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European Commission

Emerging Technologies in Electronic Components and Systems (ECS)

OPPORTUNITIES AHEAD

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Emerging Technologies in Electronic Components and Systems (ECS) - Opportunities Ahead

ANNEXES

Directorate-General for Communications Networks, Content and Technology
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1. Emerging Micro and Nano components (MNE)

A. More Moore technologies

i. Definition

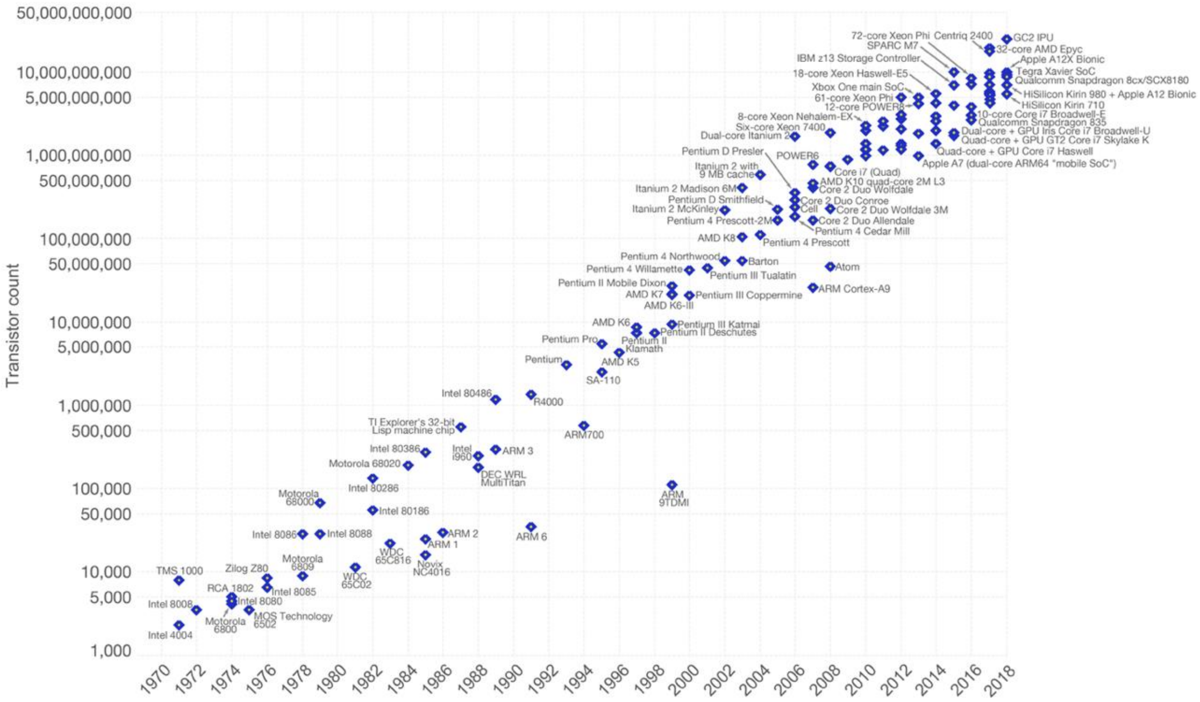
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. Four main values are scaling every 2−3 years with the introduction of new technology nodes:

- (P)erformance: >15% more operating frequency at scaled supply voltage;
- (P)ower: >35% less energy per switching at a given performance;
- (A)rea: >35% less chip area footprint;
- (C)ost: <30% more wafer cost – 20% less die cost for scaled die.

This advancement is important as other aspects of technology progress -such as processing speed of electronic products and cost per transistor- are linked to Moore's law.

Even if the speed of doubling has been reducing over the past years, the global trend is still there. **More Moore technology** simply refers to all the processes based on silicon CMOS technologies used to maintain the trend as long as possible.

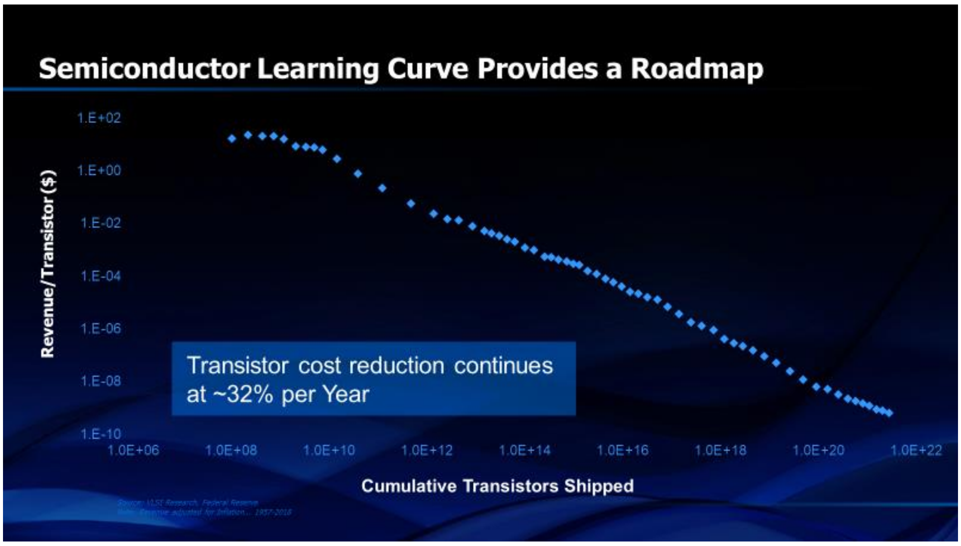
Moore's law – The number of transistors on integrated circuit chips (1978-2018)



Source: Max Roser, Our World in Data

From 1954 to 2019, the average cost of a transistor in constant dollars has decreased at an average rate of -32% per year. Since 1995, the average cost of a transistor memory has decreased at an average rate of at –35% (–23% for remaining semiconductors). This is due to the continuation (even at a slightly lower rate) of Moore's law with critical dimension of transistors in production reaching now a node range of 7 nm.

Learning curve for the transistor from 1954 to 2019



Source: Wally Rhines, CEO Mentor Graphics: “Predicting Trends in the Semiconductor Industry”.

ii. Synergies with other emerging technologies

More Moore technologies are today and will remain until 2025-2030 the basis of most electronic applications:

- Directly through classical devices (CPU, GPU, FPGA, Asics, memories, etc.);
- As parts of the systems command as logic technologies;
- Through specialized processor units made to support and implement emerging computing technologies: AI algorithms, neuromorphic computing, supercomputing, IoT, edge computing, secure elements, authentication & identification systems, cryptography, blockchain, new mobile communication systems, etc.

It is now admitted that embedding artificial intelligence (AI) in chips will drive significant long-term industry growth by processing far more big data computations and much faster than humans can with "traditional" computing methods. Over the next 10 years, the majority of both the volume and the value of those chips will be driven by More Moore technologies.

In the same manner, the emerging electronic computing architectures regrouped under the name “Rebooting computing” will be made over the next 10 years in majority on chips produced with More Moore technologies before moving to Beyond CMOS technologies like photonics. For instance, the recent IMEC, LETI and STMicroelectronics developments in neuromorphic computing are embedded in the EC Horizon 2020 project NeuRAM3. The project’s goal is to implement novel hardware specialized for neuromorphic computing and the technology used to build this hardware is based on More Moore bricks.

A separate roadmap that covers the specific memories field (DRAM, NVM-Flash, NVM emerging (FeRAM, MRAM, PCRAM and Crosspoint Memory, Resistive Memory / ReRAM, etc.), can be found in the chapter “Innovative memories”.

iii. Technology roadmap: Maturity levels and expected impacts by application area

There is a trend toward a consensus saying that **the Moore’s law** by the strictest definition of doubling chip density every two years, **is not happening anymore**[1].

[1] Jensen Huang (NVDIA CEO) at CES 2019, Mike Muller (CTO Arm), MIT, MediaTek, etc.

Companies like Intel, TSMC, Samsung, etc. continue to find ways of stretching today's silicon transistor technology. Yet, the industry is more and more embracing other kinds of computing using GPUs, stacked GPU's, FPGA's, advanced software frameworks and tools, and new ways of packaging the chip circuitry.

According to the IRDS, ground rule scaling is expected to slowdown and saturate around 2027 causing the absolute necessity to use 3D architectures to reach the 1 nm node seen in 2033. **The "last node" of 1 nm will likely enter in full production after 2033**. In the meantime, the 5 nm node should enter industrial production around 2022 and the 3 nm after 2025. Therefore, the race continues towards 5 nm, then 3 nm and 1 nm. This will be done through (see the table below that shows the main inflexion points that will come at the device level and so defines the needs in terms of materials/equipment needed for manufacturing):

- Ground rules scaling, nevertheless they are expected to slow-down and saturate for the classical 2D approach around 2027 where the 3D integration and cell architecture evolution will become the mainstream approach (see the table below);
- The transition to new devices architectures (neuromorphic in the first place);
- The use of new substrates on top of mainstream bulk Si: silicon-on-insulator (SOI) and strain-relaxation-buffer (SRB);
- High-mobility channels;
- Strain engineering;
- Reducing parasitic device resistance;
- Reducing parasitic device capacitance;
- Increasing drive per footprint;
- Improving electrostatics;
- Improving device isolation;
- Reducing process and material variation;
- Beyond CMOS for application-specific functions and architectures;
- Performance Power area scaling.

Device Roadmap enabling More Moore

	2017	2019	2021	2024	2027	2030	2033
	P54M36	P48M28	P42M24	P36M21	P32M14	P32M14T2	P32M14T4
Logic Industry « Node Range » Labelling (nm)	10	7	5	3	2.1	1.5	1.0
IDM-Foundry node labelling	i10-f7	i7-f5	i5-f3	i3-f2.1	i2.1-f1.5	i1.5-f1.0	i1.0-f0.7
Logic device structure options	finFET FDSOI	finFET LGAA	LGAA finFET	LGAA VGAA	LGAA VGAA	VGAA, LGAA, 3DVLSI	VGAA, LGAA, 3DVLSI
Logic device mainstream device	finFET	finFET	LGAA	LGAA	LGAA	VGAA	VGAA
LOGIC TECHNOLOGY ANCHORS							
Patterning technology inflection for Mx Interconnect	193i, EUV	193i, EUV DP	193i, EUV DP	193i, High-NA EUV	193i, High-NA EUV + DSA	193i, High-NA EUV + DSA	193i, High-NA EUV + DSA
Channel material technology inflection	Si	SiGE25%	SiGe50%	Ge, IIIV (TFET?), 2D Mat	Ge, IIIC (TFET?), 2D Mat	Ge, IIIV (TFET?), 2D Mat	Ge, IIIV (TFET?), 2D Mat
Process technology inflection	Conformal deposition	Conformal Doping, Contact	Channel, RMG	Stacked-device ; Non-Cu Mx	Stacked-device Non-Cu Mx	Steep-SS, 3D	Steep-SS, 3D
Stacking generation inflection	2D	2D	3D-stacking: W2W D2W	3D-device : P-over-N Hetero	3D-device : Mem-on-logic Hetero	3D-device : Mem-on-logic Hetero	3D-device : Logic-on-logic Hetero
INTERCONNECT TECHNOLOGY							
Conductor	Cu, non-Cu	Cu, non-Cu	Cu, non-Cu	Cu, non-Cu	Cu, non-Cu	Cu, non-Cu	Cu, non-Cu
Number of wiring layers	14	16	18	20	20	20	20
Barrier metal-tight pitch	Ta(N) Mn(N)	Ta(N) Mn(N)	Ta(N) Mn(N)	TiN (non-Cu)	TiN (non-Cu)	TiN (non-Cu)	TiN (non-Cu)

Acronyms used in the table (in order of appearance): FDSOI: Fully Depleted Silicon-On-Insulator (FDSOI), LGAA: Lateral Gate-All-Around-Device (GAA), VGAA: Vertical GAA, 3DVLSI: Fine-pitch 3D logic sequential integration. PxxMxxTx notation refers to Pxx: contacted poly pitch, Mxx: metalx pitch in nm, Tx: number of tiers. This notation illustrates the technology capability. Source: IRDS

The R&D and manufacturing of More Moore technology is based on 2 mains and essential pillars:

- **The manufacturing tool**, equipment and materials that are totally specific for this technology path (means developed and produced specifically for each technology node, even if to some extent, they can be reused also for other previous nodes and for More than Moore technologies);

- **The process knowledge**. This encompasses the set of rules to build the devices (layout rules, electrical rules, layer building and stacking), the technology assembly techniques and the knowledge of specific physical phenomena.

Both are equally strategic, and the manufacturing of More Moore devices is not feasible without the mastering of all those two technology bricks.

Main challenges to come (in particular to combat heating effects):

- **Materials issue**. Non-copper metalization scheme based on Ruthenium, Cobalt or other conductors' combinations coupled with new insulators are being developed for nodes below 5 nm;

- **IC issue**. At the IC level, the relative percentage of the system on chip approach should largely be increased and the interconnect technology is one of the main challenges;

- **…towards 3D**. One of the answers to build the always more complex systems needed will be the increasing use of 3D heterogeneous integration as part of the transition from 2D to 3D VLSI.

More Moore technology currently impact and will continue to impact in priority high volume end-user segments.

Technology Roadmap - Maturity of the technology at the global scale and by application area

Technology	Maturity level of the technology (2010 – 2030)			
7 nm	R&D	Test & Prototyping	Industrial production	Massive production
5 nm	R&D	Test & Prototyping	Industrial production	Massive production
3 nm	R&D	Test & Prototyping	Industrial production	
1 nm	R&D	Test & Prototyping		

N°	Electronic Segment	Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production
1	Automotive applications	Critical impact
2	Industrial & robotics applications	Critical impact
3	Health & Care applications	Critical impact
4	Aerospace applications	Medium impact
5	Defense & Security applications	Critical impact
6	Phones applications	Critical impact
7	Telecommunications infrastructures applications	Critical impact
8	PC & data processing applications	Critical impact
9	Audio & Video applications	Medium impact
10	Home appliances applications	Medium impact

N°	Crossed segments	Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production
1	Data analytics / Big data	Critical impact
2	Smart home	Medium impact
3	Smart mobility	Medium impact
4	Smart energy	Medium impact
5	Wearables	No significant impact

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain by 2023.

Source: DECISION Etudes & Conseil

Impact of More More technologies (nodes below 10 nm) by end-user electronic applications in 2023

	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Small	Small	Medium	No	Small	Small	Small	Small	Critical	Small	Small

Corresponding quantitative impact of More Moore technologies (nodes below 10 nm) in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
116	673	1 854	5 986	673	1 554	299	0	300	5 687
				Mobile phones, Consumer & Professional PC	Automotive electronics, Industrial & Robotics electronics, Defense & Security electronics, Heath & Care electronics, Telecommunication infrastrctures	Aerospace electronics, home appliances, audio & video	-	IT market service providers	Industrial equipments industry, automotive industry and Aerospace/ Defense/Security industries

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of More Moore technologies in 2023

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. In the World

There are 3 categories of industry players for More Moore:

- The suppliers of manufacturing tool, equipment's and materials specific for the very advanced nodes;
- The company's manufacturing and who will continue to manufacture More Moore technologies (nodes below 10 nm);
- The companies, fabless or IDMs, designing products based on More Moore that are or will be manufactured by manufacturing companies.

Manufacturers of More Moore technologies. As of today, it remains only 6 companies worldwide still able to participate to the More Moore race. None of them are European:

- Three of them on "standard" FinFET CMOS technology: Samsung, Intel and TSMC;

  Timescale of More Moore chips production

Company	Nationality	10 nm	7 nm	5-6 nm
Samsung	South Korea	2016	2018	> 2020
TSMC	Taiwan	2017	2018	> 2020
Intel	The USA	2019	> 2020	

  Source: DECISION Études & Conseil, based on companies' publications

  In 2018, the sales associated to 7 nm chips from TSMC and Samsung accounted for €6-8 B.

- Four of them on Memory technologies: Samsung, Hynix, Micron and Toshiba. These four players master the multilayer 3D memory technology and are investing heavily on the multiplication of the number of bits per cell to build state-of-the-art memories.

Finally, Global Foundry has a technology portfolio at the limit with 12 nm Fin FET and an FDSOI approach also existing in Samsung.

Capex dedicated to semiconductor of the Six companies still in the More Moore race

Company	2017 (B€)	2018 (B€)	2019 (B€)
Samsung	20	19	15
Intel	10	13	11
SK Hynix	7	11	8
TSMC	9	9	8
Micron	5	8	8
Toshiba	3	2	2

Source: DECISION Études & Conseil, mainly based on IC Insights estimates

More Moore technologies are manufactured only in Taiwan, South Korea and in the US.

Equipment. All the main equipment's suppliers (Applied Materials, ASML, Tokyo Electron, LAM Research, KLA, Advantest, Screen, Kokusai, Hitachi, ASM Pacific, SEMES, ASMI, etc.) who are today supplying the advanced semiconductor technologies will still be part of the race of More Moore with brand new or upgraded equipment's. Some equipment like the EUV lithography tool developed and sell by European company ASML have been developed specifically for More Moore. ASML is currently the only equipment manufacturer able to print the critical dimensions needed in a manufacturing environment worldwide.

Substrates. Bulk silicon will still remain the mainstream substrate while silicon-on-insulator (SOI) and strain-relaxation-buffer (SRB) will be used to support better isolation and defect-free integration of high-mobility channels. SOI also allows to choose device mode, either high performance or low-leakage. To be noted that like ASML in equipment's, the European company SOITEC is largely dominating the SOI market for More Moore with a recognized technological advance.

IDM (Integrated Device Manufactures). All the major IDMs (like Texas Instruments, STMicroelectronics, Infineon, NXP, etc.), are developing products using More Moore technologies but manufactured in foundry (TSMC and Samsung), whose production units are in Asia. The major fabless manufacturers like Broadcom, Qualcomm and NVidia are also largely using this technology and this global approach with manufacturing in TSMC and Samsung's plants.

Main research institutes/clusters

- In the USA in the New York state: SUNY Polytechnic Institute Albany complex;
- In the EU at IMEC (and some developments made in LETI and Fraunhofer in agreement with IMEC);
- In Japan at the university level (Tokyo, Tohoku);
- In Taiwan: the ITRI.

China has not yet manufacturing capabilities below 28 nm in its territory (two foundries of 28 nm are owned by SMIC). Nevertheless, UMC and TMSC both have at least one foundry in the Chinese territory and the Chinese government has clearly the willingness produce advanced technologies in mainland China. Besides, Taiwan is considered as a part of the Chinese territory in this report[2].

Furthermore, China has currently the greater number of microelectronics engineers in the World. Formed continuously since the 1990s, they represent hundreds of thousands of engineers working on MNE innovations.

[2] Indeed, China is for several years preventing other countries to maintain diplomatic relations both with Taiwan and China and similarly to recognize both China and Taiwan as sovereign states. As a consequence, in September 2019, only 16 countries out of 206 (8%), were still officially recognizing Taiwan as a sovereign state: The Holy See, Paraguay, Belize, El Salvador, Guatemala, Haiti, Honduras, Nicaragua, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, the Marshall Islands, Nauru, Palau, Tuvalu and the Swaziland. Kiribati and the Salomon islands have announced in September 2019 that they were not recognizing Taiwan as a sovereign state anymore, and China is putting more and more pressure on the remaining countries recognizing Taiwan in order to change their diplomatic position, so that in the coming years, Taiwan should be recognized by less and less countries.

B. In the EU

Manufacturers of More Moore technologies. European manufacturers are no longer in the innovation race for More Moore technologies. Furthermore, no capabilities exist below 20 nm in the EU territory. From 2016 to 2018, Global Foundries planned to set up a 12 nm FDSOI factory in Dresden. This plan has not been followed through. Therefore, the knowledge about manufacturing of those technologies is unfortunately no more present in Europe.

Equipment. Nevertheless, on equipment's and materials, with ASML as the only photolithographic tool supplier (193 nm immersion and EUV), the EU possess at least one unavoidable asset. Two European companies (ASML and ASMI) and one Swiss (ASM Pacific Technology), are still part of the More Moore race and are within the top 15 worldwide equipment suppliers. Smaller companies like RECIF (France) or Süss microtec (Germany) are among others significant players in terms of R&D and advanced manufacturing and can maintain or enlarge their market shares.

