDecaux, Bouygues, Futuroscope, and Air France.

The explosion of generative AI: An environmental cost:

Over the past two years, we have experienced a significant leap toward generative AI, but one requiring the training of increasingly large models on enormous datasets. This approach is computationally expensive and highly energy-intensive. Models based on natural language processing (NLP), such as ChatGPT and Bard, have recently experienced a worldwide boom in applications for after-sales service, robotization, marketing, and other areas. These are the most powerful models, but also the most costly in terms of energy associated with computing power and processing time.

According to the 2023 annual Stanford Artificial Intelligence Index report (Stanford university 2023), training GPT-3—the language that powers ChatGPT3—by OpenAI in 2022 required the equivalent of 502 metric tons of CO_2 emissions and nearly 1,300 megawatt-hours of energy. In addition, during use, ChatGPT is estimated to generate 0.14 g of CO_2 per query. The number of queries is currently estimated at nearly ten million per day.

The explosion of virtualization after COVID:

Virtualization, which divides the hardware resources of a single physical computer among several virtual computers, and mobility have been the two most pervasive technology industries over the past ten years (IDC 2018). The data center world has been gripped by virtualization for several years, but the COVID-19 crisis marked a turning point that triggered an explosion in virtualized work.

In recent years, decentralized information systems in the cloud have become the norm because these solutions make it easy to manage dispersed networks and meet real-time requirements. In terms of energy savings and environmental footprint, virtualization delivers substantial efficiency gains through resource pooling, increasing a physical server's utilization rate from 20% to 80%.

The arrival of 5G: Higher consumption in the short term but better energy efficiency in the long term:

5G technology is being rolled out in many regions of France, supporting ultrafast, more reliable connectivity and thus the arrival of new technologies such as the metaverse, holograms, and digital twins. 5G offers industrial companies a connectivity solution that enables real-time process control and live tracking in activities such as logistics, surveillance, monitoring, and maintenance.

A recent study (Arcep 2022) suggests that introducing 5G would have a positive environmental impact in terms of network energy consumption. Although network densification using 5G increases energy consumption in the short term, compared with densification using 4G alone, it could deliver cumulative savings by 2028 equivalent to three to ten times the energy consumed in 2020 and two to eight times the volume of GHG emissions.

Toward greater interoperability through the OPC (Open Platform Communications) standard:

Interoperability is a key component of the industry of the future. The arrival of new connectivity standards such as OPC has greatly facilitated communication between factories' industrial control systems. Standards of this kind increase interoperability, reduce costs, and improve the flexibility and scalability of industrial automation systems. The OPC standard has enabled the expansion of data-source networking and data

operability, as well as the proliferation of interconnected IIoT devices, becoming the standard for comprehensive industrial automation in Industry 4.0 factories (Farnell 2023).

According to Omron Industrial Automation (Omron 2023), the increasing prevalence of OPC is reflected in the steady growth in membership of the OPC Foundation, which develops and promotes use of the standard in industry. Membership rose from 440 companies in 2016 to 800 in 2020. In terms of environmental impact, most sustainability reports recommend that businesses improve their interoperability arrangements to reduce the environmental impact of replication, particularly data replication.

Expanding connectivity:

More networks, more internet, and more IIoT: Industry 4.0 is accompanied by a dramatic increase in connectivity—that is, the ability to establish communication links between two or more remote systems, whether devices, equipment, or networks. Although there are several types of communication networks, such as voice or satellite signals, the internet remains the most widely used network. At the same time, we are witnessing an explosion of private networks, particularly for data security and confidentiality reasons, including LANs (local area networks) and MANs (metropolitan area networks). The scale and expansion of these networks are driven in part by falling costs for connected devices and services, particularly connected objects (IoT).

According to the 2022 Baromètre du numérique, IoT and smart speakers continue to spread: The proportion of people owning this equipment has risen by seven percentage points since 2020, and the IPv6 usage rate, an indicator of the number of devices connected to the internet, has increased by fifteen percentage points. France has moved from eighth to second place, behind India, in IPv6 usage.