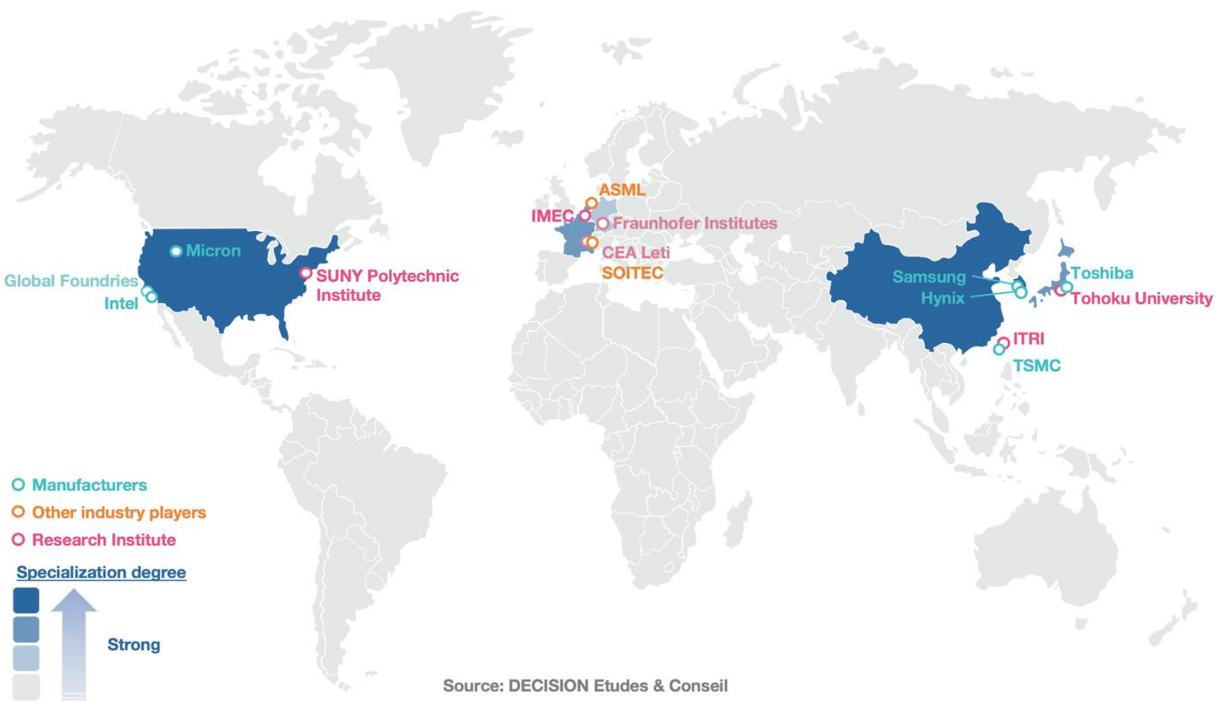
Substrates and materials. For the processes where SOI characteristics are key, SOITEC is by far the leader at the global scale. Air Liquide (France), and Linde (Germany), are global leader in gas for semiconductors. Furthermore, Linde has improved its market position since after its merger with the American Praxair in 2017. Linde-Praxair and Air Liquide are among the top 3 players of the industrial gas market along with Air Products Chemicals (The USA).

EDA (Electronic Design Automation). Research in design is and will be supported by EDA companies. The European leader in this domain is Mentor, a Siemens company.

IDM (Integrated Device Manufactures). The EU maintains some competences on design of devices (in ST, Infineon, NXP and very few fabless), but the critical data being only owned by who masters the volume of manufacturing, the efficiency of the designs and the delivery of products is totally linked to the willingness of the producers. This is a very clear strategic issue for European electronic and final markets.

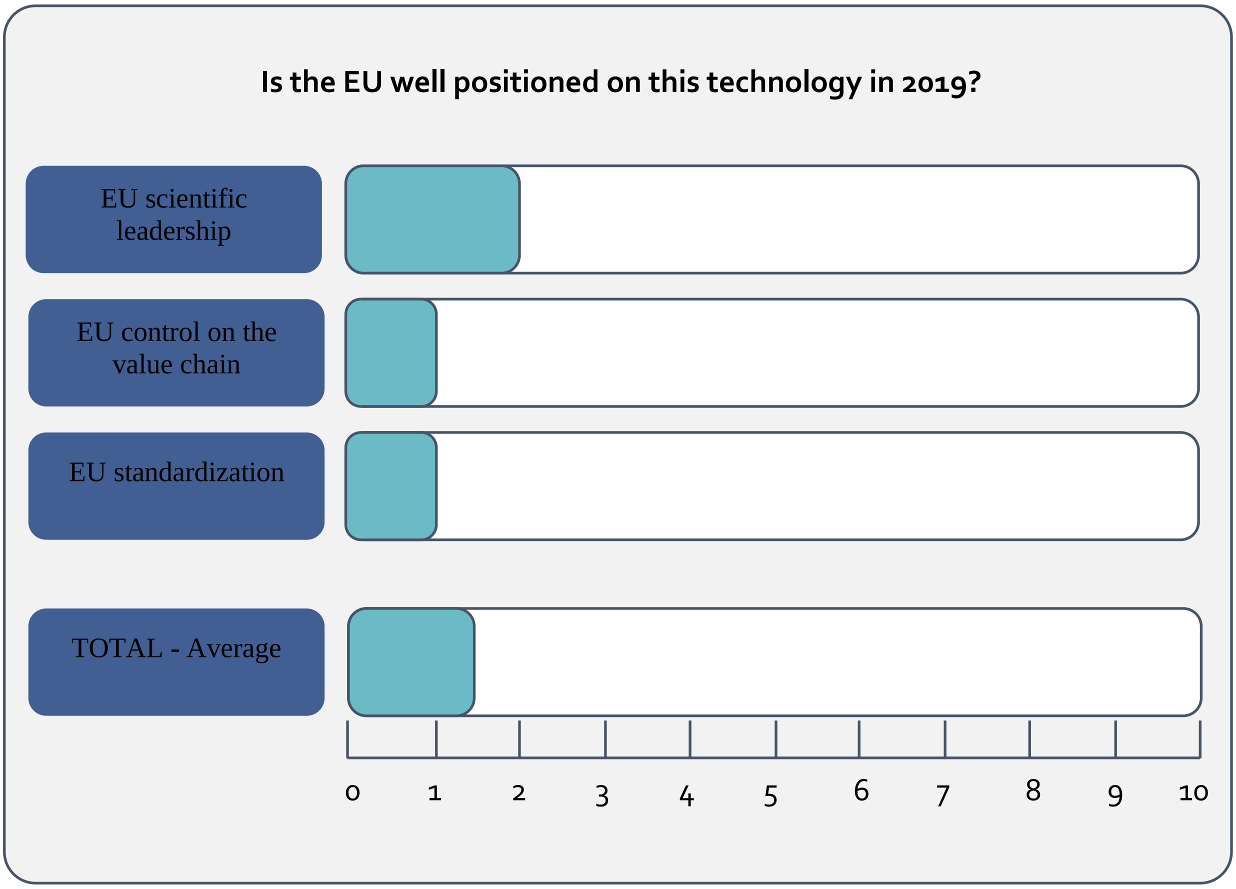
Research institutes/clusters. IMEC (supported by the CEA Leti and the Fraunhofer Institutes), remains a key player which compete with main R&D centers in the US, Taiwan and Japan.

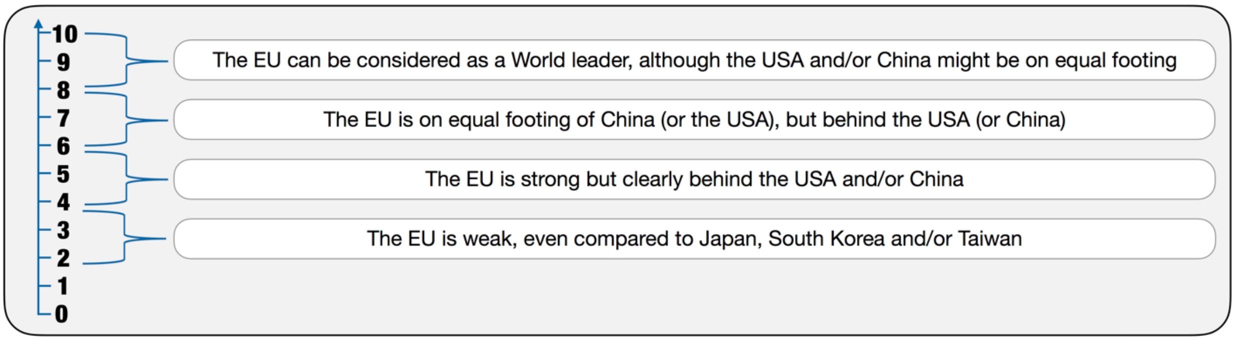
World Map - More Moore key players



V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

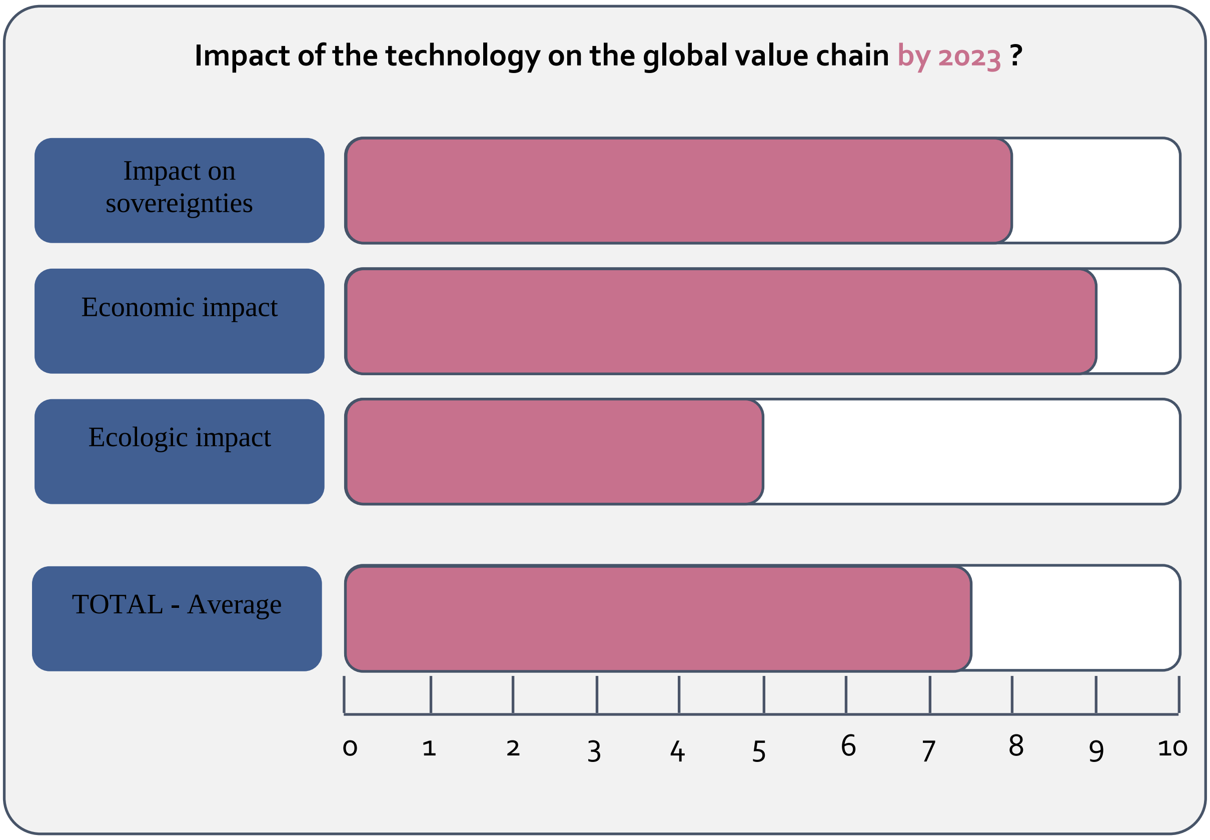
A. Position of the EU in the World in 2019





Source: DECISION Études & Conseil

B. Expected impacts of the technology



Source: DECISION Études & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.
- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023**.
- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

In terms of pure R&D, the EU maintains a relatively good position thanks to the IMEC (supported by the CEA Leti and the Fraunhofer Institutes). Yet, the EU can hardly compete on the critical knowledge and innovation linked to the production steps as no European players manufacture more moore technologies and no manufactures of more moore technology exist in the EU territory.

EU control on the value chain

No More Moore technologies are produced neither in the EU territory, nor by EU players. The only two remaining key players in the more moore innovation race in the EU are ASML and SOITEC, at the level of equipment and substrates. Besides, the principal shareholders of the main “European player” ASML are American (93.6%

floating capital of which 15.6% owned by Capital Research & Management Co (US), 3% owned by Intel (US); 2.6% owned by the Vanguard Group (US), the rest being owned by smaller shareholders).

Standard analysis

Within semiconductor manufacturing, standards set by states correspond to safety & security rules related to chemicals (like REACH or equivalent in other countries), to electrical power rules, to people employment rules that are not specific to the semiconductor and to the RoHS rules (or equivalent in non-EU countries), that ban the use of certain chemicals like lead, cadmium or phthalates.

At the level of chip manufacturing, more than one thousand "SEMI standards" for the materials and equipment are set by the profession at worldwide level to assure the standardization of the materials and of the equipment's interfaces (mechanical, electrical and software). They will continue to evolve together with the advance of the technology. Yet, States are not involved in these standards.

There is no standard related to the semiconductor technologies themselves (design rules, electrical rules, reliability and so on...). In fact, each supplier has its own standards and specifications, depending on the technology processed that are provided to the different users and are possibly negotiated with them. As a consequence, the state of play of the EU regarding standards corresponds exactly to the competitive position of the European players (like ASML and Soitec), able to impose their specifications to other players. As a consequence, as these specifications are mainly decided by the non-European players that master the volume of manufacturing, the EU is considered subtle in terms of standards.

Finally, technological standards exist for the final products specifications made like communication devices (GSM, TV, radio...), measurement devices, medicine devices, automotive devices and so on. They are related to the characteristics of the signal to measure or to emit that is standardized or to the reliability of the device (like the Mil Standards).

Impact on sovereignties

More Moore technologies are currently the only functioning technology that can be used for computing applications requiring high processing capabilities (that is most of emerging computing applications: ADAS, 5G, etc.). More Moore technologies will continue to be used for a long time, alongside new technologies coming from beyond CMOS that, as soon as they become industrialized, will gradually grow and then move on.

Besides, a technological security issue cannot be excluded when using chips that are not produced in the EU territory and / or by European players. The rise of protectionism can also lead to a situation where non-European players and / or states might refuse to deliver such products to the EU, placing the EU in a less competitive position towards its competitors.

This is currently the situation of the EU regarding More Moore technologies and this situation should continue unless the EU decides to invest in order to build a European player with More Moore technologies facilities in the EU territory (more than €15 B required plus market support to grow the company to a competitive level). Even if the EU were to invest in players using material(s) that will replace More Moore technologies by 2030-2040 (beyond CMOS technologies and / or biochips and / or molecular electronics), those technologies will not replace More Moore technologies but will rather be used in a complementary manner.

Economic impact

More Moore technologies:

- Are currently the only functioning technology that can be used for computing applications requiring high processing capabilities;
- Are largely used in consumer/stand-alone end-user segments (accounting for nearly 50% of the global electronic markets in 2019);
- Are more and more used in embedded/professional end-user segments (accounting for more than 50% of the global electronic markets in 2019).

As a consequence, the economic indirect impact of More Moore technologies over the 2019-2027 period is maximum. In terms of pure market value, the estimated market of More Moore technologies is €116 B. This market value is based on the estimated SC sales in 2023 of the six players still involved in advanced technologies in 2023: Samsung, Intel and TSMC (for the chips with nodes below 10 nm), and SK Hynix, Micron and Toshiba (for advanced memories)[3]. We forecast More Moore processors and ASICs sales to account for around 50% of the SC sales of Intel, 30% for TSMC and to 15% of the SC sales of Samsung by 2023: mainly composed of 7 nm chips, but also 5 nm chips that should have been released. These chips' sales should be dedicated to the consumer markets demanding the greatest processing capacities and to the takeoff of edge AI, neuromorphic computing, etc. In terms of volumes of production, 5 & 7 nm chips should not account for more than 25% of the total, but with far higher prices than the average (especially for 5 nm chips in 2023). Regarding the memories, the speed of replacement of old technologies by advanced memories should be faster, leading to advanced memories accounting to nearly 60% of the SC sales of SK Hynix, Micron and Toshiba by 2023. Indeed, emerging memory technologies can replace the older ones on the same production lines.

Ecological impact

The only ecological impact of More Moore technologies occurs through their increasing energetic yield. As a consequence, with an equivalent level of raw materials and energy consumption, a 7 nm chip will lead to greater speed and processing capability than a 20 nm chip.

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, the positive ecological impact of More Moore technologies is entirely conditioned on the used made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if More Moore technologies are used to develop ever new and more consuming applications, then the ecological impact will be null at best.

[3] Forecasts based on figures from the WSTS, the SIA and IC Insights.

B. Beyond CMOS technologies

i. Definition

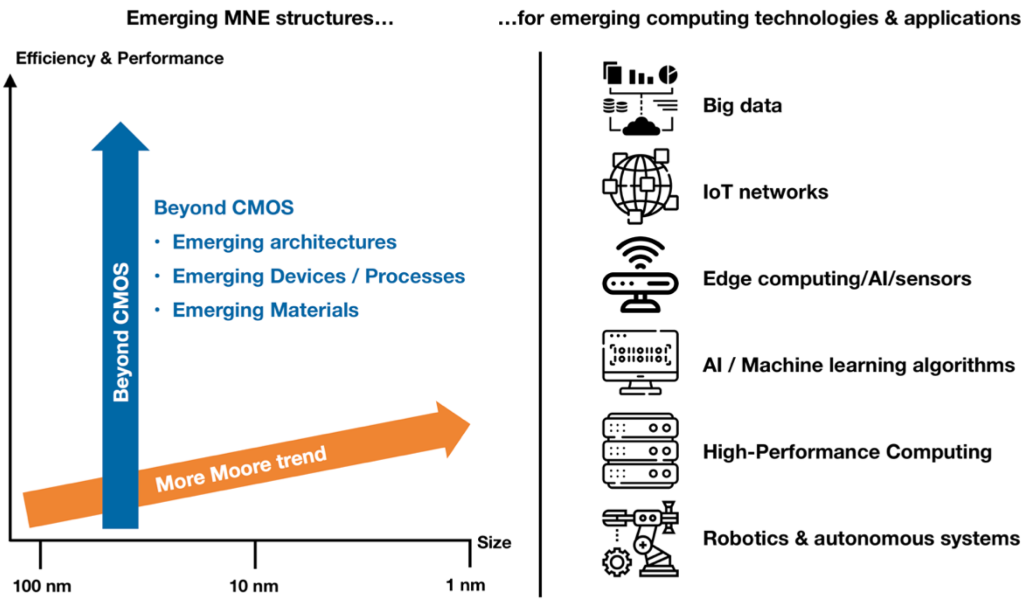
The persistent scaling of CMOS technology (Complementary Metal Oxide Semiconductors), no longer yields exponential performance gains. To overcome those limits of CMOS devices in speed and power, researchers are looking for technologies that will replace More Moore technologies when the pure shrink of CMOS transistor will no more be possible. This technology mutation is being accomplished by addressing two technological issues:

- Extending the functionality of the CMOS platform via heterogeneous integration of new technologies ("More than Moore")[4];
- Stimulating inventions of new information processing paradigms ("Beyond CMOS").

Therefore, **Beyond CMOS technologies refers to potential future digital logic technologies that expand beyond the present CMOS scaling limits**. Digital logic is a fundamental component in the creation of electronic and logic devices, allowing to create circuits, check computer chips and perform other functions that are necessary to a system's success. The acronym CMOS, which is short for complementary metal oxide semiconductor, is typically used to describe the fundamental switches that are normally on and off in modern semiconductor products. This means that "Beyond CMOS" refers to future technologies concerning digital logic, or future technologies, which is what we rely on to represent the sequences and signals within a digital circuit.

As illustrated in the diagram below, emerging computing technologies and applications (e.g., big data, IoT, artificial intelligence, autonomous systems, Exascale computing), require higher-performance and energy efficiency, which will progressively lead to the rise of Beyond CMOS technologies as the More Moore law progressively ends.

Relationship between emerging MNE structures and emerging computing technologies



Source: Japanese Beyond-CMOS IRDS group, DECISION Études & Conseil

It is largely expected that those technology changes will be made thanks to <u>the introduction of new emerging materials</u> both in More than Moore technologies and obviously in Beyond CMOS.

[4] More than Moore technologies (Power electronics innovations, RF innovations, Analogic innovations such as MEMS, etc.), are not studied in detail in this study as they are not directly linked to emerging computing technologies. Yet, the EU is very well positioned on More than Moore technologies and should support their development.

Nevertheless, Beyond CMOS should not be only limited to More Moore device replacement. More than Moore technologies also benefit from emerging materials like SiC and GaN that are now entering volume production. Furthermore, RF front-end technologies for mobile handsets that meet the requirements of 5G are developed with hybrid III-V/Si technology to take RF beyond the speed and power limits of CMOS technologies. As an example, the following RF architectures are now in R&D phase with the objective of co-integration with Si CMOS under Monolithic or 2D integration or 3D integration (3D stacking and sequential3D):

- IIIV high electron mobility transistors (HEMTs), both GaAs and InP based, and III-N HEMTs;
- IIIV and III-N MOSFET devices;
- IIIV heterojunction bipolar transistors (HBT).