The IIoT market, meanwhile, is expected to reach a value of $500 billion in 2025, driven by sustained demand from Industry 4.0 (McKinsey 2022). Sales of industrial 5G IoT devices are expected to increase from 0.2 million units in 2022 to seven million in 2024 and more than twenty-two million in 2030.

Toward more green technology policy: Calls to twin the technological and ecological transitions:

Alongside funding mechanisms for technological innovation, and with almost the same intensity, programs and initiatives supporting the circular economy and sustainability are multiplying in France and the EU. The Green Deal, one of the European Commission’s flagship priorities, emphasizes the need to twin the digital and environmental transitions by 2050. The Body of European Regulators for Electronic Communications (BEREC) has also incorporated issues related to the environmental footprint of digital technology into its 2021–2025 strategy. Several proposed regulatory texts have been published at the European level to advance efforts to reduce technologies’ environmental footprint, particularly new ecodesign and energy-labeling rules for smartphones and tablets, as well as a proposed revision of the Consumer Rights Directive to better combat planned obsolescence and greenwashing. The European Commission has also put forward a proposal for a new ecodesign regulation providing circular economy standards for products circulating in the EU, including technology products.

Technologies’ environmental impact has also attracted increasing attention nationally. Numerous reports published in recent years have raised concerns about the sector’s carbon footprint and its trajectory (ADEME et Arcep 2022) (Sénat France 2020). In a recent report, ARCEP identified five ways to promote digital sufficiency that ultimately converge with the pillars of the circular economy: (1) questioning the scale of development of new digital products or services, (2) reducing or stabilizing the number of devices, (3) extending the lifespan of user devices, (4) expanding equipment refurbishment and repair, and (5) raising consumer awareness of issues surrounding equipment reuse (Arcep 2023).

European regulations on data and AI:

After tightening its restrictions on data storage, data processing, and privacy through the GDPR in 2016, the European Union (EU) began publishing a series of reports in 2018 aimed at governing the use of autonomous, AI-based programs. These reports stress the need for clear explanations in professional settings when implementing autonomous programs. The EU also seeks to restrict the use of autonomous or semiautonomous intelligent programs, particularly when they raise ethical questions.

These initiatives represent the first concrete measures to govern the development and application of artificial intelligence (AI). They also affect connected objects (IoT) that collect or process data subject to ethical regulations. Big data analytics is similarly affected, as it must now adapt to restrictions on processing all available data. These developments mark a turning point in the regulatory landscape, significantly influencing the future development and use of these emerging technologies.

France's nuclear-centered electricity mix and the growth of renewables:

France's electricity mix currently has a low carbon intensity, particularly because of the scale of its nuclear fleet. France has Europe's largest nuclear fleet and the world's largest nuclear share of an electricity mix, at 70% (Fondapol report). Between 2010 and 2020, although gross electricity generation remained stable at around 540 TWh per year, the installed generation fleet saw increased capacity in solar photovoltaics (+9 GW) and onshore wind (+11 GW), alongside a decline in nuclear electricity generation. In particular, the closure of the Fessenheim nuclear power plant in 2020 reduced nuclear capacity by nearly 2 GW (ADEME report).

Since the early 2000s, France has implemented an ambitious policy supporting renewable electricity. Total government commitments between 2000 and 2020 amounted to approximately €60 billion for solar photovoltaics and €60 billion for onshore and offshore wind. These investments helped structure the sectors and reduce production costs, both key factors in successfully transforming the electricity system. In recent years, China has taken the lead in renewable energy, with the largest installed capacity in wind, solar, and hydropower. It has sharply increased industrial production in these areas and made these technologies economically viable.

Plastic: An essential material whose negative externalities encourage the search for an alternative—bioplastics:

Today, plastics are a key component of sectors such as packaging, construction, transportation, health care, and electronics. Global plastics production rose from fifteen million metric tons in 1964 to 348 million metric tons in 2017. Plastics are increasingly replacing other packaging materials. Between 2000 and 2015, their share of total packaging volume rose from 17% to 25%.

Since plastics first emerged, only 9% of the plastics produced have been recycled, and 12% have been incinerated. This means that a large majority ends up in the environment or in landfills, where they take centuries to decompose, releasing greenhouse gases that contribute to climate change. Oil consumption for plastics production is equivalent to the global consumption of the aviation sector and could more than triple by 2050 if current trends continue.

In response, efforts to find an alternative to conventional plastic are accelerating significantly, and demand for bioplastics and recycled plastics is growing considerably. Global production capacity for biobased and/or biodegradable polymers was estimated at 2.11 million metric tons in 2018, less than 1% of all plastics produced annually. Of this total, 43% are biodegradable, including 30% that are both biobased and biodegradable. The market remains driven by biobased, nonbiodegradable PET, which accounts for 27% of the market, and biodegradable starch-based blends, at 18%. Growth in Europe is approximately 6.4%. PLA and PHAs, which are biodegradable, will be the main market drivers in the coming years (European Bioplastics association). Companies such as Coca-Cola, Danone, IKEA, Samsung, Procter & Gamble, and Heinz

offer some of their products and/or packaging in bioplastic. LEGO plans to produce everything from bioplastics by 2030.

5. Foresight exploration

Structural trends

Tension between technology and circularity:

Today, the circular economy occupies a central place among the challenges facing industry in France, driven in particular by legislative changes such as the AGEC law (2020) and the RE2020 law. Alongside these developments, industry is also undergoing profound digital transformations resulting from the increasing integration of increasingly widespread technologies such as AI, big data, and blockchain. Industry 4.0 must incorporate automation, optimization, and intelligence capabilities while facing the new challenges of the circular economy. One of the main pillars of this transformation lies in the technologies themselves, which significantly influence the circular model during manufacturing, use, and operation. The emergence of the digital pollution rebound problem underscores the need to incorporate digital sufficiency into the circular economy approach. The next decade in French industry will continue to be marked by significant tensions in simultaneous efforts to bring technology and ecology into alignment. It will continue to face the challenge of reconciling the circular economy with technological developments.

Toward greater decentralization and interconnectivity:

According to Forbes 2022 (Forbes 2022), in the future, everything that can be connected will be connected in businesses and organizations of all kinds. This applies not only to devices and products but also to living and working spaces. From smart factories to smart offices, everyday spaces will increasingly be equipped to monitor what is happening and act accordingly.

According to the McKinsey 2022 report (McKinsey 2022), the overall IIoT market is expected to grow by 12% annually through 2025 and beyond, driven by strong underlying demand from industrial infrastructure and the greater availability of use cases, which are proliferating in construction, manufacturing, raw-material production, and transportation.

Datafication: Toward “very” big data:

With the combination of data-hungry AI, big data analytics, and data-producing IoT, the world will become increasingly datafied! The massive quantities of data generated by machines and people in industry currently show no sign of slowing, despite growing warnings about storage space and increasing cybersecurity risks. Because datafication is a powerful means of designing systems that can create better products and services, improve business processes, strengthen decision-making, and even generate new revenue streams, businesses are not ready to slow it down.

Intensive development of AI in businesses:

AI integration is advancing rapidly and intensively in businesses, driven by the imperative to create value (Gartner 2023).

An infallible tool for decision-making and the automation and optimization of industrial processes, AI will take a leading role in most companies’ business objectives in the coming years. According to the McKinsey 2022 report, between 2025 and 2028, pioneers in AI integration can expect their cumulative cash flows to increase by 122%, compared with only 10% for followers. Companies that have not adopted AI, meanwhile, will see their cash flows decline by 23%. By 2028, 75% of enterprise software engineers will use AI coding assistants, compared with less than 10% at the beginning of 2023.