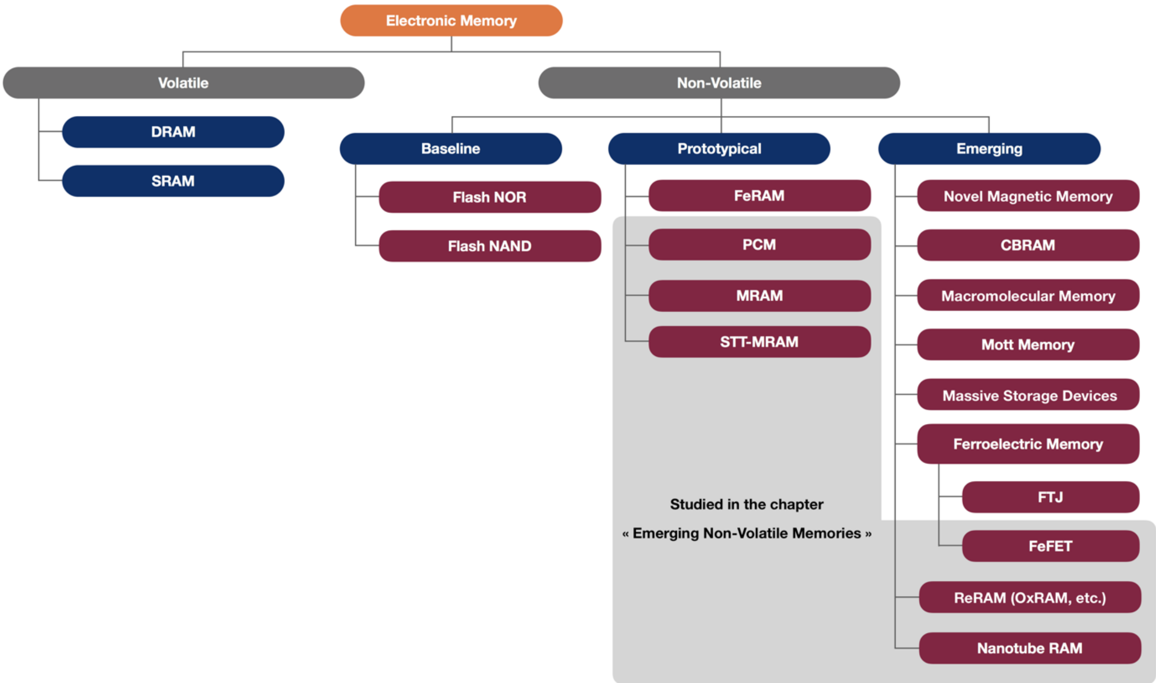
Within the objective of CMOS More Moore replacement, the main emerging technologies considered are:

1. In-memory computing (Phase Change Memory (PCM), ReRAMs / RRAMs);
2. Logic and information processing technologies (Mosfets, charged-based beyond CMOS, alternative information processing devices);
3. Emerging Devices for Security applications or Cryogenic electronics (Optical Communications; quantum bits, Cold CMOS, Superconducting Electronics, Spintronics).

A. In-memory computing

The IRDS has mapped the taxonomy of emerging memory devices (see the diagram below):

Taxonomy of emerging memories

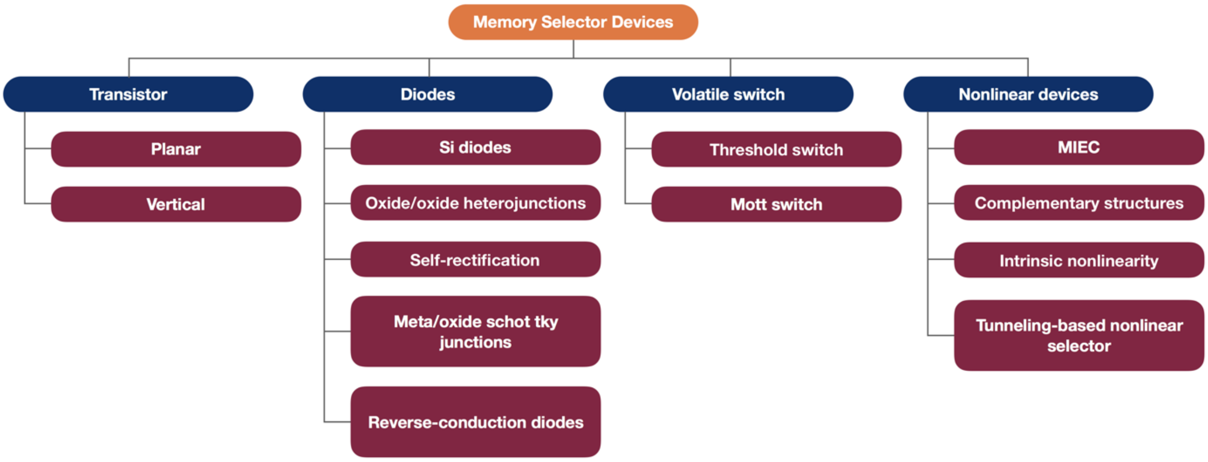


Source: IRDS, DECISION Etudes & Conseil

It shows 7 types of emerging memories families, each of them composed of different sub technologies. In the same way the storage class Memory devices are to evolve from traditional HDD and Flash solid-state drives to Storage Class Memories: Storage-type SCM or Memory-type SCM with new memory architectures.

The selected devices used can also be mapped in different categories, each of them having different domains of application, as shown below.

Taxonomy of memory select devices

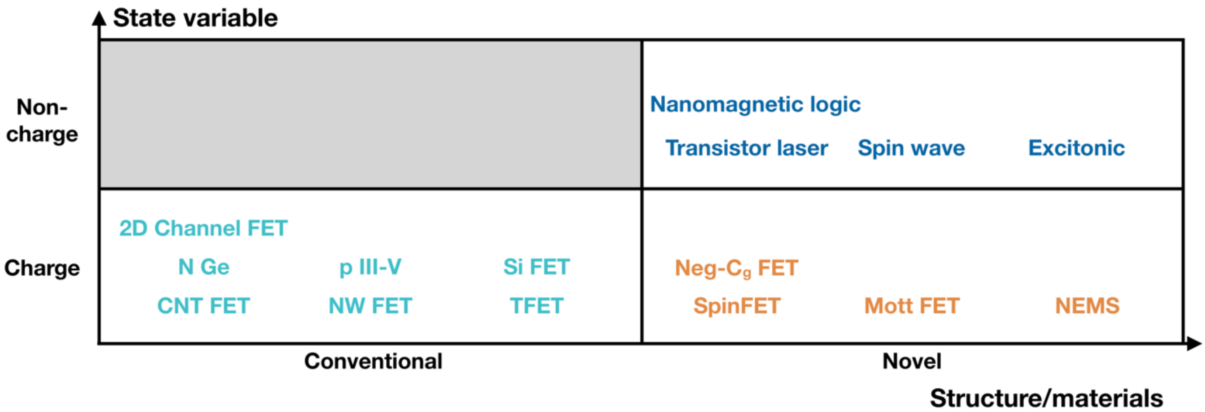


Source: IRDS

B. Beyond CMOS Logic and information processing technologies

Beside the memories, emerging logic and alternative information processing technologies have been mapped by the IRDS as shown below:

Taxonomy of emerging logic and alternative information processing technologies



Source: IRDS

The diagram above shows three areas of research:

- MOSFETS: Extending MOSFETs to end of Roadmap (bottom left). CMOS extension comprise carbon nanotube FETs, nanowire FETs, 2D material channel FETs, P-type III-V channel replacement devices, N-type GE channel replacement devices and tunnel FETs;
- Charge-based Beyond CMOS: Non-conventional FETs and other charge-based information carrier devices (bottom right), comprise spin FET and spin MOSFET transistors, negative gate capacitance FET, NEMS switch and MOTT FET;

- Alternative Information Processing Devices (upper right). Alternative information processing devices comprise: Spin wave devices, nanomagnetic logic, excitonic devices and transistor lasers.

C. Emerging Devices for Security applications or Cryogenic Electronics

Emerging Devices for Security applications or Cryogenic Electronics (EDSCE), correspond to the field of beyond CMOS technologies supporting the development of high processing applications (for which cryogenic tools might be required or useful), and in particular quantum computing. "Security applications" designs the current main applications of quantum that are in Cybersecurity.

The developments on alternative technologies are mainly done about:

- Cold CMOS (77°K) with the challenge of operating computers at ultra-low temperature;
- Superconductivity and Josephson junction circuits opening a way to quantum computing but also at cost of control of extremely low temperature;
- Spintronics opening the way to semiconductor spintronic devices and to Spin Qbits;
- Photonics, possibly with CMOS integration through hybrid devices (see the chapter on Photonics Interconnection Networks).

ii. Synergies with other emerging technologies

Beyond CMOS technologies are for the most part at the stage of R&D and should progressively replace More Moore technologies as key enabling technologies only after 2025:

- Directly through classical devices (CPU, GPU, FPGA, Asics, memories, etc.);
- As parts of the systems command as logic technologies;
- Through specialized processor units made to support and implement every emerging computing technologies: AI algorithms, neuromorphic computing, quantum computing, supercomputing, IoT, edge computing, secure elements, authentication & identification systems, cryptography, blockchain, new mobile communication systems, etc.

Anyhow, inside the majority of future advanced subsystems More Moore technologies and Beyond CMOS will likely cohabit.

iii. Technology roadmap: Maturity levels and expected impacts by application area

Most of Beyond CMOS technologies are still currently at the stage of pure R&D. Historically, it takes 12-15 years from the date of a technological breakthrough to the first commercialization of the related technology, as shown in the four following examples[5]:

- Strained silicon: Discovered in 1992, commercialized in 2003 (incubation time: 11 years);
- HKMG: Discovered in 1996, commercialized in 2007 (incubation time: 11 years);

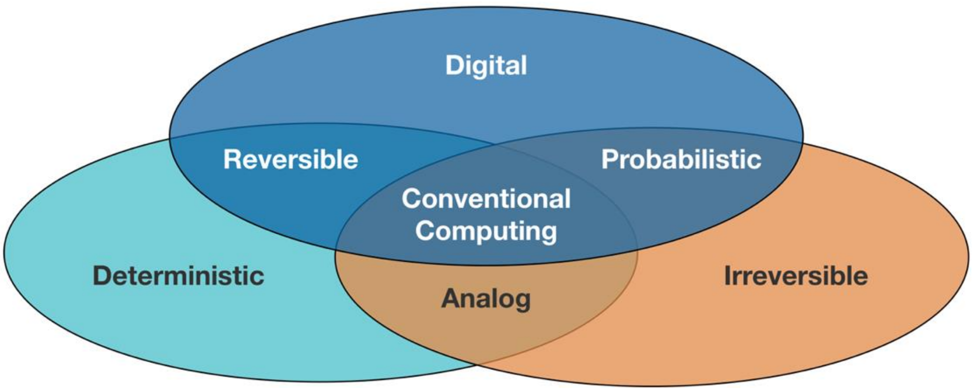
[5] Source: Extremetech

- Raised S/D: Discovered in 1993, commercialized in 2009 (incubation time: 16 years);
- MultiGates: Discovered in 1997, commercialized in 2011 (incubation time: 14 years).

Even if companies like Intel, IBM, and others have been working on their projects for years, there are a huge number of discoveries and advances that still need to happen before any commercialized product would ever come to market.

The list of open research fields in Beyond CMOS technologies is very large and the different benchmarking has not been able to determine a "technology of choice" among the different and numerous proposals of Beyond CMOS technologies for computing. The final technology choice will depend on the final application that will become the industry standard and this process should take several years. The emerging device classes that are currently being explored are not intended simply as "drop-in" replacements for CMOS devices but will require new types of circuit designs, new functional module architectures, and new software. As a consequence of the technology changes, Beyond CMOS development may lead to different device-architecture interactions, Devices may be organized in radically new ways to carry out computation in a very different style from what we may consider the most "conventional" computing paradigm which has relied on standard combinational and sequential irreversible Boolean logic.

Categorization of Conventional vs. Alternative Computing Paradigms generated by Beyond CMOS technologies and depending on the final application



Source: IRDS

Yet, the **key forecasted technology developments** that are known so far are the following:

- The Beyond CMOS application that is the most likely to become the next industry standard according to the last communication from the ACM (Association for Computing Machinery, January 2019), is quantum effects, such as tunneling FETs and spintronic devices[6].

[6] As explained in this communication: "The Nano-electronics Research Initiative (NRI), has narrowed the field of possible CMOS successors to five *types of bit carriers—charge (as used by CMOS today), electric dipoles (as in ferroelectric field-effect transistors/FeFETs), magnetic dipoles (as in all-spin logic and spin-wave devices), orbital state (as in Bilayer-pseudo-Spin Field Effect Transistors/BiSFETs), and strain (as in Piezoelectric FETs). The* general conclusion *of the NRI is that "Spintronic devices are slower than charge-based devices because of the limited ferromagnet switching speed and domain wall propagation speed. However, voltage-controlled spintronics devices are more energy efficient than current-driven ones. In addition, spintronic devices show great performance in neuromorphic computing circuits based on the deep-learning paradigm, which differ significantly from their results in Boolean circuits, such as a 32-bit ALU (Arithmetic Logic Unit). This indicates that post-CMOS devices need to be complemented with novel circuit architectures, such as neuromorphic, to achieve their full potential. Use of CMOS likely will fade during the next decade, with last-ditch efforts to prolong its use including three-dimensional (3D) stacking, gate-all-around silicon nanowire FETs, heterogeneous architectures using novel accelerators with CPUs, and the use of mixed materials such as gallium arsenide transistor channels atop silicon substrates, along with extreme ultra-violet (EUV) lithography, and innovative chip-layout schemes, according to both NRI and the European Union's*

- No matter which new technology will be adopted, it must be integrated with the existing CMOS process as some CMOS transistors will be needed for the clocking and I/O analog circuits (see reports from Intel and major ICs suppliers);

- Whatever the choice of technology will be, the impact on every technology where Beyond CMOS will be a direct successor of More Moore will depend on the base component density. As a consequence, all the technological developments made for More Moore will be used (wafer fab facilities, material purity, ultra-precise equipment, etc.), with the same volume effect on production cost, efficiency and reliability developed for More Moore components. Manufacturing plants will likely be built thanks to the experience already developed by More Moore suppliers and at a cost in the same range. Therefore, the countries the most advanced in More Moore production will be the most advantaged for Beyond CMOS production;

- No matter which new technology will be adopted, either for Boolean and non-Boolean logic applications, new devices need to be complemented with novel circuits to achieve their full potential.

Limitation. The most difficult challenge for Beyond CMOS is to deliver materials with controlled properties that will enable operation of emerging research devices in high density at the nanometer scale.

semiconductor innovation hub IMES. However, while the post-CMOS era to follow was once predicted to switch from silicon to carbon materials such as graphene and nanotubes, the consensus at NRI and IMEC is rather that **the most promising post-CMOS paradigms will turn to quantum effects, such as tunneling FETs and spintronic devices***."*

Technology Roadmap - Maturity of Beyond CMOS at the global scale and by application area

N°		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	Maturity level of the technology (global insight)	R&D							Tests & prototyping											Industrial production							
	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																									
1	Automotive applications	No significant impact																		Small impact			Medium impact				
2	Industrial & robotics applications	No significant impact																		Small impact			Medium impact				
3	Health & Care applications	No significant impact																		Small impact			Medium impact				
4	Aerospace applications	No significant impact																					Small impact				
5	Defense & Security applications	No significant impact																Small impact					Medium impact				
6	Mobile phones applications	No significant impact																Small impact					Medium impact				
7	Telecommunications infrastructures applications	No significant impact																Small impact					Medium impact				
8	PC & data processing applications	No significant impact																Small impact					Medium impact				
9	Audio & Video applications	No significant impact																					Small impact				
10	Home appliances applications	No significant impact																					Small impact				
	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																									
1	Data analytics / Big data	No significant impact																Small impact					Medium impact				
2	Smart home	No significant impact																					Small impact				
3	Smart mobility	No significant impact																					Small impact				
4	Smart energy	No significant impact																					Small impact				
5	Wearables	No significant impact																									

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

Every major semiconductor research center worldwide is investigating Beyond CMOS technologies. There are dozens of possible successors to CMOS technologies, and the Nano-electronics Research Initiative (NRI, in the USA), is a worldwide center of excellence benchmarking them against each other. The NRI is sponsored by the non-profit Semiconductor Research Corporation, which is underwritten by 2,400 academic researchers and 3,100 industry liaisons at companies including Analog Devices, ARM, Global Foundries, IBM, Intel, Mentor, Micron, Microsoft, Mubadala, NXP, Qualcomm, Samsung, SK Hynix, Texas Instruments, Taiwan Semiconductor Manufacturing Co., Tokyo Electron, and Veeco Instruments.

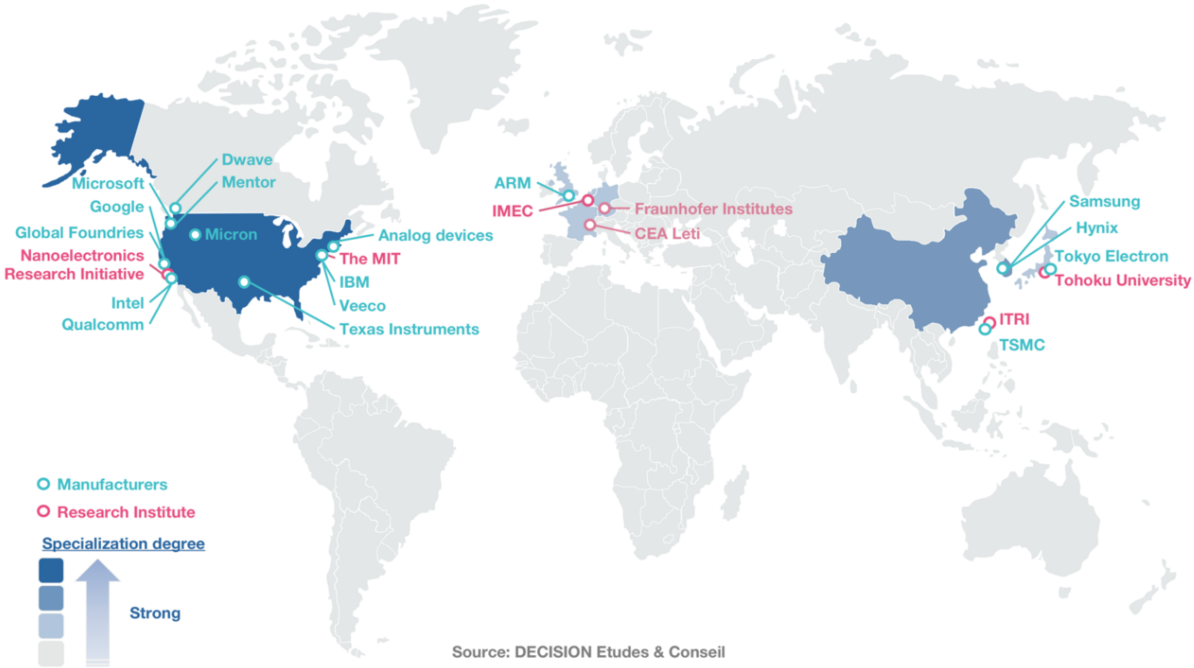
Major examples of State of the art:

- **IBM** (the USA). Quantum computer like IBM's 16-qubit quantum computer is still at demonstration phase and working at 4° Kelvin.

- **The MIT** (the USA). Very recently (August 2019), MIT researchers have built a modern microprocessor from carbon nanotube transistors, which is widely seen as a faster, greener alternative to their traditional silicon counterparts. This new approach harnesses the same fabrication processes used for silicon chips, offers key advances toward next-generation computers. Research indicates CNFETs have properties that promise around 10 times the energy efficiency and far greater speeds compared to silicon. Although the main goal is to get this chip made entirely from carbon nanotubes out into the real world, no one can say when it will hit the shelves (likely more than 5 years). The work was also supported by Analog Devices, the National Science Foundation, and the Air Force Research Laboratory.

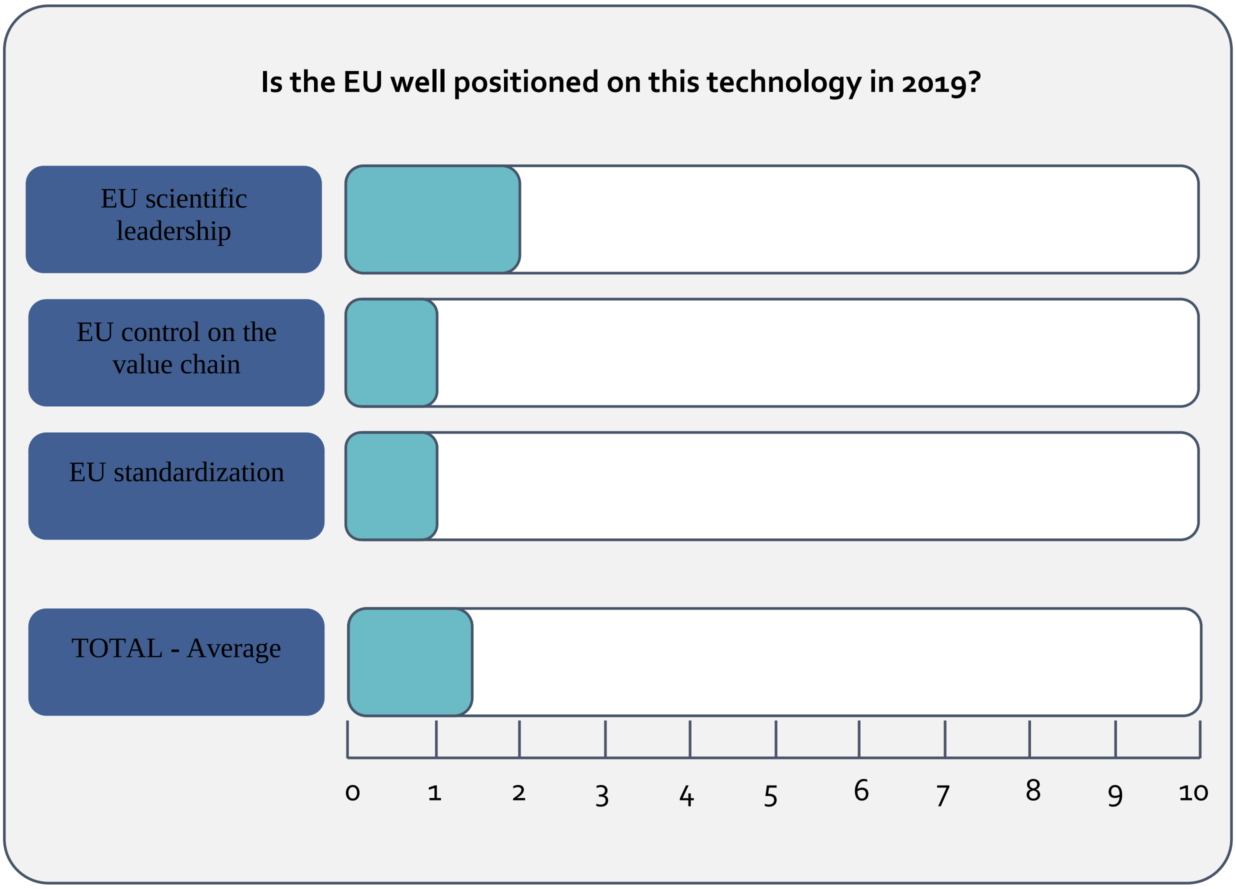
- **Intel** (the USA). Within the last years, Intel has been exploring (in conjunction with universities and the Semiconductor Research Corporation Industry Consortium), more than a dozen technologies to transcend the limitations of CMOS (all-spin, magneto-electric, spin orbit coupling logic devices, etc.). While the best approach has not been found out yet, many innovative and practical technologies are being discovered. The main discovery occurred in late 2018, when Intel proposed a scalable spintronic logic device that operates via spin–orbit transduction (the coupling of an electron's angular momentum with its linear momentum), combined with magnetoelectric switching. It is called a Magneto-Electric Spin-Orbit (MESO) chip and is up to 100 times more energy efficient, up to 30 times faster, uses a fifth of the voltage, is five times denser, and achieves ultra-low sleep state power, compared to CMOS. After evaluating more than 25 proposals for Beyond CMOS computing, Intel believes MESO holds the most long-term promise for improving voltage scaling, interconnect scaling, energy efficiency improvements, and scaling over multiple generations. One of the advantages claimed for this new spintronic MESO technology is that it is a device built with room temperature quantum materials (contrary to "classical" quantum computing approach).