Moore's law and exponential growth: An increasing carbon footprint:

The rapid growth of computing capacity under Moore's law, with electronic component capacity doubling every eighteen months, has enabled many technologies to mature. It will, however, cause a considerable increase in demand for computing resources, energy, and abiotic materials. According to the International Energy Agency, digital technology currently accounts for 3.7% of global greenhouse gas emissions, a share expected to rise to 14% by 2040.

An Arcep report (ADEME et Arcep 2023) indicates that the carbon footprint generated in France would increase by approximately 45% by 2030 compared with 2020, rising from 17.2 million to twenty-five million metric tons of CO_2. This would be accompanied by a 35% increase in resources used, from 63.7 million to eighty-eight million metric tons; a 14% increase in consumption of materials and minerals, from 952 to 1,081 metric tons; and a +4 increase in energy consumption, from 52 to 54 TWh.

According to a Senate report, in 2020 the carbon footprint of digital technology was primarily associated with user devices, which accounted for 79% of the footprint, followed by data centers at more than 16% and networks at around 5%. The manufacturing phase of technology equipment—user devices, servers, machines, and so on—reportedly accounted for 78% of the total, while the use phase accounted for 21%.

Increasing electricity consumption through the electrification of end uses:

Electrifying energy end uses is one of the main ways to achieve carbon neutrality and is a major European Union objective through measures such as Fit for 55. Even with strong energy sufficiency measures, electricity generation will therefore have to increase substantially through low-carbon sources, both nuclear and renewable. There is unanimous agreement on this point among the IPCC, the International Energy Agency (IEA), the European Union, and RTE, which expect French electricity consumption to grow by 30% to 50% by 2050. Electrification of end uses will primarily concern the three largest greenhouse gas–emitting sectors: transportation, at approximately 30% of emissions; buildings, at 23%; and industry, at 25%.

Advancing research on bioplastics:

Research on biobased and biodegradable materials is currently particularly active, with more than 1,400 scientific publications per year over the past ten years. Research is progressing and innovation is developing around the world, particularly in Europe.

Uncertainties

A crisis of confidence in AI:

Last year, Italy became one of the first countries in the world to ban the use of ChatGPT platforms—conversational generative AI—in public digital spaces following noncompliance with European GDPR restrictions and misuse of the tool in schools and academic settings.

In response to such concerns, the phenomenon of "AI trust" is emerging. According to the latest Gartner 2023 report (Gartner 2023), managing AI trust, risk, and security will become one of the ten strategic technology trends beginning in 2024. According to the same report, by 2026 businesses are expected to increase AI trust and security controls in an effort to eliminate 80% of erroneous and illegitimate information.

The evolution of cybersecurity:

Cybersecurity will remain an ongoing concern, particularly with the growth of open systems using short- or long-range connectivity, such as ubiquitous computing (Banâtre 2007) and pervasive computing (ZDNet 2022). According to a Gartner report published in 2020 (Gartner 2020), 75% of businesses were expected to restructure their digital risk and security governance to address new security needs in information technology, operational technology, and IoT in 2023, compared with less than 15% in 2020. Although cybersecurity is crucial for protecting business activities, companies struggle to balance cybersecurity with operational requirements.

Since 2015, cyberattacks have become increasingly frequent. For example, in October 2016, many major service providers' websites—PayPal, Reddit, Airbnb, and others—were inoperative after being hacked through malware transmitted via IoT devices (Le journal du Geek 2016). Experts believe that ubiquitous computing is suffering from its relative immaturity, but improvements can be expected over a ten- to fifteen-year horizon, by 2034–2039, and the situation should reverse in the coming years. Nevertheless, there are still cyberattack techniques for which no response currently exists. Relay attacks are one example (Interstices 2015).