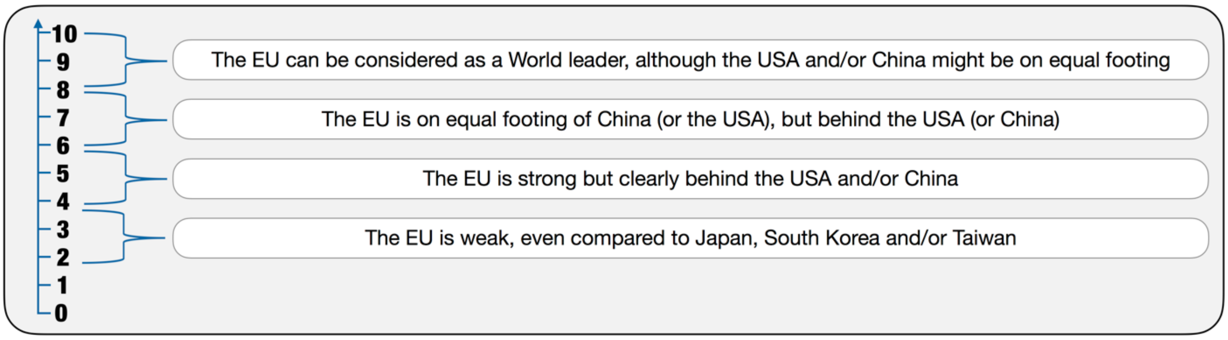
World Map - Beyond CMOS technologies



V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

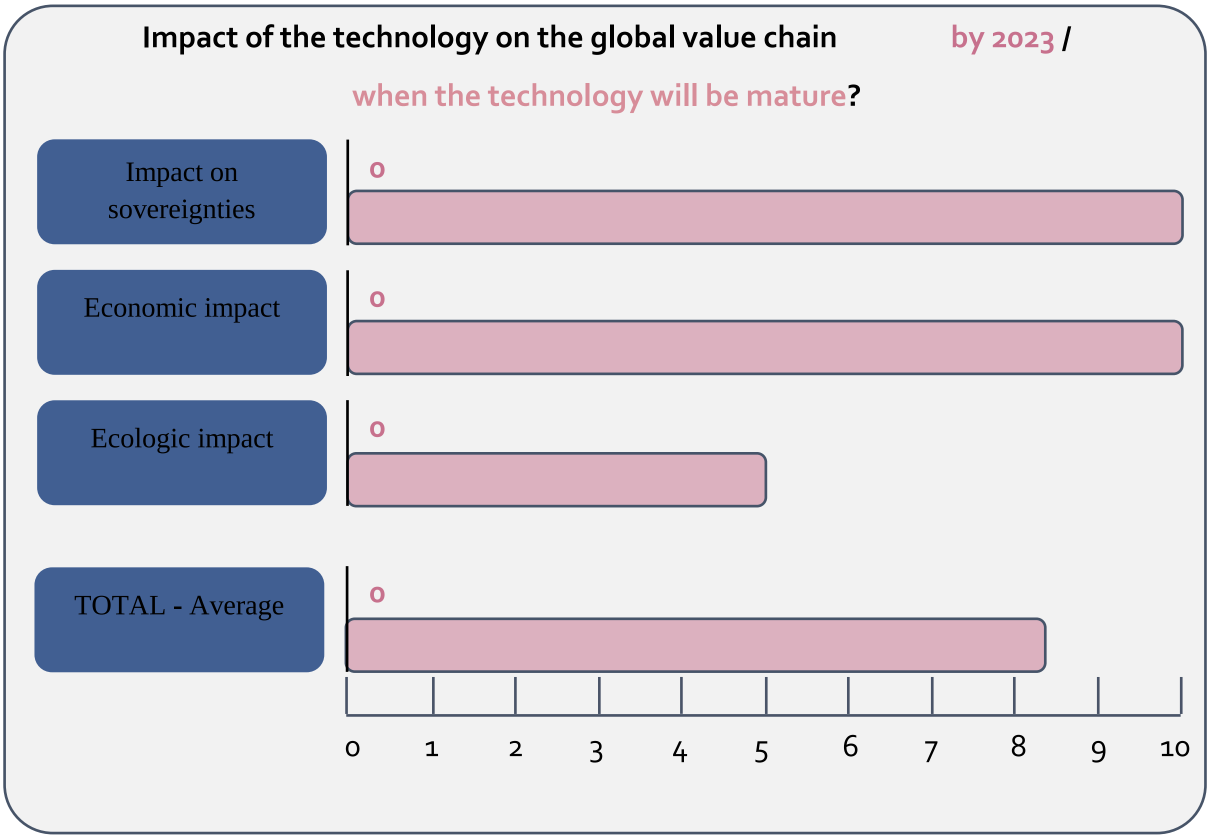
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The largest European R&D center working on those technologies is IMEC, who is associated with many of the worldwide initiatives. At a lower level, the CEA Leti, Fraunhofer Institutes and other European research centers (like the INRIA), are working on different subjects but are more focused on More than Moore technologies and on emerging usages (AI, neuromorphic computing, quantum computing, etc.), than on basic hardware components.

EU control on the value chain

As a consequence, and due to the positioning of the EU on More than Moore, the EU is limited on control of the value chain. On the contrary, regarding the More than Moore part of Beyond CMOS, not part of this study, the EU is still very active and well positioned.

Standard analysis

Due to the still early stage of R&D level, there is no standard definition yet.

Impact on sovereignties

Beyond CMOS being the continuation of More Moore, the potential long-run impact on sovereignty is the same as the long run impact described in More Moore.

Economic impact

Beyond CMOS being the continuation of More Moore, the potential long-run economic impact is the same as the long run impact described in More Moore.

Ecological impact

Beyond CMOS being the continuation of More Moore, the potential long-run ecological impact is the same as the long-run impact described in More Moore.

Conclusion

Regarding manufacturing, the EU is no longer active for More Moore technologies. The unique possibility to go back and participate to the next turn on advanced technologies and to be strategically independent in the information technology equipment of the future would be to master the R&D of beyond CMOS technologies and build the corresponding manufacturing machine able to supply the system manufacturers.

C. Advanced packaging

i. Definition

A. Historical evolution of packaging

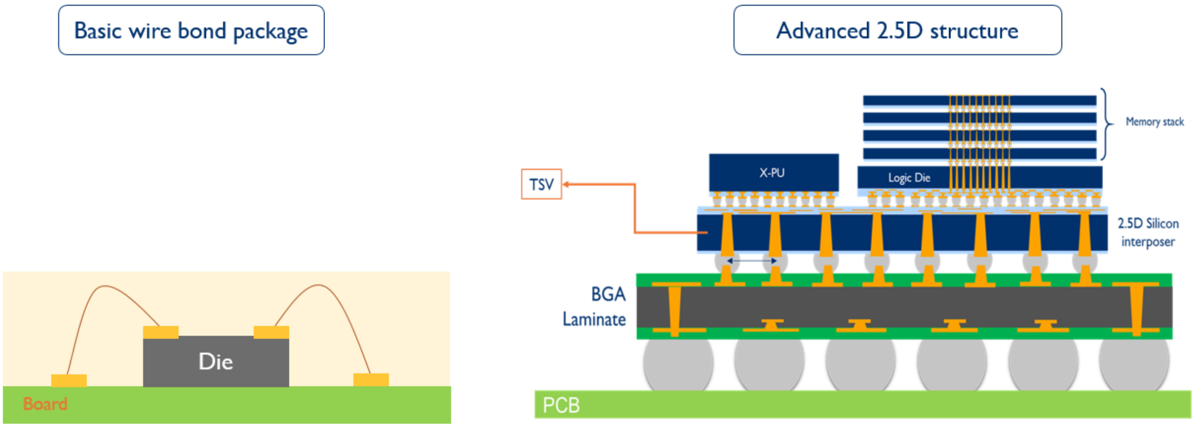
The semiconductor industry started around 1947 with the invention of the point-contact transistor, followed by the junction transistor in 1948. The first semiconductor package was invented in 1965. Since then, the semiconductor packaging technologies grew exponentially, and many different package types have been invented. Till the 1990s most of the packages were the following (Dual Inline Package (DIP), Quad Flat No-lead Package (QFP), Small Outline Package (SOP)…). In the1990s, new packages such as Ball Grid Arrays (BGAs) and QFNs began to be used. In the 2000s, Chip Scale Package (CSP) and System-in-Package (SiP) surfaced. Wafer-level packaging jumped into production before the 2010s.

The first Fan Out packaging was invented around 2007 by Freescale (part of NXP today). It was named Redistributed Chip Packaging (RCP) and is still used by NXP today. In 2008, Infineon followed and created the popular embedded Wafer-Level Ball grid array (eWLB) technology that is today widely licensed to non-European Outsourced Semiconductor Assembly and Test (OSATs). That means that the first Fan-Out technologies were developed in the EU but were very quickly licensed and adopted by Asian & US OSATs. The latest innovations in Fan Out packaging are no longer coming from the EU but from Asian countries, with players like TSMC, SEMCO, PTI, JCET & ASE widely involved in the innovation loop. Stacking technologies, such as 2.5D & 3D, started to get traction in the 2010s with the need for higher performance, higher bandwidth, and lower power consumption systems. The first 2.5D structure was used by Xillinx back in 2011, and the first 3D stacked DRAM memory was introduced by Samsung in 2014 using through silicon via (TSV) interconnections. TSV technology is an enabler for devices like High Bandwidth Memory (HBM) and the 2.5D structure based on silicon interposer.

Regarding the embedded die technology, the very first developments started in 1968 with General Electric. The first product came on the market a decade ago in 2010. Since then, different companies have entered this field, and today we find European (AT&S, Schweizer, and Würth Elektronik) and non-European substrate makers working and commercializing it, likewise OSATs and Integrated Device Manufacturers (IDMs).

Historically the package was a simple interconnection between a die and a substrate and thus its added value was limited. With the semiconductor evolution and die innovation reaching very complex levels today, the package switched from an interconnection into a functionality. Nowadays, the package is designed to improve the die's performance and reliability, to make it easier to integrate and in some advanced cases as an enabler for new advanced hardware with multiple function dies gathered in the same package (see the figure below).

Basic wire bond interconnection VS. advanced functional package



Source: Yole Développement, 2019

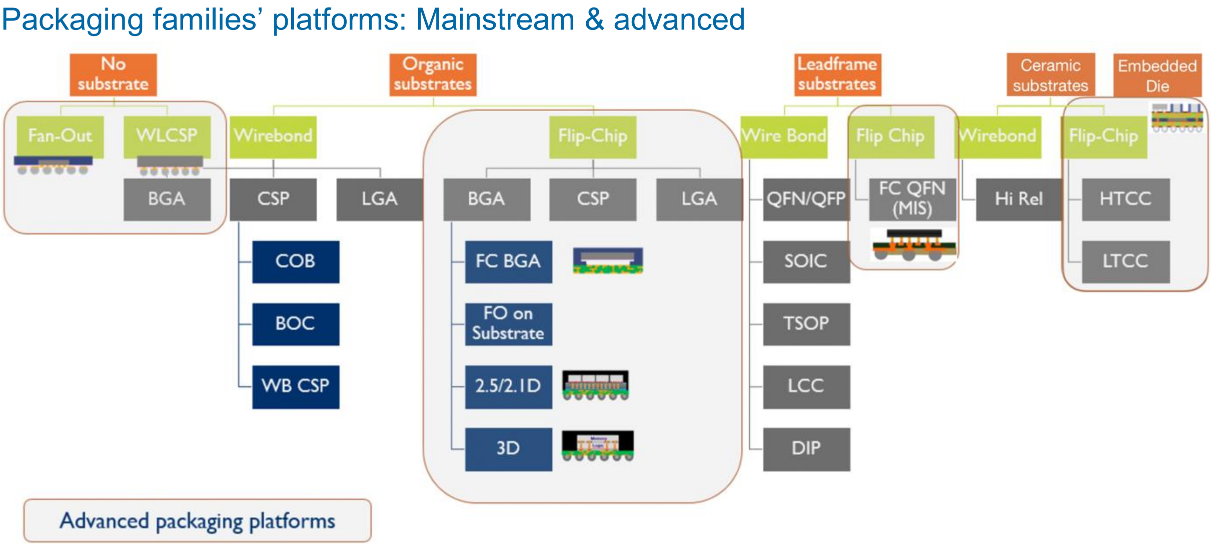
B. The emergence of two packaging families

Semiconductor packaging technologies are essential building blocks for every electronic die integration and system. The primary function of the packaging is to connect a chip to a substrate or a board.

The packaging industry has gone through different evolutions to fulfill the different requirements of the industry, as well as products that have emerged from the electronics industry. Historically, the legacy packaging family is still widely used as a solution. In the last 20 years, the semiconductor market has boomed driven by numerous applications such as smartphones, industry automation, big data, supercomputing, artificial intelligence, autonomous driving and others… In the early stage of the semiconductor industry, one die was packaged in one package. Later, the trend to integrate several dies in one package emerged to improve performance, lower footprint and lower power consumption.

Technology node scaling followed Moore's law till around the 12 nm turning point. Below this node, only 3 players are still scaling the technology as the investment required is significant. This is where a new packaging family, named advanced packaging, emerged as a solution to the slow-down of Moore's law.

We can now separate semiconductor packaging into two families: legacy & advanced packaging, as shown in the diagram below.



Source: Yole Développement, 2019

ii. Synergies with other emerging technologies

More Moore technologies. As seen above, only 3 players are still scaling More Moore technologies after the 12 nm turning point, as the investment required are massive. Advanced packaging became increasingly important around the 12 nm as they came as a solution to the slowdown of Moore's law.

Advanced memories. More and more memories such as DRAM are to be packaged using Flip-Chip with Cu pillar bumping instead of wire bond (WB). Samsung has already migrated most of their DRAM packaging to Flip-Chip while SK Hynix started the conversion and Micron will start soon. The other memories including EEPROMs, EPROMs, ROMS, SRAM and emerging non-volatile memory (eNVM) are mostly low pin count devices using lead frame packaging (~60%) and WB BGA (~25%). However due to smaller form factor trend, WL CSP (~15%) is being increasingly adopted.

High-Performance Computing. HPC is the real driver for stacking technologies. These technologies enable higher integration, lower latency, higher bandwidth and lower power consumption that are vital parameters for this market. The 2.5D & 3D stacking technologies are the only solution for applications requiring low latency and high bandwidth. These stacking technologies are, to our knowledge, currently the only solution that meets the extremely stringent requirement for HPC. The HPC segment includes hardware such as GPU, CPU (Central Processing Unit), ASIC (Application Specific Integrated Circuit), FPGA (Field Programmable Gate Array), servers, routers, advanced memories (HBM, 3DS…) and computing units. For more details, see chapter III)B)1-Synergy between stacking technologies and HPC / networking markets and applications.

iii. Technology roadmap: Maturity levels and expected impacts by application area

A. Advanced packaging technologies

The advanced packaging area includes different packaging technologies.

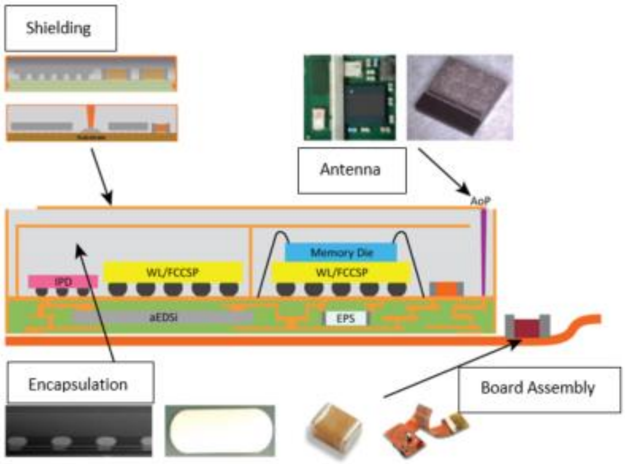
1. System in Package (SiP)

All the below advanced packaging platforms, except the fan-in and Flip Chip Chip Scale Package (FC CSP), can be considered as a System-in-Package. By definition, a SiP is a conglomeration of two or more dies with different functionalities in the same package. This term is a hype in semiconductor packaging. It is used, and will continue to be used, in all the markets for multiple applications. It's already used for antennas in 5G hardware for smartphones with the so-called Antenna in Package (AiP). A 2.5D structure is also considered as a SiP as in the same module, a logic die is placed just besides a High Bandwidth Memory (HBM). The Fan Out package also encompasses several different functionalities dies just as for the embedded die where passives and actives are placed "In" and "On" the substrate.

This hype is still in its early stages, but the growth of SiPs is expected to be exponential in the near future. The need for functional packages is becoming a must for critical applications with all the advantages it can allow, such as reduced data path, better surface usage, higher performance, enhanced wave protection (Electromagnetic interference, EMI) and better heat management…

The SiP is an OSAT business even if it's pushed by IDMs. This means that the business is mostly outside the EU, but a part of the need is dictated by the big European IDMs.

ASE example of a SiP



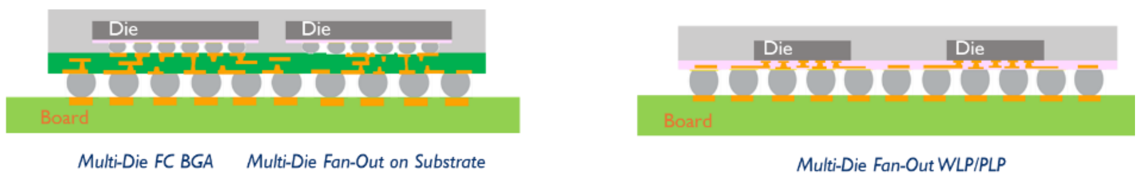
Source: Yole Développement, 2019

2. Fan-Out / Fan-In

Fan-Out (FO): Definition. By definition, a FO package is a package where the interconnections are fanned out from the die's surface and thus bump size is not dependent on the die's surface. The popular FO packages are those that don't use any substrate, which makes them thinner than a substrate-based package. The dies are flipped and placed on top of a Re-Distribution Layer (RDL) and then embedded into an epoxy/polymer mold. This type of FO without substrate uses semiconductor tools enabling line/space down to 1/1µm. The substrate-based FO technologies are using PCB manufacturing processes and have lower L/S resolution.

The first FO technology, called eWLB, was invented in Europe, but today innovation in FO is coming mainly from Asia. This technology is flourishing in the consumer mobile market and is also used in the automotive market. In the coming years, it is expected to enter the HPC market and to be a potential packaging option for 5G.

Two FO technologies (with & without substrate)



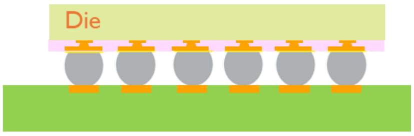
Source: Yole Développement, 2019

Fan-out technology started to become known in 2007-2008 pushed by European IDMs like Freescale (NXP today) and Infineon, both having put on the market their proprietary technologies. One of the most used FO technologies ever since is Infineon's eWLB technology (developed and commercialized by Infineon, licensed to OSATs).

New improved versions of FO are today on the market for more complex applications. TSMC developed and released in 2017 their Gen2 integrated FO (inFO) for Apple's iPhone application processor. They are qualifying the inFO on substrates for HPC devices and inFO memory on substrates for data centers. SEMCO entered high volume production for Samsung's Galaxy smart watch while PTI started a low volume production line for MediaTek's automotive application and are eager to enter high volumes in the year to come. FO innovation today is coming from Asia, and more precisely from Taiwan & Korea, with the above-cited players dominating manufacturing and investments in this advanced packaging technology.