Explainable AI: The emergence of new constraints on AI:

In 2018, the EU report on the right to the interpretation of autonomous programs and the Villani parliamentary report brought the requirement for explainable AI to the fore. This new regulation would impose greater oversight of AI programs and affect their use and the limitations on their applications. The explainability of AI models must be constantly tested through model monitoring. This ensures that explanations and interpretations of AI models remain active while the model operates. Despite growing interest in these explainable AI models, their design and implementation remain technically complex.

Limiting data centers' environmental impact:

The data centers required for big data analytics are a major driver of energy consumption and generate the greatest impacts on the depletion of natural abiotic resources—metals and minerals—as well as on the carbon footprint and ionizing radiation. Servers and data centers consume large amounts of energy and have a significant environmental impact in terms of greenhouse gas emissions and carbon footprint, whether during manufacturing, throughout their lifespan, or through the cost of their disposal. According to the Gartner 2023 report (Gartner 2023), by 2027 more than 50% of businesses will use industry cloud platforms to advance their business initiatives, compared with less than 15% in 2023.

Arcep's 2023 activity report (Arcep 2023) on the environmental impact of digital technology in France from 2030 onward recommends making ecodesign standard practice for all digital equipment and infrastructure, especially data centers. According to the report, this should reduce digital technology's environmental footprint by 2030, with a reduction in the carbon footprint of up to 16% compared with 2020.

As early as 2021, the Fit for 55 project (Ministere TECT 2021) proposed by the European Commission included a number of measures relating to data centers' energy consumption and environmental footprint of at least 55% by 2030 compared with 1990.

The pace of renewable energy growth:

A number of foresight studies project massive growth in renewable energy. The IRENA report, for example, indicates that renewable energy capacity worldwide is expected to reach 10,770 GW by 2030, almost four times its current level. Nationally, in the scenarios developed by ADEME, renewables account for more than 70% of electricity generation by 2050, and even reach 97% in one scenario.

At the same time, however, renewable energy technologies face constraints on their use, including mandatory distances from homes and military and civilian radar facilities, the load-bearing capacity of commercial building roofs, roof orientation, and registered and listed heritage sites. They also face environmental constraints, such as Special Protection Areas, Natura 2000 sites, and wetlands, and social acceptance constraints, including growing public opposition to the damage done to the landscape heritage, noise pollution, and the loss of value of nearby homes. These constraints could limit the development of renewable energy.

The pace of renewable energy growth will also depend on technological innovation. In recent years, China has seen the emergence of floating solar power plants exceeding 150 MW, such as the plant in Huainan, and new floating or ultrahigh-performance photovoltaic modules. In wind power, innovation focuses on very

large, low-speed blades—nearly sixty meters long, produced by Sino Wind Energy—and blade materials, including high-strength silicon-aluminum-magnesium glass fiber.

Uncertain nuclear development dependent on technological innovation (EMR, fusion, Generation IV):

France plans to reduce nuclear power's share of its electricity generation from more than 70% today to 50% by 2035 by closing fourteen of its oldest units. One reactor is currently under construction, and the government is considering a program of six new EPRs to begin partially renewing the nuclear fleet in the early 2030s.

The future trajectory of nuclear power nevertheless remains uncertain. All ADEME scenarios assume that most existing nuclear reactors in France will be decommissioned by 2050. At the same time, however, the European Commission's scenarios for the same horizon envisage nuclear generating capacity of between 100 and 120 GW in Europe. The FONDAPOL report therefore estimates that 75 GW of nuclear capacity should be built in Europe by 2050, half of it by France. According to this analysis, 16 GW of new capacity would be commissioned by 2035 and 59 GW would be built by 2050. For France, this means commissioning one to two EPR reactors by 2035 and an additional twenty-two to twenty-three reactors by 2050.