Fan-In: Definition. By Yole's definition (and industry standard), a Fan-In package is a package type where any signal redistribution and bumping does not exceed the surface of the silicon die and which is assembled directly to the board. This technology is widely used in consumer markets, smartphones and tablets, but its penetration into other markets is limited. The developers and manufacturers of this technology are mainly the Taiwanese foundry TSMC that has 2/3 of the fan-in market, while the other third is in the hands of non-European OSATs.

Fan-In package



Fan-In WLP

Source: Yole Développement, 2019

Fan-in technology development started in the 1990s and the first products were presented early 2000s. Since then this package has grown continuously in terms of volumes, but the growth is slowing as its adoption in markets other than mobile is unclear.

3. Advanced IC substrates (Flip Chip based packages)

In order to meet the performance requirements leading to more complex packages, the substrate and the die to substrate interconnection have evolved. In terms of substrate, lower line/space is required for computing-intensive applications and markets such as HPC, AI, mobile, etc., motivating substrate makers to innovate in terms of process or switch to new processes such as modified Semi Additive Processes (mSAP) instead of conventional subtractive ones. Developing advanced IC substrate is a way of differentiation for substrate makers within a very competitive market. On the other hand, to reach higher I/O count per package, better reliability and improved performance, flip chip (FC) with bumps interconnections were invented to replace wire bond interconnections where performance and high I/O parameters were crucial.

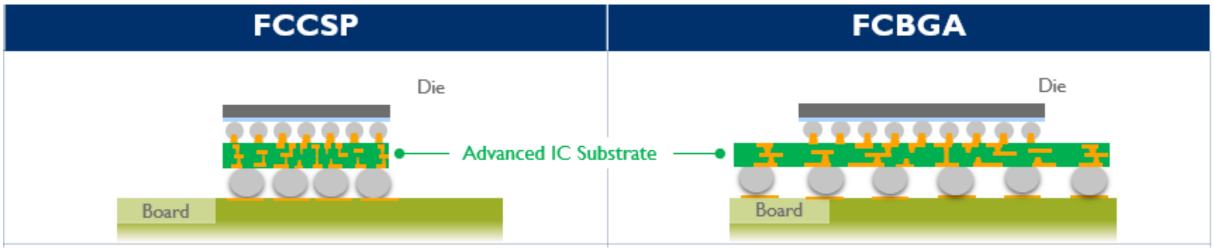
These technologies are very widely used in most of the application processors used in mobile and HPC, and are starting to get into automotive ADAS computing units… FC CSP packages are used for smaller devices in mobile such as PA, PMIC, etc.

Flip chip interconnection can be seen as an improvement of the wire bond. Flip chip is mainly based on ball interconnections that are placed beneath the die's surface. Development of this technology began before the 1990s but didn't reach maturity before the end of the 1990s, beginning of the 2000s. Manufacturing these kinds of interconnections and improving their reliability while scaling the ball size and pitch were major difficulties to overcome.

Flip chip interconnections allow higher I/O count per package and lower footprint as no need to do wire bonding. FC CSP packages were adopted before FC BGA due to their added value at the time with the need in semiconductors to reduce the die's footprint. In the last 10 years, performance and die complexity increased to meet extensive requirements. This is where FC BGA, considered as a suitable package for high I/O count and big package size dies, becomes interesting for those applications where performance is the key parameter. FC

BGA is already in mass production for a few years but will ramp up with higher demand driven by HPC and automotive ADAS computing units in addition to the continuous need for mobile and data center.

FC CSP & FC BGA packages using advanced IC substrate

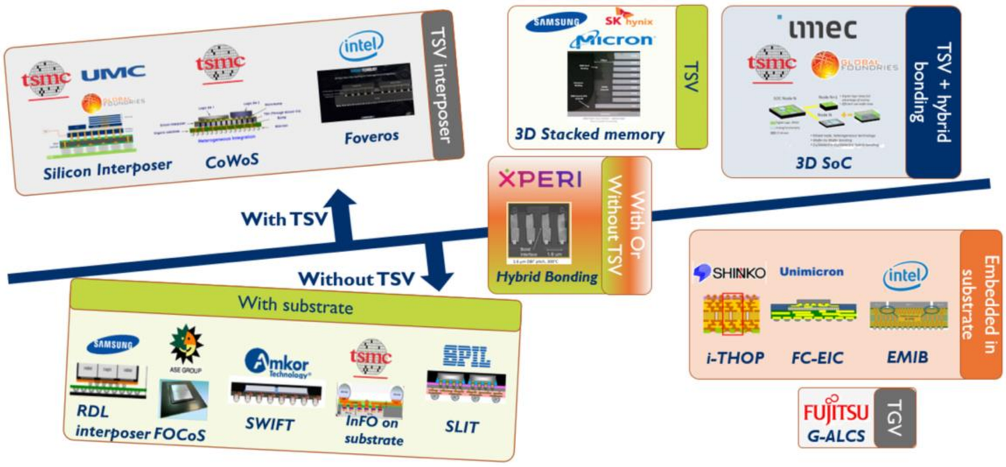


Source: Yole Développement, 2019

4. Stacking technologies

Considered as one of the most promising solutions to the slowdown in Moore's law, 2.5D and 3D stacking are backed by various semiconductor players. TSV (Through-Silicon Via) was the initial stacking technology, hybrid bonding is another that is widely used and growing. Many different stacking technologies exist on the market, with the most prominent based on TSV as interconnection. For the 2.5D structures, however, the players are looking to replace the expensive bulky TSV interposer by other technologies. These stacking technologies are very popular in HPC, stacked memory and CIS.

2.5 D & 3D stacking technologies: With / Without TSV



Source: Yole Développement, 2019

<u>2.5D stacking</u>

R&D on 2.5D stacking started long before its adoption in 2011 by Xillinx. The 2.5D structure includes a layer, called the interposer, that is to say a bulk Silicon substrate with TSV. It took years to demonstrate the TSV manufacturing capability and to find market applications that meet the requirements and the cost. The volumes were still very low till the entry of AMD who used this structure for their Fiji GPU in 2015 followed by Xillinx for their Virtex FPGA, Intel & Nvidia for their Xeon Phi processor and Pascal 100 GPU in 2016. This is when this packaging structure jumped into mass production. Since 2016 a multitude of new players such as Broadcom, Fujitsu, Nokia, NEC, and Google adopted this advanced packaging structure for different hardware related to HPC and data center.

As for today, R&D is focusing on the development of new 2.5D structures. The goal is to replace the complex bulky Silicon interposer by another simpler and cheaper structure. Foundries and OSATs are leading this R&D,

helped by some European research centers. CEA Leti (France), IMEC (Belgium), Fraunhofer (Germany) are active in R&D in these technologies and are contributing to their improvement. Nevertheless, most of the innovation in 2.5D structures is coming from outside the EU, especially Asia, from players like TSMC, UMC and ASE. The USA-based companies are also very active in this field, especially Intel and AMKOR. Until an alternative to this costly and complex packaging technology is found, it will continue to be massively used for very intensive computing hardware.

3D stacking (TSV & patterned hybrid bonding)

The use of TSV as interconnection between stacked devices was pushed by AMD early 2008. One of the first stacked products using TSV was a DRAM memory module from Micron in 2011 (3D stacked DRAM and Hybrid Memory Cube HMC). Meanwhile, other IDMs specialized in memory, like SK Hynix and Samsung, entered the race for stacked memory and in 2014 both players announced their proprietary stacked DRAM module using TSV (3DS DDR4). The same year, Micron released their second generation of HMC that was used in Fujitsu's SPARC64 processor. In 2015, a new turning point in stacked memory occurred with SK Hynix releasing the first High Bandwidth Memory (HBM) that was used in the AMD's Radeon R9 Fury X GPU. The same year, Samsung released a 3D RDIMM with 128 GB capacity. In 2016 HBM became a JEDEC standard, while HMC couldn't be standardized which was the start of this technology's decline. Meanwhile, Samsung released their proper HBM2 that was used in Nvidia's Tesla P100 GPU.

In 2016 TSV also entered the smartphone CIS market, with the first stacked image sensor using TSV that was provided by Sony and used in the iPhone 7+. The same year, Samsung released their galaxy S7 smartphone with a stacked CIS but using Hybrid bonding as an interconnection replacing TSVs. In 2017, Sony released a three stacked image sensor (image sensor on top of a DRAM memory on top of the logic circuit) using TSV that they implemented in their XZ smartphone. Samsung and SK Hynix continued developing higher capacity HBM and released products in 2018. It's expected that new HBM generation 3 will be released in 2020-2021 by Samsung followed by SK Hynix.

For the image sensors, hybrid bonding will take ever more market share from TSV stacked CIS in the future.

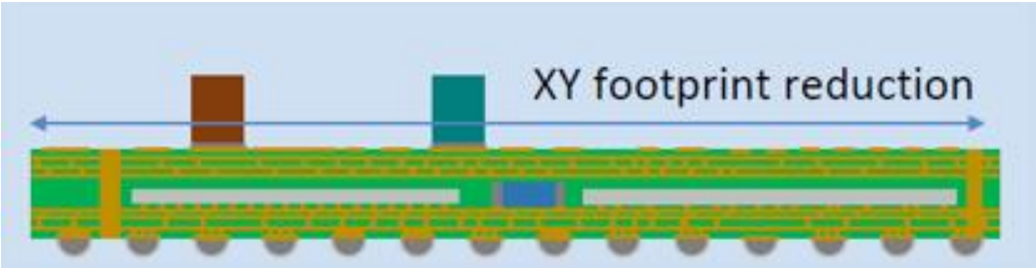
5. Embedded Die (ED)

In this technology, as its name indicates, one or more dies, actives &/or passives, are embedded into an organic substrate. Production started with technology based on a single passive embedded die reaching yields of above 98% for this kind of structure. The future is towards more embedding of passives and complex active dies with higher I/O. Some players are developing substrates embedding >> 30 dies, active(s) and passives.

Besides the interest in die integration, this technology is known for its good thermal management with the possibility of having a double-sided cooling system. In addition to the mobile phone market, and with the emergence of vehicle electrification and the need for more efficient telecom infrastructure for 5G, ED will find gaps to fill in terms of packaging needs.

Embedded die technology development is active in Europe backed by two substrate manufacturers, namely AT&S and Schweizer. Würth Elektronik is also active in the ED field.

Example of AT&S (Austria) Embedded Component Package (ECP)



Source: Yole Développement, 2019

Embedded die technology has been under development for many years, the first deposited patents by GE were in 1968. But the development of this technology was halted for a while and it only hit the market in 2010. Since then, the technology added value was proved in various applications. As of today, it is used in mobile phones, but its expected growth will come from automotive and telecom infrastructure applications. Investments by both European and Asian players are ongoing to prepare for a potential boom in the volumes of embedded die required starting 2021. The potential of this technology is big especially for high-power applications where its good heat management properties are crucial for enhanced performance and reduced power consumption. Further developments and tests are still to be done and presented by ED players to convince customers of this technology's utility compared to existing packages.

Comments on the following roadmap:

- *A packaging technology, once commercialized, will continue to be developed, improving it, reducing its cost, making it more reliable and more flexible for its adoption in more and more markets and applications. The development lifetime of a packaging technology is relatively long despite the step of massive production reached;*

- *In the next 5-10 years, the innovation will continue to improve the below advanced packaging platforms. It is unlikely that a revolutionary new technology will be introduced due to the efforts given on the improvement of the actual technologies.*

Technology Roadmap - Maturity of the technology at the global scale and by application area

<table>
<tr><th colspan="2"></th><th>2007</th><th>2008</th><th>2009</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td colspan="2">System In Package (SiP)</td><td colspan="24">Massive production</td></tr>
<tr><td colspan="2">Fan In (FI or WL CSP)</td><td colspan="24">Massive production</td></tr>
<tr><td colspan="2">FC CSP</td><td colspan="24">Massive production</td></tr>
<tr><td colspan="2">Fan Out (FO)</td><td></td><td colspan="23">Massive production</td></tr>
<tr><td colspan="2">FC BGA</td><td colspan="5">Industrial production</td><td colspan="19">Massive production</td></tr>
<tr><td colspan="2">3D stacking (TSV)</td><td colspan="2">R&D</td><td colspan="2">Tests</td><td colspan="3">Industrial production</td><td colspan="17">Massive production</td></tr>
<tr><td colspan="2">2.5 D stacking structure</td><td colspan="4">Tests & prototyping</td><td colspan="5">Industrial production</td><td colspan="15">Massive production</td></tr>
<tr><td colspan="2">3D stacking (patterned Hybrid bonding)</td><td>R&D</td><td colspan="3">Tests & prototyping</td><td colspan="5">Industrial production</td><td colspan="15">Massive production</td></tr>
<tr><td colspan="2">Embedded die (ED)</td><td colspan="3">Tests & prototyping</td><td colspan="12">Industrial production</td><td colspan="9">Massive production</td></tr>
<tr><th>N°</th><th>Electronic Segment</th><th colspan="24">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="12">No significant impact</td><td colspan="5">Small impact</td><td colspan="7">Medium impact</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="11">No significant impact</td><td colspan="3">Small impact</td><td colspan="10">Medium impact</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="11">No significant impact</td><td colspan="6">Small impact</td><td colspan="7">Medium impact</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="24">No significant impact</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="24">No significant impact</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="4">Small impact</td><td colspan="4">Medium impact</td><td colspan="16">Critical impact</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="11">No significant impact</td><td colspan="3">Small impact</td><td colspan="3">Medium impact</td><td colspan="7">Critical impact</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="3">No significant impact</td><td colspan="4">Small impact</td><td colspan="4">Medium impact</td><td colspan="13">Critical impact</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="11">No significant impact</td><td colspan="3">Small impact</td><td colspan="10">Medium impact</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="24">No significant impact</td></tr>
<tr><th>N°</th><th>Crossed segments</th><th colspan="24">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
<tr><td>1</td><td>Data analytics / Big data</td><td colspan="11">No significant impact</td><td colspan="3">Small impact</td><td colspan="3">Medium impact</td><td colspan="7">Critical impact</td></tr>
<tr><td>2</td><td>Smart home</td><td colspan="16">No significant impact</td><td colspan="3">Small impact</td><td colspan="5">Medium impact</td></tr>
<tr><td>3</td><td>Smart mobility</td><td colspan="16">No significant impact</td><td colspan="3">Small impact</td><td colspan="5">Medium impact</td></tr>
<tr><td>4</td><td>Smart energy</td><td colspan="24">No significant impact</td></tr>
<tr><td>5</td><td>Wearables</td><td colspan="9">No significant impact</td><td colspan="3">Small impact</td><td colspan="12">Critical impact</td></tr>
</table>

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

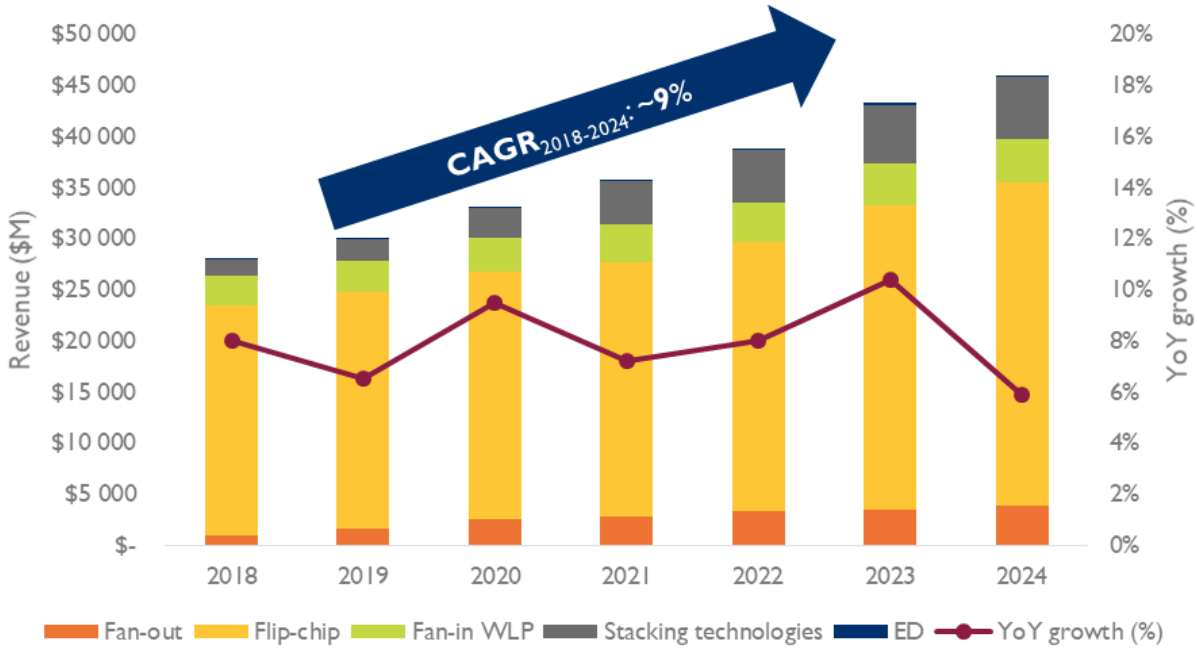
…on the global electronic value chain.

Source: DECISION Etudes & Conseil

B. Advanced packaging market

The semiconductor industry is at a turning point. The slowdown in complementary metal-oxide semiconductor (CMOS) scaling, coupled with escalating costs, have prompted the industry to rely on Integrated Circuit (IC) packaging to extend the benefits of the More-than-Moore era. Thus, advanced packaging has entered its most successful period, boosted by the slowdown of Moore's law, widespread need for better integration and megatrends in transportation, 5G, consumer, memory & computing, Internet of Things (IoT, and industrial IoT), Artificial Intelligence (AI), and High-Performance Computing (HPC). After experiencing double-digit growth and achieving record revenue in 2017 and 2018, a slowdown (negative YoY growth) in the semiconductor industry for 2019 is evident. However, advanced packaging is expected to maintain its growth momentum, with ~ 6% YoY growth in 2019 expected. Overall, the advanced packaging market will grow at a 9% Compound Annual Growth Rate (CAGR) over the 2018-2024 period, reaching ~€354B in 2023 from €23B in 2018. Conversely, during the same period the traditional packaging market will grow at a 2.4% CAGR, and the total IC packaging business will exhibit a 5% CAGR.

2018-2024 advanced packaging revenue forecast – Split by platform



Note: These market values correspond to "advanced packaging" and therefore do not include any legacy packaging nor any IDMs packaging revenue

Source: Yole Développement, 2019

C. Advanced packaging applications

The advanced packaging platforms are appropriate solutions for advanced markets and applications that require increased performance, smaller footprint and more die integration. The main markets for this kind of technology are high-performance computing (artificial intelligence, supercomputers, cloud & edge computing, crypto mining, advanced memories, advanced processing units…), networking (telecom infrastructure, servers, routers…), mobile (application processors, dedicated processors, advanced electronics…), and lately automotive (converters, lighting, computing units, chargers…). The specifications of some applications in these markets are so stringent that legacy packaging cannot meet them. Each advanced packaging technology is more or less linked to one or more markets according to its performance with regard to the requirements:

1 - Synergy between stacking technologies and HPC / networking markets and applications

The HPC market segment includes all the computing units needed to perform complex calculations in a very short timeframe. This market segment includes hardware such as GPU, CPU (central processing unit), ASIC (Application Specific Integrated Circuit), FPGA (Field Programmable Gate Array), HBM and other specific computing units. The networking market includes hardware such as servers and routers.

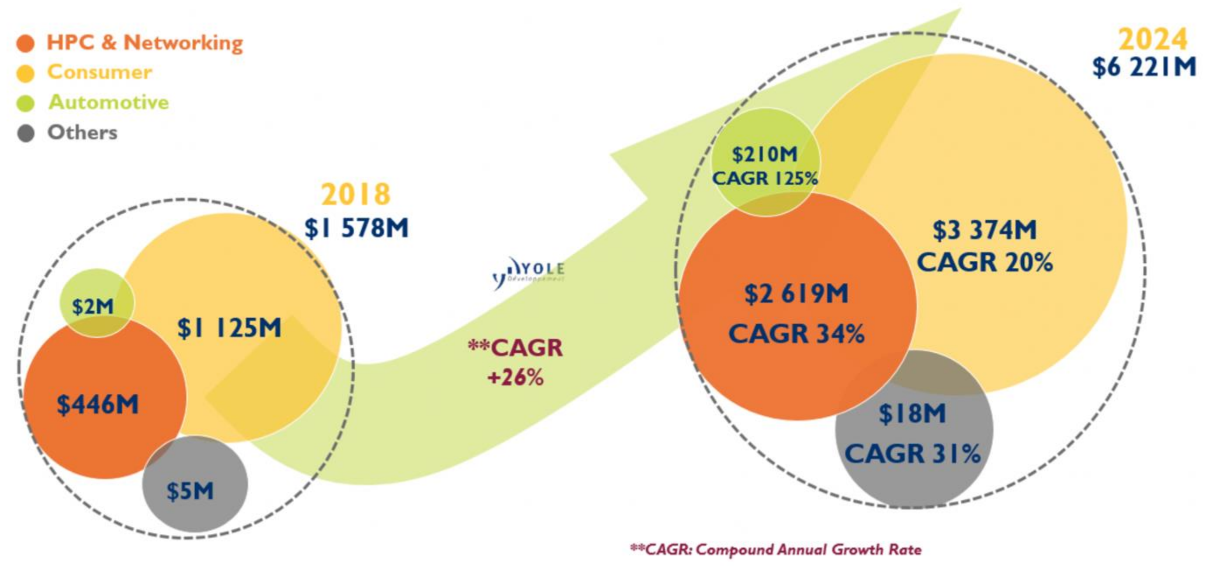
These systems are very complex units, requiring a large die surface and having a big number of I/Os. They are used for data centers, supercomputers, Advanced Driver-Assistance Systems (ADAS) vehicles, crypto-mining…

HPC is the real driver for stacking technologies. These technologies enable higher integration, lower latency, higher bandwidth and lower power consumption that are vital parameters for this market.