The future development of nuclear power is limited by several constraints: high initial investment costs, costly financing arrangements, longer construction times—first-of-a-kind (FOAK) projects in France and Finland experienced major construction delays and very substantial cost inflation—and strong opposition from sections of the population, which has already led some European countries to halt or gradually phase out their nuclear programs.

This trajectory will also depend on technological advances enabling the design of future reactors that are safer, easier to operate, and more effective in managing waste. Current R&D focuses particularly on SMRs—small modular reactors with a capacity below 300 MW, enabling decentralized generation, whose deployment planned from 2025 onward will depend on their ability to achieve the expected cost reductions—Generation IV reactors, comprising six technology families1 at various research stages, most with gas-cooled fast reactors (GFR); lead-cooled fast reactors (LFR); molten salt reactors (MSR); sodium-cooled fast reactors (SFR); supercritical water-cooled reactors (Supercritical water-cooled a closed fuel cycle to minimize waste). And nuclear fusion: With very limited nuclear waste and no risk of a reactor core meltdown, this technology is highly promising but will not be commercially viable for several decades. Innovation within power plants also involves digitalization, digital twins, and robotization, supporting flexibility, maintenance, and cost reduction.

Electrifying thermal processes to decarbonize industry:

Thermal end uses offer the greatest potential for industrial decarbonization. Electrification already provides a number of established solutions whose deployment must be accelerated: generating steam with electric boilers, electrifying furnaces, and deploying thermal solutions using resistance, induction, microwaves, or infrared. It also requires breakthrough technologies to reach maturity, including recovering waste heat through high-temperature heat pumps and replacing blast furnaces with iron electrolysis. Some processes will nevertheless be difficult to electrify, such as chemical processes and very high-temperature processes, and require decarbonization strategies involving CO_2 capture and storage.

Developing dedicated bioplastics recycling streams:

Most biodegradable plastics break down in a controlled environment available only in industrial composters. There are currently no suitable sorting bins for bioplastics or dedicated recycling streams. If they are mistakenly placed in yellow packaging recycling bins, they will therefore be incinerated with residual household waste.

Lower bioplastics production costs and market growth:

Today, biobased, biodegradable plastics are at least twice as expensive as conventional petrochemical plastics. “This difference is associated with the cost of raw materials and processing, as well as the amortization of research costs” (ADEME). However, economies of scale from higher volumes, improvements in manufacturing processes, and rising oil prices are tending to make biobased, biodegradable plastics increasingly competitive with petrochemical plastics. Reducing bioplastics production costs and developing viable business models are therefore central challenges for research in this field.

The global bioplastics market is expected to grow from 1.78 million metric tons in 2023 to 3.95 million metric tons by 2028. Europe accounts for the largest market share and is expected to dominate the market. The availability of cheaper alternatives, however, is likely to hinder market growth.

Weak signals

Toward Industry 5.0: More technology, with people more deeply integrated:

Industry 5.0, which has been taking shape since 2020, places people back at the center of technological transformation (uTrakk 2023). The term used is the “augmented” human. This is a further step toward automation that includes people, with more AI, more robotics, and more human-machine collaboration. Human-machine technologies will therefore be a focus of R&D and innovation, including conversational AI, IoT with visual and voice recognition, speech synthesis devices, blockchains, intelligent gesture interfaces, 3D printing, VR/VA, and digital twins. According to the World Robotics 2021 report (marketsandmarkets 2023), growth in installations of collaborative human-machine robots in Industry 5.0 is expected to exceed 6% in 2024 compared with the three million installed in 2021, in just three years.

Industry 5.0 is expected to bring an exponential increase in connectivity among people, machines, and data. Big data and datafication are therefore expected to increase considerably. The transition to Industry 5.0 is beginning gradually and remains in its early stages, with think tanks emerging at the European level beginning in 2020.

Quantum computing: The emergence of a likely revolution:

According to an article in Forbes 2022 (Forbes 2022), the next major leap forward will probably come from quantum computers. These computers are so fast and powerful that they could perform new tasks previously impossible and unfeasible with current technologies. A quantum computer should enable parallel computations to be carried out simultaneously, rather than sequentially as with our current machines.