The 2.5D stacking technologies are the only solution for applications requiring low latency and high bandwidth. The most common 2.5D structure is one based on silicon interposer with TSV. A logic die (GPU, ASIC, FPGA…) is placed just beside an HBM (High Bandwidth Memory) on the silicon interposer. HBM is using a 3D stacking interconnection (TSV) to stack 8 or more DRAMs on top of an IC driver.

These stacking technologies are, to our knowledge, currently the only solution that meets the extremely stringent requirement for HPC. Nevertheless, as shown in the figure below, the biggest market for stacking technologies was, and will remain, the consumer, due to the high volumes of stacked CIS used in smartphones. In 2024 stacking packaging market for consumer will reach $3.3B or 54% of the Total Available Market (TAM).

Stacking technologies, packaging revenues repartition per market



Source: Yole Développement, 2019

The global stacking packaging revenue will experience a +26% CAGR between 2018 & 2024, exceeding the $6B mark.

The stacking technologies for HPC & Networking will have a +34% CAGR over the forecast period (2018-202) with mobile & consumers only 20%. Stacking technologies in automotive were only recently introduced and the market was only $2M in 2018. Its growth is important over the next 5 years, mainly due to the use of embedded die technology in numerous applications.

2 - Synergy between advanced IC substrates (flip chip) and mobile / automotive & HPC markets

All the developments and innovation occurring in the advanced IC substrates field are driven by the need for higher integration, improved performance, smaller footprint and reduced power consumption, like the needs in packaging. Depending on the market segment and application, some of those requirements may be more or less important.

For mobile market, footprint is a key factor without neglecting any of the other parameters, while for HPC, performance and power consumption are crucial. Both markets require substrates with Line/Space < 30/30µm, so that the traditional substrate manufacturing process known as subtractive is no longer sufficient. This is where new substrate processes such as mSAP & SAP are developed and used. More and more players are switching to these advanced processes. Most of the applications requiring an advanced IC substrate have high I/O numbers, thus the interconnection between the die and the organic substrate is also switching to a more advanced one (Flip Chip, FC). The main advanced IC substrates packages considered are FC BGA and FC CSP.

OSATs are projecting increased demands for FC BGA adoption in AI processors for automotive. At the end of 2018, the market was unable to meet the demand for FC BGA due to overwhelming demands from 5G base stations and High-Performance Computing (HPC). The FC BGA supply chain was not expecting such a strong new demand from 5G players. As a result, the ASP of advanced IC substrate for FC BGA rose, which pushed players like Kinsus and Unimicron (Asia) to boost further their production capacity to meet the demand.

AT&S, the Austrian substrate manufacturer (biggest European substrate maker), announced very recently the expansion of its IC substrates business for HPC by investing nearly $1B in a new plant in Chongqing and capacity expansion at the Leoben plant.

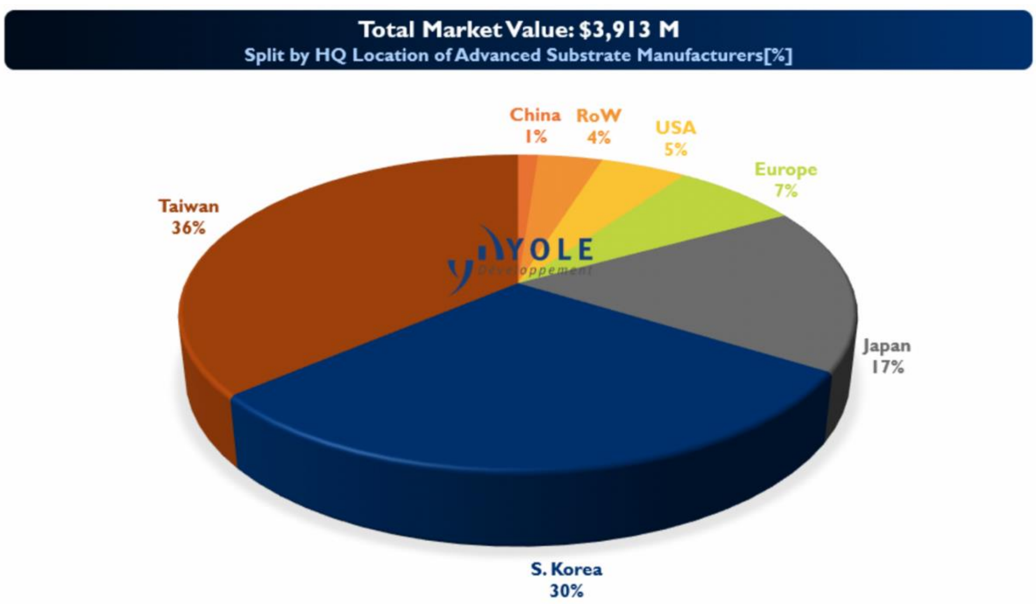
However, the demand for FC CSP substrate is continuing to grow even if it is slowing. As FC CSP is mainly driven by the smartphone market, its growth is slower due to the sluggish outlook for smartphones in 2019. Nevertheless, a switch from wire bonds into FC CSP with Cu pillar bumping is ongoing for PC/laptop DRAM and server DDR DRAM. Samsung has already migrated to this substrate type, while it is still work in progress for SK Hynix while Micron is expected to start soon. Furthermore, some 5G RF chips and power amplifiers are also shifting to FC CSP.

For the advanced IC substrates, substrate manufacturers will provide the advanced substrate while the OSATs will take care of the advanced packaging steps (bumping, bonding, etc.).

The production volumes of FC CSP are much higher than those for FC BGA. The FC BGA's Average Selling Price (ASP) is higher than that for FC CSP because of bigger dimensions as well as more complex and more performant substrates and packages. Generally, the FC CSP substrate and package covers applications with lower I/O counts and smaller package sizes while FC BGA covers applications with higher I/O counts and larger package sizes.

The advanced IC substrate manufacturing market is dominated by Asian countries and players, as shown in the pie chart below. The combined revenue of Taiwanese and South Korean companies accounts for more than 65% of the total advanced IC substrate market with Japan completing the podium (based on 2017 revenue).

Advanced IC substrate: 2017 Market Revenue by geographical area



Source: Yole Développement, 2019

The global flip chip market (FC BGA & FC CSP, substrate and assembly) is expected to grow from $22B in 2018 to $31B in 2024.

3 - Synergy between Fan-Out / Fan-In packages and consumer/automotive market

These two packaging technologies are a bit in opposition to one another, as one fans-out the interconnections and the other keeps them underneath the die's surface. The common point for both is their primary market which is the mobile market (smartphones).

The first Fan-Out technology was created and licensed by a European player named Infineon. It has been adopted by Asian and American players like ASE Group, Amkor, JCET Group as well as Intel (by virtue of its acquisition of Infineon's wireless operations which has Fan-Out Packaging capabilities). After considerable innovation by various players, Fan Out technologies are flourishing in the consumer mobile market and are also used in automotive radar applications. Looking forward, Fan-Out packaging is a potential packaging option for 5G connectivity and High-Performance Computing (HPC).

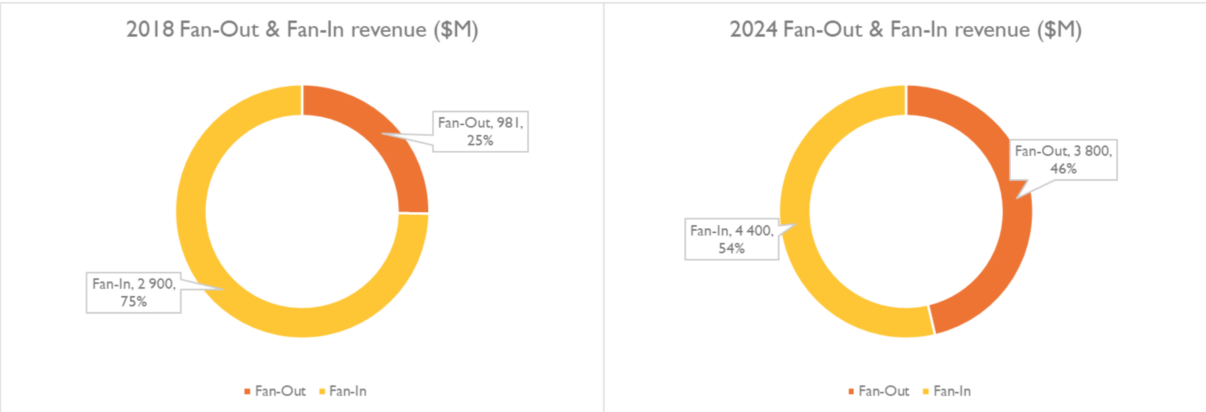
Fan-In is also a very interesting solution for smartphones and tablets. Its main point of interest is in the reduction of the die's footprint, and it is suitable for applications such as transceivers, Power Management IC (PMIC), DC/DC converters, image sensors, etc.

Both technologies are already widely used and are expected to continue growing in future years.

More and more manufacturers are being attracted by FO, but unfortunately none are European players. The FO technology is mainly an OSAT business except for TSMC (foundry). Lately, the only European player developing, and commercializing FO was Nanium (Portugal) before its acquisition by AMKOR (USA). OSATs like ASE, Deca Technology, PTI and others like SEMCO are stepping up into FO and are aiming to get increased market share from the FO TAM that will grow from $981M in 2018 to around $3.8B in 2024, as shown in the pie charts below.

With regard to FI technology, the market will also grow but at a slower pace than FO, reaching $4.4B in 2024 ($2.9B in 2018). The Taiwanese foundry TSMC has 2/3 of the FI market, while the other third is distributed between the Asian/USA OSATs. More than 90% of Fan-In packages are found in mobile devices.

Fan-Out & Fan-In revenue comparison between 2018 and 2024



Source: Yole Développement, 2019

4 - Synergy between embedded die (ED) technology and multiple markets

Embedded die technology was initially used for mobile phones for applications such as power amplifiers, switches, filters, power management units, etc. Still considered an infant technology, the interest around it is increasing considerably for its capacity to bring integration with good form factor at the same time than power management.

The mobile market will remain a good market, but prospective markets such as automotive, telecom and infrastructure are to be monitored as they are expected to be even more important markets for ED technology in the coming 3-5 years. ED main applications will be power devices where this technology allows better heat management and thus increased efficiency and reduced power consumption that are crucial parameters for electrical and hybrid/electrical vehicles (EV/HEV) in addition to base stations.

For once, European countries are involved in the supply chain. This is a bit more complex than that for the other advanced packaging platforms. It includes the substrate manufacturers that will have an important role embedding the die into the substrate. Few substrate makers have assembly capabilities. Thus, they are partnering with OSATs to subcontract these steps.

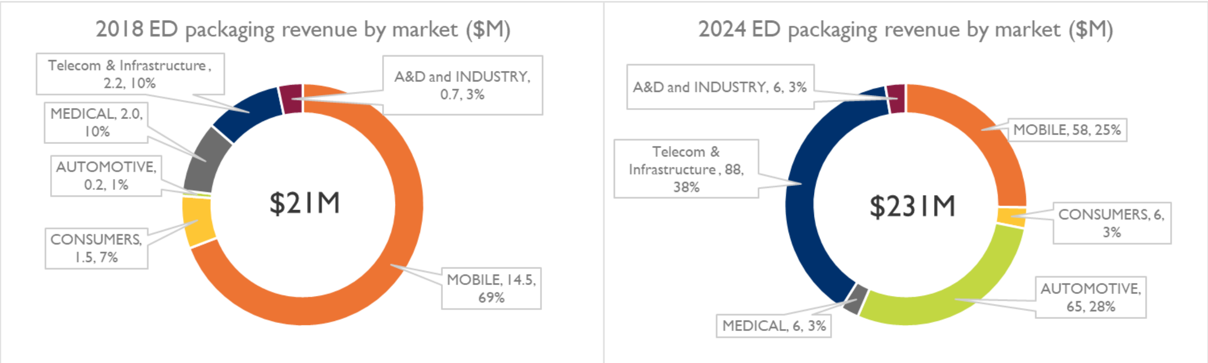
European substrate manufacturers such as AT&S, Schweizer (with Infineon) and Würth Elektronik are active in the ED field. Fraunhofer, the German R&D institute, is also active in R&D. Although these players' production plants for ED are and will remain in Asia, R&D is still performed in the EU. Besides a small part of FO & stacking, this is almost the only advanced packaging platform where the EU is still in the game. Chinese players are stepping up into ED and it's foreseen that the battle will be fierce in the future to identify the best ED technology, the best manufacturer and its killer application(s) for each market.

Although this technology is not yet very well known on the market, and to anticipate the forthcoming demand, huge investments are being made by players like Schweizer and Access semiconductor in new factories based in China.

In 2018 the ED market was relatively small, accounting for only $21M and dominated by the mobile market. The growth of ED is expected to exceed 49% CAGR 2018-2024. By 2024 the market is expected to reach $231M mainly driven by automotive, telecom & infrastructure markets, as shown in the diagram below. Mobile will still be an important source of revenue for ED but will no longer drive its expansion.

As this technology is still in its infancy, there are still plenty of different ED technologies coming from various players trying to break ground. This packaging platform will require consolidation in the future. Determining which technology and which company will have "THE" ED technology is difficult to predict and will depend on the application. R&D will progress, and more players will enter production in the coming 2-3 years.

ED packaging revenue by market, 2018 VS. 2024



Source: Yole Développement, 2019

5 – Summary by end-user applications

- <u>Automotive electronics</u>. Automotive is known as a very conservative industry when it comes to the adoption of new technologies and packages. Things are starting to move a bit with vehicle electrification and autonomy megatrends especially with regard to the adoption of the latest innovations for the computing system. Automotive is in need, and will be even more in need, for more electronic systems in a car. Vehicle electrification will require new packages, such as embedded die, for example, to handle high-power devices allowing a better efficiency through enhanced heat management. Other electronics, especially the sensing units, will also have a need for more sophisticated packages and automotive will be forced to accelerate their adoption curve. Automotive qualifications are very stringent and require between 3 to 5 years before a package or system is qualified. Reliability is a key factor for any of the advanced packaging platforms to be used in automotive in the future. Stacking technologies are not expected to enter the vehicle computing units before at least ADAS level 3, though they may be used for other applications such as the CMOS Image Sensors or the intelligent lighting systems prior to that. European car makers (Audi, Volkswagen, Renault…), IDMs (Bosch, Infineon, NXP, STMicroelectronics) and integrators (Continental, Valeo, ZF…) will be pushing for new package adoption into automotive according to each company's strategy, willingness and need.

- Industrial & Robotics. Industrial and robotics applications will be implementing leading-edge technologies and thus advanced packaging. Reliability is important but not crucial, while cost together with performance are key factors.
- Health & Care. Health & Care applications are a prospective market for advanced packaging driven by their need for miniaturization and high reliability. However, the market is expected to remain small in the near future.
- Aerospace, Defense & Security. Aerospace, Defense & Security are highly reliable segments. The use of advanced packaging may be possible, but it will take more than 5-10 years to breach these very stringent markets.
- Phones. Mobile phone has been the driving market for packaging innovation since 2007, with the appearance of the first Apple smartphone. Since then, although mobile is the main market for advanced packaging, it has paved the way toward new markets and applications in HPC, telecom and data centers. Mobile phones are using all the different advanced packaging platforms except the 2.5D structures. They use 3D stacking for the CIS, FO/FI/ED for multiple RF systems and APE. This usage will continue to grow within the next smartphone generations as the need for more sophisticated electronics is continuing with packaging answering the requirements in terms of performance, miniaturization and cost.
- Telecommunication infrastructure. Telecommunication infrastructure with the coming 5G demand is expected to explode in the future 10 years. One major problem of this type of infrastructure is their power consumption. Any package, for example ED, which can enhance the heat management and thus increase the efficiency (even slightly), could become an enabler. 2.5D structure is also playing a key role in switches and routers.
- PC & data processing. The datacenter market will be key in the future. The huge amount of data collected by all the sensing units will have to be processed. This market is the main driver for stacking technologies related to HPC, which offers impressive performance even if their price is still relatively significant. HPC and datacenter markets are less sensitive to cost than mobile and automotive but will highlight the performance parameters. Advanced packaging platforms, including stacking, are already well implemented in these segments and will continue to flourish as the need will be gigantic in the future. High-end consumer PC is also a market for stacking technologies where 2.5D and 3D technologies are used in advanced GPUs (AMD, Nvidia), and in advanced cores as Intel's i7 8809 core using their proper embedded multi-die interconnect bridge (EMIB) stacking technology.
- Audio & Video. Audio & video applications will become more and better known in various markets (automotive, mobile, smart homes, surveillance…). These systems, especially those based on video, will need high performance sensors that will most probably be using a 3D stacked architecture as is already the case today in smartphones' CIS. The computing systems for these electronic devices will also become more complex and thus packages like FC BGA will be required.

Impact of advanced packaging by end-user electronic applications in 2023

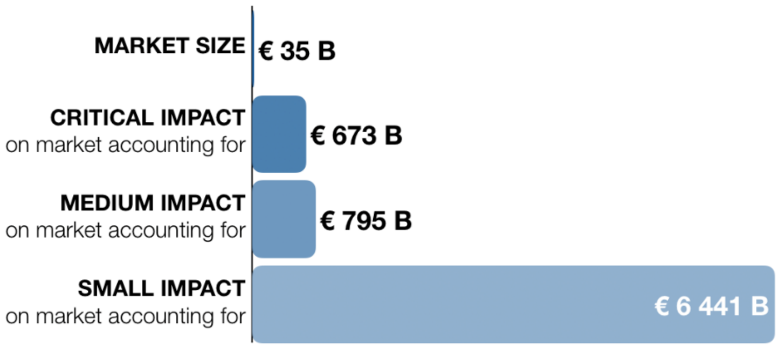
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Small	Critical	Critical	Medium	No	Small	Small	Critical	No	No

Corresponding quantitative impact of advanced packaging in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
35	673	795	6 441	673	795	754	0	0	5 687
				PC & data processing, Phones	Telecommunication infrastructures	Automotive, Audio/Video, Health & Care	-	-	Finance sector

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of advanced packaging in 2023



Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

Driven by the megatrends, the need for more and more electronics is forcing the supply chain to adapt. The IDMs that historically were doing in-house packaging see their lines full very quickly with the volume explosion, thus are subcontracting more and more of their packaging to OSATs. Many of the top IDMs, European players like Bosch, NXP, STMicroelectronics, Infineon and others, are subcontracting, especially the advanced packages, to non-European OSATs. This emphasizes the ongoing trend of the last few years: the EU is more and more disengaging from the packaging ecosystem, with only some R&D and design still done in the EU.

Top 15 OSATs worldwide, European packaging IDMs & substrate manufacturers

N°	Type of player	Name of the organization	Nationality of capital ownership	World estimated annual R&D budget/investment (M€)	World number of employees /researchers
1	Packaging & Test	ASE (w/o SPIL & USI)	Taiwan	496	> 30 000
2	Packaging & Test	AMKOR	The USA	157	29 000
3	Packaging & Test	JCET/ Stats ChipPac	China	134	> 10 000
4	Packaging & Test	SPIL	Taiwan	136	> 10 000
5	Packaging & Test	Powertech Technology Inc	Taiwan	62	4 000
6	Packaging & Test	Tongfu Microelectronics	China	80	4 000
7	Packaging & Test	Tianshui Huatian Microelectronics	China	247	> 10 000
8	Packaging & Test	UTAC	Singapore	16	> 5 000
9	Packaging & Test	King Yuan Electronics	Taiwan	30	5 000
10	Packaging & Test	Chipbond Technology	Taiwan	15	Unknown
11	Packaging & Test	ChipMOS Technologies	Taiwan	31	> 5 000
12	Packaging & Test	Orient Semiconductor Electronics	Taiwan	9	> 7 000
13	Packaging & Test	SFA Semicon	South Korea	1	< 2 000
14	Packaging & Test	AOI Electronics	Japan	11	< 2 000
15	Packaging & Test	Greatek Electronics	Taiwan	6	< 4 000
16	3D integration & WLPP	3DiS technologies	France	Undisclosed	< 10
17	Mainstream packaging WLP	Sencio	Netherlands	Undisclosed	Unknown
18	Advanced IC substrate, ED	AT&S	Austria	76	10 000
19	Advanced IC substrate, ED	Schweizer	Germany	4	< 1 000
20	Basic advanced substrate	Somacis	Italy	Undisclosed	1 000
21	Substrate manufacturer: ED	KSG group	Germany	Undisclosed	< 1 000
22	IDM	Bosch	Germany	< 100	> 10 000
23	IDM	Infineon	Germany	< 100	> 10 000
24	IDM	NXP	Netherlands	< 100	> 10 000
25	IDM	STMicroelectronics	Switzerland – France – Italy	< 100	> 10 000

Source: Yole Développement, 2019

In this table are displayed companies with packaging capabilities from three different business models: OSATs, IDMs and substrate manufacturers.

Looking at the top 15 OSATs in the world (1-15), a quick perusal will show the absence of any European player in this list. Even if we take our analysis deeper and plot the top 25 OSATs (not shown here), we will still not find any European player. This illustrates the extent to which the advanced packaging business is today mainly an Asian one with AMKOR as the lonely non-Asian player in the top ranks.

World Map – Advanced Packaging

Source: DECISION Etudes & Conseil, Yole Développement, 2019

Initially, packaging was very simple and the attractiveness of Asian countries in terms of regulations, workforce, salaries, etc. drove players from other countries to subcontract to, or develop plants in, Asia. Asian governments seized the opportunity, helped local companies flourish by investing massively in them and gave special incentives to overseas companies willing to set up their packaging plants in Asia.

Nowadays, Asia is the center of innovation in packaging. The US is still in the game thanks to AMKOR (producing in Asia), while the EU is far behind with only IDMs like Bosch, NXP, STMicroelectronics and Infineon (22-25) trying to innovate in packaging. They cannot, however, be compared with Asian players as packaging is not their core business. These IDMs are more and more subcontracting packaging to Asian OSATs. European IDMs have neither the capability nor the willingness to develop any of the advanced packaging platforms in-house, and nowadays prefer the OSATs for these tasks. Some of these IDMs are still developing their proprietary packages (legacy) in-house and are co-designing and manufacturing the advanced packaging in partnership with Asian OSATs.

In terms of substrate manufacturing and substrate based advanced packages, only few players are still in the EU (18-21). AT&S ($1B revenue in 2018) is the leading European substrate manufacturer, while Schweizer ($132M revenue in 2017) and KSG group ($159M) are also active in this field within the EU. Both are smaller than AT&S in terms of revenue and investment in innovation.

European main packaging R&D institutes

N°	Name of the organization	Nationality of capital ownership	Estimated annual R&D budget/investment (M€) in the main R&D center	Number of employees /researchers in the main R&D center	Country location of the main R&D center	City location of the main R&D center
1	IMEC	Belgium	< 20	> 1 000	Belgium	Leuven
2	CEA-LETI	France	< 20	> 1 000	France	Grenoble
3	Fraunhofer IZM	Germany	< 20	> 1 000	Germany	Berlin
4	EPFL	Switzerland	< 2	> 20	Switzerland	Lausanne
5	Tyndall	Ireland	< 2	> 20	Ireland	Cork

Source: Yole Développement, 2019

European main packaging equipment suppliers

N°	Name of the organization	Nationality of capital ownership	Estimated annual R&D budget/investment (M€) in the main R&D center	Number of employees /researchers in the main R&D center	Country location of the main R&D center	City location of the main R&D center
1	Besi	Netherlands	35	1 700	Netherlands	Duiven
2	EVG	Austria	NA	> 850	Austria	Sankt Florian
3	Süss MicroTec	Germany	18	< 800	Germany	Garching
4	PacTech	Germany	Undisclosed	< 500	Wafer level packaging (WLP) services	Nauen
5	Ficontec	Germany	Undisclosed	> 200	Germany	Achim
6	Boschman	Netherlands	Undisclosed	< 30	Netherlands	Duiven
7	Disco hightec Europe	Germany	144 (Disco Group)	< 100	Germany	Munchen
8	SET	France	Undisclosed	< 50	France	Saint jeoire
9	Finetech	Germany	Undisclosed	> 50	Germany	Berlin

PacTech also provides packaging services

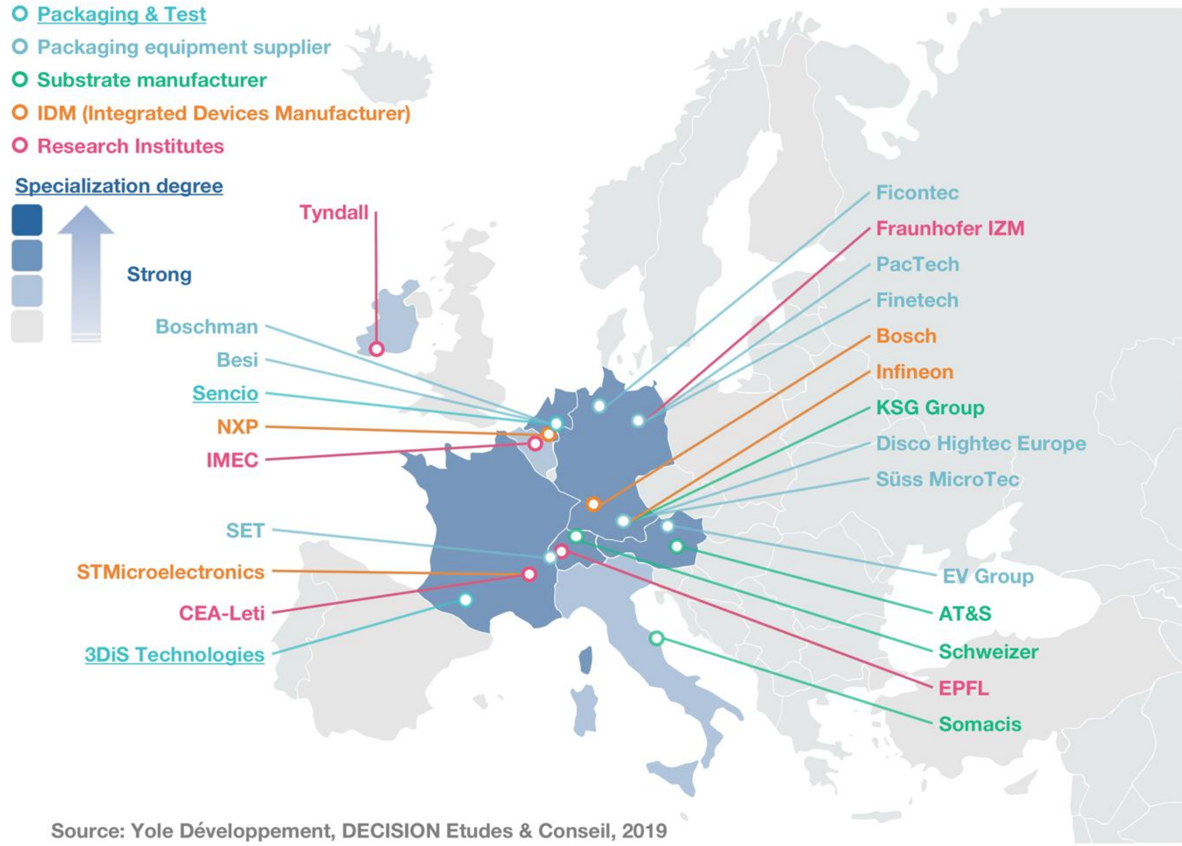
Source: Yole Développement, 2019

Nevertheless, some advanced packaging R&D (especially at wafer level) is still ongoing in the EU via the big R&D centers in France, Germany, Belgium, etc., who are still trying to innovate. Each of these R&D centers has a privileged industrial partner with whom they work on developing advanced packaging solutions according to their proprietary needs. In France, STMicroelectronics is an important partner of CEA-LETI. In Belgium, IMEC is partnering with TSMC, while Fraunhofer is working closely with numerous German companies including Global Foundries. These partnerships are crucial for the EU. Effort is needed to accelerate the innovation and to push the R&D into industrial solutions. Many of the European partnerships and programs struggle to get further than the research. This should be changed so that R&D centers in the EU become even more involved in industrialization.

The added value of the EU in the supply chain for advanced packaging is in its leadership in tool manufacturing for these processes. A multitude of packaging equipment suppliers are located in the EU territory and are leaders in their fields. Some of these are specialized in a certain market, such as Ficontec in the optoelectronics field, while others are global. Companies like Besi, EVG, SÜSS MicroTec and others have worldwide reputation while others are known more locally but are trying to expand their business. They have the knowledge in-house and they have this European quality label that is much appreciated in the semiconductor industry, even if in terms of price they are more expensive than competitors from the other continents.

Globally, it seems difficult for the EU to catch up with the advanced packaging train, especially in terms of manufacturing. Asia is today the uncontested leader in terms of production and innovation. Producing the packaging in the EU seems impossible today, neither in terms of competitiveness (cost) nor in terms of environment (implementation difficulties in meeting European regulations). The European companies are mostly producing in their Asian plants and keeping the R&D in the EU. The EU should encourage the European companies involved in packaging to enhance their R&D with the goal of industrializing. Encourage the existing European companies that are facing fierce competition to continue with innovation and aid them financially if needed (as Asian governments are doing, especially in China). The EU should also help companies that are willing to produce in the EU, to implement, support and facilitate their activities.

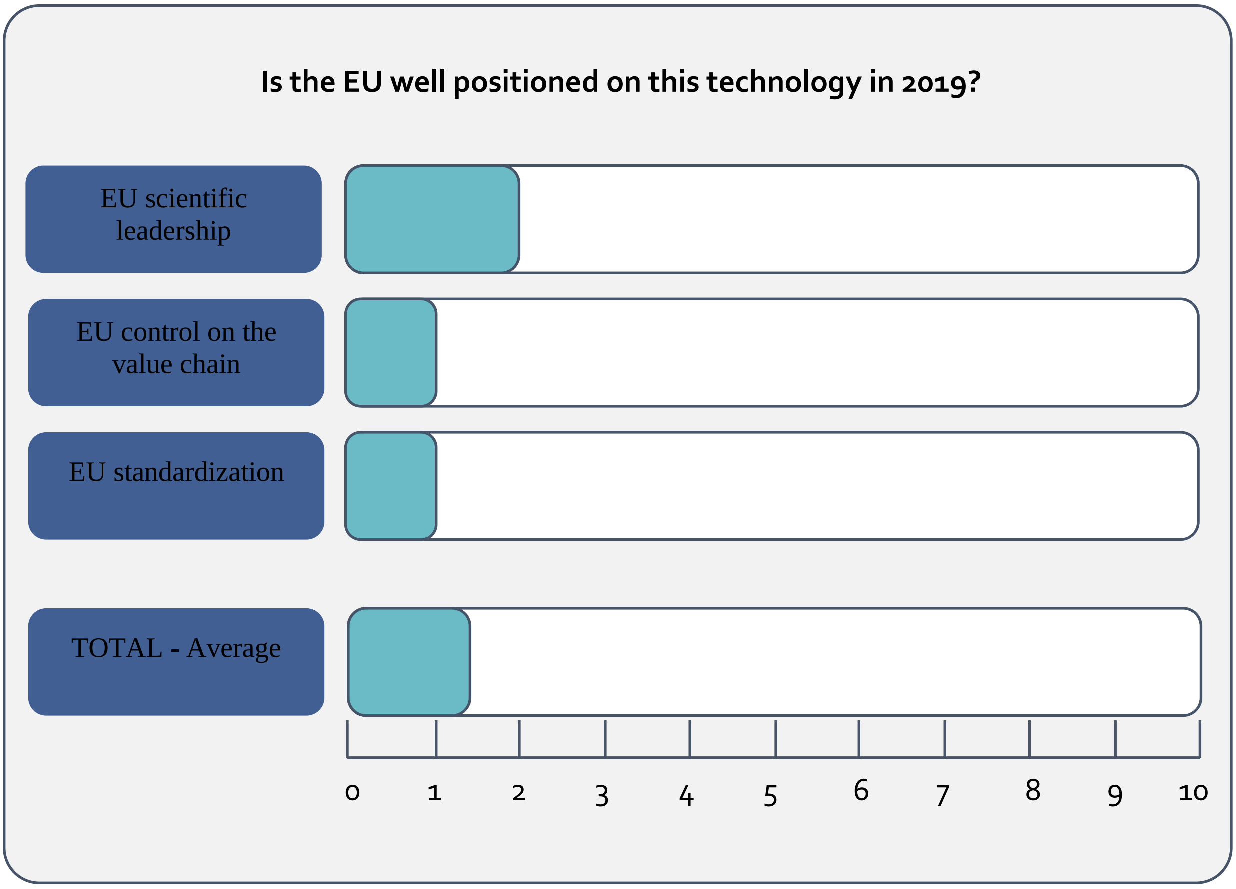
Europe Map – Advanced Packaging

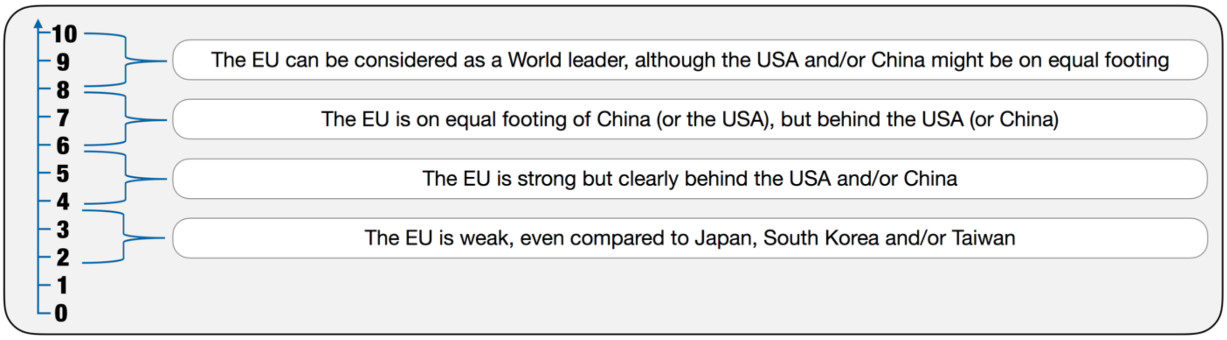


Source: Yole Développement, DECISION Etudes & Conseil, 2019

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

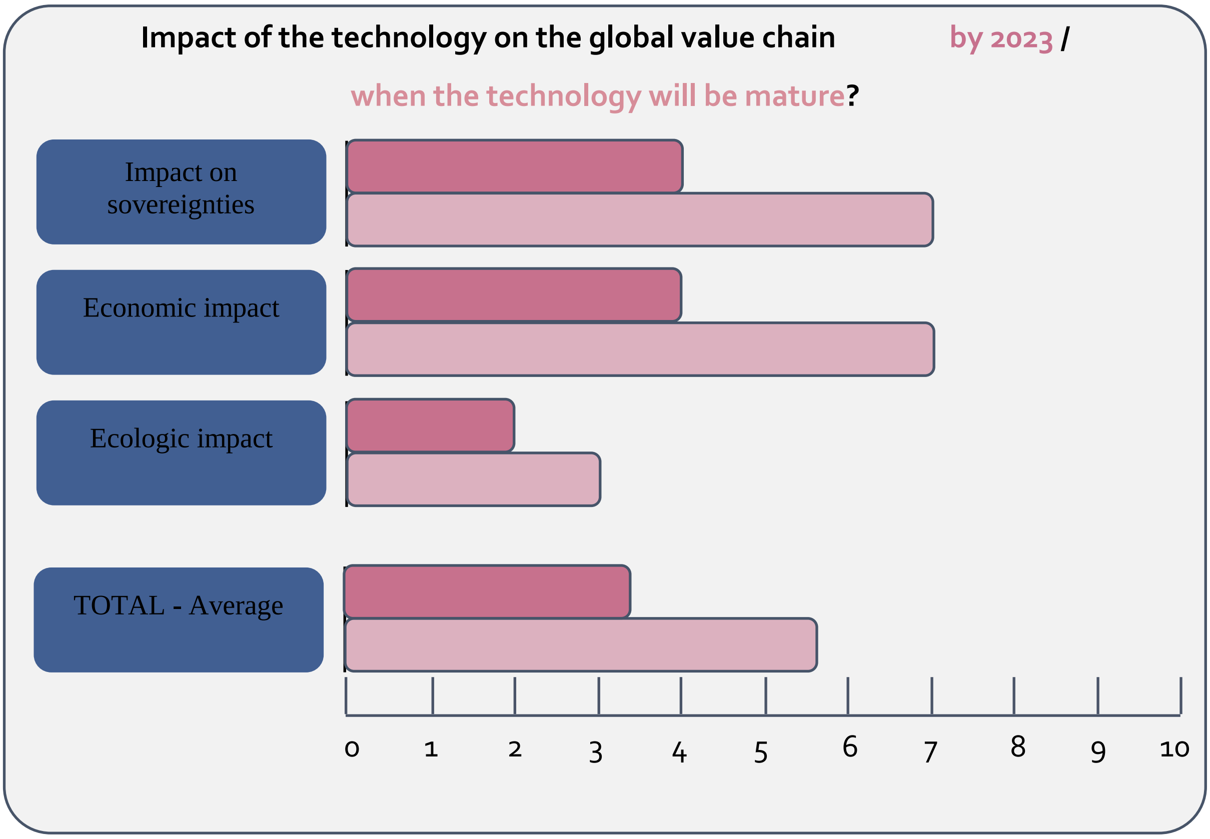
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.
- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.
- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU remains in a relatively good position in terms of pure R&D. Historically, packaging innovation was happening to a small extent in the EU. Even if today that is still partly the case, with R&D centers investing, developing and innovating especially on wafer-level packaging, the pace has slowed compared to that of Asian players.

Yet, the European know-how, quality of work and the propitious development environment remain much appreciated by Asian players, to the extent that European R&D centers are continuously attracting huge industrial players like TSMC to co-develop packaging technologies.

To emphasize these points with an example, it is believed that TSMC and IMEC are close to commercializing their co-development work on a “wafer-on-wafer” stacking technology for the high-end devices market, most likely for telecommunication applications.

EU control on the value chain

As shown in the previous sections, the EU position in the packaging (legacy & advanced) value chain is clearly in need of strengthening.

The EU is a relatively small player in this field compared to Asia and specifically Taiwan as:

- The EU has no company among the top services packaging companies (OSATs);
- The EU has a few companies specialized in packaging in fields such as MEMS, power, photonics etc., but that are too small to compete with the world-leading companies;
- The European IDMs remain significant players worldwide in terms of technology, revenue, size and have in-house packaging capabilities (Bosch, NXP, Infineon and ST Microelectronics). These companies are still having in-house legacy packaging lines for products as power devices and different types of sensors. As for today, they are still representing the majority of this legacy packaging revenue for each of their specialty devices. Furthermore, the European IDMs are world leaders in terms of packaging for power applications (IGBT, etc.). Yet, in the coming years, this dominance should be reduced as IDMs are progressively outsourcing these activities to non-European OSATs;
- The EU also has some advanced substrate manufacturing players, but the EU’s main role is supplying equipment for advanced packaging developments.

The outsourcing trend will continue in the coming decade, weakening the packaging activity in the EU territory. Legacy packaging is mainly settled in Asia and consequently the efforts for developing Advanced Packaging are also concentrated there. The EU puts more effort on the chip development (including IP) and on the systems’ businesses.

Due to the very high cost pressure on most of the semiconductor segments, the EU has lost its competitiveness compared to Asian countries. It makes the EU dependent on other continents. Investments in advanced packaging manufacturing lines are high and make a reverse of the current situation more difficult.

Standard analysis

In terms of standardization, the European players are members of international standardization organizations such as JEDEC, Automotive Electronics Council (AEC), SEMI standards and others. European players are contributing to the standardization processes.

Impact on sovereignties

Not having packaging activities in the EU is somehow a threat to the EU’s sovereignty, as integration is essential for each component. In other words, advanced Packaging is affecting sovereignties as an enabling technology.

Economic impact

The advanced packaging Total Available Market (TAM) in 2018 was around €23B and will reach €35B in 2023. Yet, over the coming decade, advanced packaging will mainly impact the world electronics value chain in terms of added value in embedded/professional systems (especially through the rising importance of System-in-Package in embedded products).

Ecological impact

Some advanced packaging platforms play an important role in reducing the power consumption of the products using them. This is the case for the 2.5D and 3D structures that are widely used for HPC in data centers that are high power consumers. Other platforms, such as embedded die, for example, play an indirect role by increasing the die's efficiency and thus indirectly impact its power consumption. However, producing such packages will require building plants and thus affecting the environment even if the plants built are considered ecofriendly. In this case, the plant investment will be more consequential and will have a direct impact on the package production cost. It's a vicious circle when ecology meets with production and low cost. This is why Asia is "ahead" of the EU, because their ecological regulations are less stringent than those in the EU.

C. Conclusion

A way for the EU to grow further in the Advanced Packaging business is to deliver solutions with more functionality, like RF features (Integrated Passive Device, Antenna in Package, etc.).