By considerably improving the use of big data, qubits will ultimately enable a giant leap in AI research. Quantum computers have not yet left the laboratory, but technology companies and researchers are investing in this field. Google, for example, is pursuing several projects simultaneously with the University of Santa Barbara and NASA. Intel unveiled a forty-nine-qubit processor developed with the Dutch university in Delft at the most recent CES. IBM and Microsoft are also designing their own computers based on quantum bits.

Traceability through blockchain:

“Digital trust” refers to the trust consumers place in organizations to build a secure digital world in which transactions and interactions can take place safely. Blockchain is considered a key technology for building this digital trust and securing interactions. However, it still has a long way to go before becoming truly accessible to all types of organizations because of the technical complexity of its implementation.

Unlocking data controls in Europe:

Because of the constraints that the 2016 GDPR places on the development of AI programs, the EU has recognized the need to “free” data and facilitate its sharing. Over the past three years, it has launched new legislative initiatives involving several regulations to unlock and open digital ecosystems. At the same time,

the EU is working to promote greater data sharing within these ecosystems through open data. It therefore already proposed adoption of the Data Governance Act (DGA) in 2022, followed by the Digital Markets Act (DMA), which entered into force in 2023 to ensure fair and open data markets, and then the Data Act, creating the category of "data intermediation services" on January 11, 2024. This should further promote R&D developing big data analytics and AI technologies.

The emergence of pervasive computing (Ubicamp):

Also called "ambient computing," or "ubicomp," from the English term "pervasive computing," ambient computing would be the next phase after ubiquitous computing, which likewise places the user at the center of its socioeconomic model (Waldner 2007). For Weiser, the father of pervasive computing, these systems must not only become widespread but also become invisible to users to qualify as pervasive computing. This requires changes to every configuration of human-machine interaction, something pervasive computing does not yet accomplish.

At the 2022 Google I/O conference, a special session was devoted to pervasive computing, presented as a rapidly evolving field. According to an article in ZDNet (ZDNet 2022), Amazon and Google both seek to lead this sector by increasing the number of devices connected to their voice assistants.

Pervasive computing would provide everyone with access to information through dispersed devices instead of centralized equipment and databases. Examples are beginning to emerge, such as IoT sensors that manage fleets and pipeline components, or lighting systems controlled through simple mobile applications.

In the Ubicamp environment, technological tools are networked and permanently available. These technologies must incorporate wirelessly connected mobile IoT devices, radio-frequency identification (RFID) tags, middleware, and autonomous software agents with AI capabilities, but above all embedded computing devices that enable completely invisible interactions between equipment and people.

Using red algae–based bacteria to degrade plastic:

Recent laboratory research shows that certain highly abundant bacteria, referred to as "platisphères," can make "holes" in plastic and thus contribute to its biodeterioration. Ongoing work seeks to demonstrate that these laboratory results can be achieved in natural environments. In addition, BASF's venture capital company and a Dutch investment fund have been investing in Sea6 Energy since 2022 to develop bioplastics from tropical red algae.

Controversies

Green technology: Myths versus reality!

Artificial intelligence: Between optimization and energy consumption

AI can optimize logistics flows, reduce losses in physical flows (Willemot and CHaussat 2020), optimize flows, and reduce waste. Data analytics and big data support data collection, monitoring, and advanced analysis to improve resource management. They thereby help businesses develop and adhere to a circular model and optimize their use of raw materials, energy, and resources (Demer 2022). However, training ever larger AI models, such as large language models (LLMs), requires substantial computing power and energy consumption. According to the article (Excluvité 2024), AI workloads accounted for approximately 4.3 GW in 2023, or 8% of overall data center consumption of 57 GW.

Blockchain

Blockchain can track every transaction associated with a product and provide greater traceability, as in IBM Food Trust. This can offer solutions to combat greenwashing, reduce waste, and improve recycling, as in CircularChain. However, blockchain's consumption is substantial because of its network-based proof-of-work mechanism and continuously automated transactions. According to a study by Selectra (Selectra 2023),

bitcoin's electricity consumption in 2021 was sixteen times its 2017 level—equivalent to 75% of the combined consumption of everyone in France!

Internet of Things

IoT devices can monitor and improve product life cycles, as in Clothes ID, and collect information on and improve the management of recycling points, among other uses. However, manufacturing, using, and disposing of IoT devices consume energy and natural resources in the form of materials. The recycling or degradable disposal phases of IoT devices also raise major questions for manufacturers.

The Big Brother effect: Seeking technology yet resisting it:

Big Brother refers to the concept of extensive surveillance or excessive control by authorities—governments, organizations, businesses, and others—over citizens' private lives through surveillance technologies, security cameras, online data collection, and similar means.

According to Weiser, the computerization of all spaces as pervasive computing expands would generate many future concerns associated with the "Big Brother" phenomenon (Méadel and Musiani 2016). Consumers today seek technological and intelligent tools and devices, but when these tools are associated with workplaces or managed by others, reluctance emerges in working environments. This may affect the adoption and development of these technologies.

Pressures that large-scale bioplastics development could place on agricultural land:

Most biobased plastics use plant raw materials grown on agricultural land. Some therefore see a risk of future competition over the use of food resources. In addition, reliance on conventional agriculture entails the use of chemical inputs, puts pressure on water resources and soils, and creates a carbon debt.

These legitimate concerns about food security and pressure on agricultural land should not, however, be exaggerated. Production of biobased polymers, still low in volume, currently uses very few agricultural resources. In 2018, however, bioplastics production amounted to 2.11 million metric tons, or 1% of plastics, using 0.02% of the world's agricultural area.

To prevent this issue from becoming a real problem in the longer term, research is now focusing on producing biopolymers from diverse resources that do not compete with food crops, particularly organic waste such as crop residues and agrifood byproducts, whose use currently remains very limited. The issue of pressure on agricultural markets may nevertheless become a source of controversy.

Disruptions

Cable failure: Undersea vulnerability at issue:

Today, the internet runs beneath the seas. Thousands of kilometers of submarine cables provide approximately 99% of global connections for internet and telephone communications. An estimated more than $10 trillion in daily financial transactions, equivalent to four times France's annual GDP, currently travels under the sea. In a scenario in which submarine internet cables were cut simultaneously, the consequences for global connectivity would be severe, because most international communication networks depend on this infrastructure. As a result, big data technologies, AI, connected factories, IoT, online services, smartphones, e-commerce, and other technologies would all be affected.

Several articles also point out that the vulnerability of submarine cables poses a real threat to Europe (20Minutes 2021). Following the recent Red Sea crisis, these threats are becoming more likely than before.

Wi-Fi's impact on health:

Wireless technologies, including Wi-Fi, have been the subject of numerous health-impact studies to date. The International Agency for Research on Cancer (IARC) and the World Health Organization (WHO) have classified the radiofrequency electromagnetic fields emitted by Wi-Fi relay devices as "possibly carcinogenic"

(Choisir 2023). France's 2015 Abeille law also established several rules and limitations governing Wi-Fi use. If diseases potentially linked to Wi-Fi were suddenly discovered, the technology industry would face major changes. Manufacturers of Wi-Fi devices could be required to rethink them, find alternatives, or return to wired networks for connectivity.

A halt to AI: War and deadly mistakes at issue:

On Tuesday, July 28, 2023, the United Nations secretary-general reaffirmed his intention to regulate AI use, particularly in armed conflicts2. If wars increasingly use AI and the public witnesses more and more deadly mistakes—killer drones striking in error!—a blanket ban could become likely in military, civilian, and economic settings alike.

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