D. Emerging Non-Volatile Memories

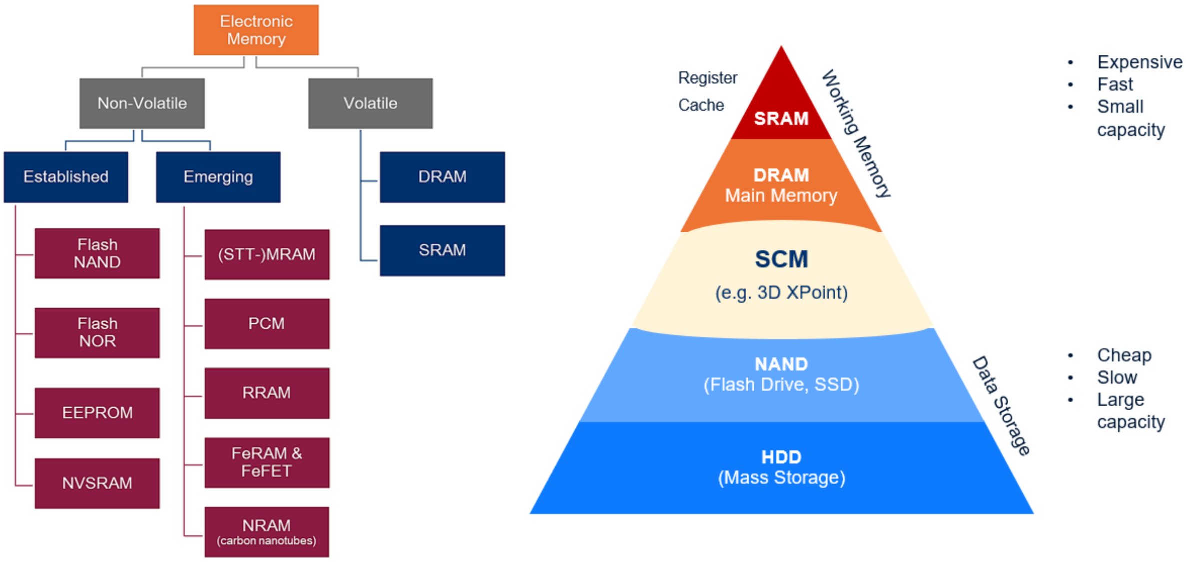
i. Definition

Semiconductor memories are essential building blocks of modern electronic systems and have played a key role in enabling numerous applications that are changing and improving our lives, such as new smartphones, wearables and healthcare, factory automation, internet of things (IoT) and artificial intelligence (AI). The main types of memories are the following:

- Dynamic Random-Access Memory (DRAM, volatile), and Flash NAND (non-volatile)[7], are the stand-alone workhorse options and will maintain their leading position for another several years thanks to new technical solutions that enable further scalability;
- Static Random-Access Memory (SRAM), is a very common volatile memory and is typically used in embedded form, particularly for application in CPU caching;
- Nowadays, there exists a large speed-capacity-cost gap between NAND and DRAM, one which must be reduced to improve the overall performance of computing systems. Storage-Class Memory (SCM), serves precisely this purpose and has been recently enabled by emerging Non-Volatile Memory (NVM) technologies, in particular by 3D XPoint, a Phase Change Memory (PCM), jointly developed by Micron and Intel and commercialized since 2017 as Intel's Optane™.

[7] Glossary. (Non-)Volatile: the information is (not) lost in the absence of power supply. Stand-alone: the chip is fully dedicated to the memory function. Embedded: the memory function is integrated within a broader system, such as for instance a microcontroller (MCU) or a system on chip (SoC). Stand-alone and embedded memories are very different in terms of manufacturing processes, industrial ecosystems and supply chains.

Memory taxonomy (left) and memory hierarchy within a traditional Von Neumann system architecture (right)



Source: Yole Développement, 2019

Historic overview

DRAM. The first DRAM device was demonstrated by Robert Dennard (IBM, US), in 1966, and mass production began in the first half of the 1970s. At first, American companies dominated the market with their superior DRAM technology. In the 1980s, Japanese players took the leadership due to strong government support and efficient manufacturing. From the mid-1990s, Samsung (South Korea), grabbed the number one position[8]. Infineon (Germany), was the only European player active in the DRAM business. In 2006, Qimonda split out of Infineon, forming the second-largest memory company worldwide (based in Germany). During the DRAM-market turndown in 2007-2008, Qimonda started suffering significant financial losses and in 2009 they had to declare bankruptcy and cease all worldwide activities.

Flash memories. A prototype of Flash memory was presented for the first time by Fujio Masuoka (Toshiba, Japan), in 1984, a fact that paved the way to the rise of the Flash industry. Nowadays, NAND is making inroads in high-capacity solid-state drives (SSDs), that complement/replace magnetic hard-disk drives. High-density storage has been enabled by vertical stacking of multiple NAND layers in the so-called 3D NAND technologies. These entered into the market in 2014-2015 and are now the most mature industrial approach to maintain the pace with the ever-growing bit demand fueled by novel AI/IoT applications and systems, such as smart cities, connected homes and intelligent factories, smartphones and Echo-like personal assistants, virtual and augmented reality and autonomous vehicles. South Korea (Samsung, SK Hynix), the USA (Micron, Intel, Western Digital), and Japan (Toshiba) are the leading countries in the NAND market. STMicroelectronics (France-Italy) has been shipping NOR, as well as NAND flash, but has never been in the race to get a significant portion of the market.

Emerging Non-Volatile Memories (NVM). Emerging NVM, such as Magneto-resistive RAM (MRAM), Phase-Change memory (PCM), and Resistive RAM (ReRAM), are now ramping up after several years of R&D (sometimes even a few decades), but there are still other new technologies in the pipeline (see the diagram above representing the memories taxonomy). For instance, Nanotube RAM (NRAM), and Ferroelectric Field-EffectTtransistors (FeFETs), are currently being investigated as potential non-volatile high-density "working" memories. With unique combinations of power consumption, speed, and non-volatility, emerging NVM have the potential to replace DRAM, SRAM or flash memory in various applications, such as for instance low-power IoT. MRAM could eventually serve as a fast, dense, cache memory, while ReRAM and PCM show potential as

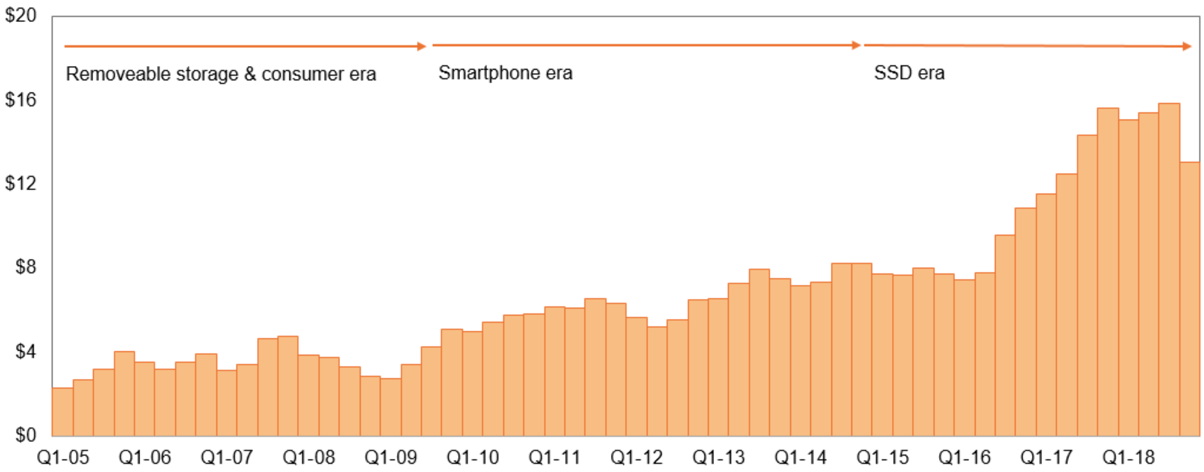
[8] And maintained it until today.

storage class memories. Nowadays, emerging AI applications are also driving important architectural changes, such as the shift from conventional Von Neumann architectures (see the diagram above representing the memory Von Neuman hierarchy), to novel near or in-memory computing approaches, which bring the processing tasks near or inside of memory (see the chapter on edge AI).

Memory market overview

Stand-alone memory market. Despite some cyclicality and seasonality (see the chart below), the stand-alone memory market has experienced extraordinary growth over the past decade. NAND and DRAM revenues hit a record high of around US$160 billion in 2018, recording an impressive compound annual growth rate (CAGR) of 32% between 2016 and 2018. At the end of 2018, both NAND and DRAM markets started experiencing oversupply caused by unseasonably weak demand, including lower-than-expected smartphone sales and a slowdown in datacenter demand. However, in the long-term revenues are forecast to grow with CAGR of 4% and 1%, respectively, between 2018 and 2024.

Historical of NAND Market Revenues, showing the cyclicality/seasonality of the market (by quarter) (in $B)

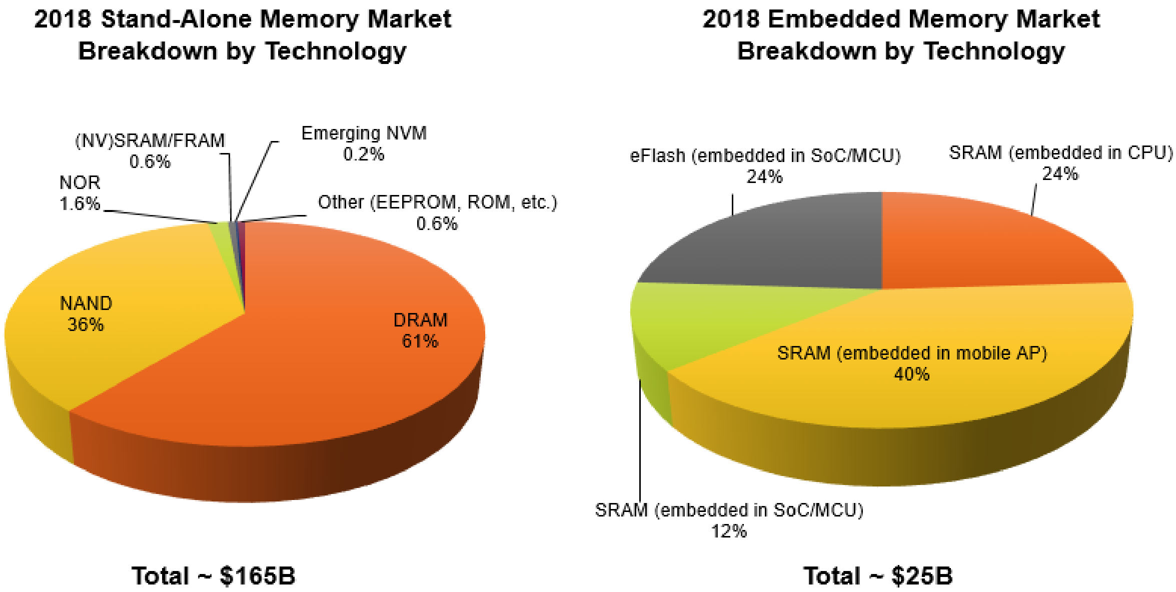


Source: Yole Développement, 2019

NAND and DRAM account together for around 97% of the overall stand-alone memory market, while the remaining 3% consists of a plethora of technologies, among which NOR flash (1.6%), volatile and non-volatile SRAM, ferroelectric FRAM and emerging NVM (see the pie chart below, left). The stand-alone emerging NVM market will be driven by SCM applications enabled by 3D XPoint (PCM), which will remain for long the leading emerging NVM technology thanks to the support of leading players such as Intel. Further density improvement and bit-cost reduction are needed towards mass adoption of emerging NVM technologies, and top-player involvement remains essential. Overall, emerging NVM will not replace NAND and DRAM but will complement them in hybrid memory solutions, remaining below 3% of the overall stand-alone memory market in 2023.

Embedded memory market. The embedded memory market is significantly smaller than its stand-alone counterpart, representing ~$25B (see the pie chart below), with 40% of the revenues coming from SRAM for mobile-phone application processors (APs), followed by SRAM in CPU chips and by eFlash integrated in MCUs and SoCs (~24%). Noteworthy, eFlash scaling is nowadays reaching its end – 28 nm / 22 nm will be likely the last technology node – and SRAM scaling is also slowing, so that alternative embedded memory technologies are highly investigated as potential replacements for advanced nodes. Among the various emerging NVM, MRAM is picking up steam in the embedded business thanks to the strong involvement of top foundry/integrated device manufacturers (IDM) players and equipment suppliers, who are providing new solutions to critical technical challenges. In the EU, STMicroelectronics is developing embedded PCM as a replacement of eFlash at the 28 nm lithography node and is qualifying the technology for the automotive market. NXP (Netherlands), has also recently adopted embedded emerging NVM (e.g., MRAM), for MCU and IoT devices *via* a collaboration with its South Korean foundry partner (Samsung Foundry).

Stand-alone (left) & embedded (right) market revenues in 2018 (technology breakdown)



Source: Yole Développement, 2019

Forecast in units and by application (2018-2023)

Throughout its history, the stand-alone memory market has experienced up- and downturns due to cyclical/seasonal unbalances between demand and supply. Nevertheless, the explosive memory bit demand from data-centric systems and applications will drive a long-term memory market growth.

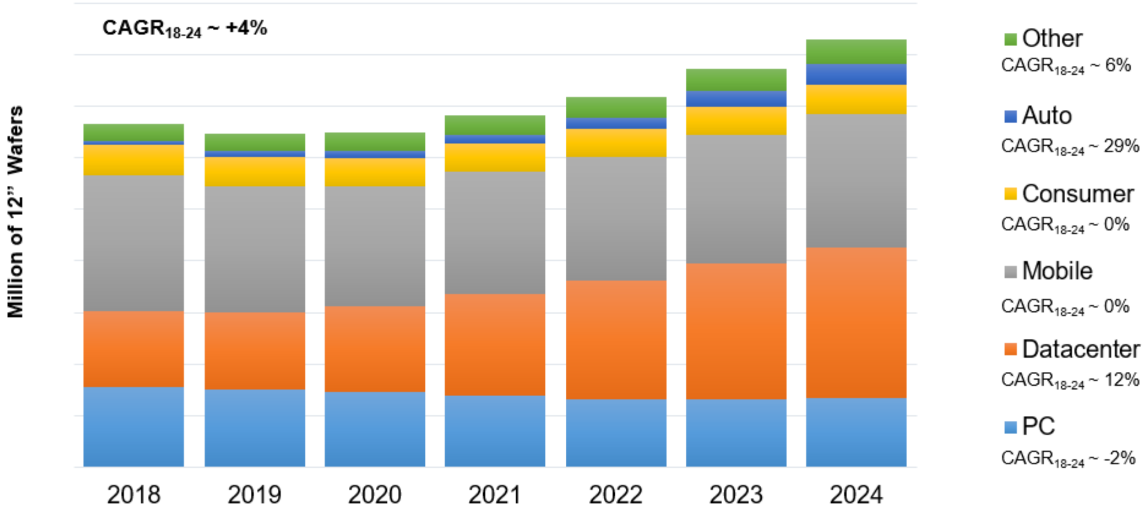
The diagram below shows combined NAND- and DRAM-wafer demand projections. In 2018, mobile is the largest end-market segment, followed by personal computers (PC) and data centers. Memory wafer demand from PC and mobile is not expected to grow in the next 5 years (CAGR of -2% and 0%, respectively).

On the contrary, wafer demand from datacenter is expected to grow vigorously with a CAGR of ~12%, due to the increasing number of systems and applications relying on datacenter resources. Noticeably, the datacenter segment is in the middle of two important megatrends, i.e., artificial intelligence and internet of things, which are at the forefront of demand expansion for memory, including both NAND and DRAM.

Automotive is nowadays a relatively small memory market segment, but it should grow very fast (CAGR of ~29%) thanks to the increasing penetration of autonomous driving systems and technology requiring large amounts of working memory and data storage. In the past, processors for automobiles had modest memory requirements served by static random-access memory (SRAM) and NVM technologies, such as NOR Flash. Today, advanced driver-assistance systems (ADAS) tools, navigation and infotainment systems, and instrument clusters for displaying gauge information on High-Definition (HD) color displays and for streaming music/video, are dramatically boosting the demand for both fast working memory (DRAM) and onboard storage (NAND). At the same time, the need for fast booting through infotainment systems and engine control units (ECU), is augmenting the demand for highly reliable NOR and is triggering R&D investments on novel NVM technologies, such as for instance MRAM.

In summary, established and emerging memories will have a strong market potential in the coming years, thanks to an ever-growing bit demand from many key emerging applications, among which IoT (totally connected objects, building, cars, etc.), big data, cloud storage, real-time analytics, autonomous vehicles, security systems, smart houses and smart objects based on AI processing carried out both at the edge at in cloud-based data centers.

NAND and DRAM wafer demand from 2018 to 2024



Source: Yole Développement, 2019

ii. Synergies with other emerging technologies

Neuromorphic computing, AI algorithms & edge AI.

Emerging NVM are being regarded as promising components of neural networks for AI applications based on in-memory computing, which are becoming more and more popular in our society. In-memory computing would indeed benefit from the advantageous properties of emerging non-volatile memories when used as artificial synapses, which are the basic building block of neuromorphic networks.

The growing importance of AI is driving the need for more computing power, which in turn demands for new system architectures to overcome the so-called "memory wall" that is unavoidable in conventional Von Neumann architectures. Near- and in-memory computing, which consists in processing the information in situ (near or in the memory unit), are the main strategies pursued nowadays to increase system performance and avoid detrimental data-transfer between processing and memory units.

However, existing memory technologies are ineffective to in-memory compute billions of data, as it happens within the human brain. Emerging NVM technologies – such as RRAM and PCM – are being intensively investigated as a potential response to this problem; these devices are based on resistance-switching in two-terminal cells that mimic the function of the synapses in the human brain, and therefore are ideal for the physical implementation of neural networks. Emerging NVM can also be directly integrated on a chip with the processing logic, enabling brand-new memory-centric SoC architectures.

Interestingly, a French start-up company called UPMEM, which has raised > €3 million since 2015, is developing a new promising type of DRAM module with processing-in-memory (PiM) functions. The basic idea behind PiM consists in building data processing units (DUPs) into the DRAM chip and connecting them to the internal bit lines; this allows harnessing the outstanding internal bandwidth of the memory chip by limiting speed losses due to continuous data transfer from the memory to CPU.

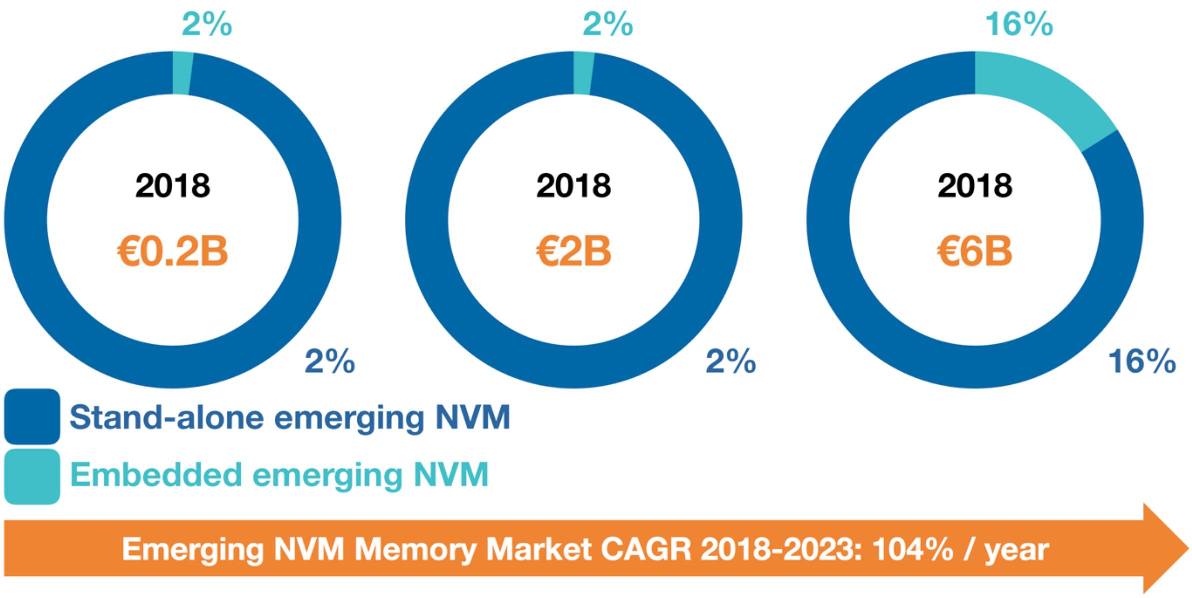
iii. Technology roadmap: Maturity levels and expected impacts by application area

This section evaluates the maturity level and the potential impact on different application areas of emerging NVM technologies, namely MRAM, PCM, and RRAM. We point out that these technologies have been developed in both embedded and stand-alone forms with different maturity levels, as discussed below.

Emerging non-volatile memory technologies are expected to have a remarkable economic impact in the coming years (see the diagram below), with an estimated **market value of €6 B in 2023**, as they could enable the next generation of low-power IoT and edge-AI devices which are becoming mainstream technologies in our society.

The embedded emerging NVM market is now taking off and could reach up to €1 billion in 2023, driven by adoption of embedded NMV – particularly STT-MRAM – in low-power technology processes (≤ 28 nm) offered by major foundries. The stand-alone market will be fueled by the growing demand of SCM devices (e.g., 3D XPoint), for filling the speed-density-cost gap between NAND and DRAM. SCM technologies will serve at first the datacenter market and will be adopted by hyperscale companies targeting real-time analytics applications, such as in-memory databases.

Market projections for embedded and stand-alone emerging NVM market (PCM, STT-MRAM and RRAM)



Source: DECISION Études & Conseil, based on estimates from Yole Développement, 2019

Roadmap of Technology Maturity

Stand-alone PCM. PCM technologies have been investigated for very long time. In 1970s, Intel's Gordon Moore and two authors from Energy Conversion Devices, Ron Neale and D.L. Nelson, published an article in the magazine *Electronics*, showing a 256 bits PCM memory device. Today, PCM is the technology behind Micron & Intel's 3D XPoint Memory. In the 2000s, PCM R&D was carried out by major companies, among which Ovonyx, STMicroelectronics, Intel, Micron, Elpida, Macronix, IBM and Samsung. In 2006, Micron and Intel started a joint venture called IMFT (i.e., Intel-Micron Flash Technologies) dedicated to Flash Memory and 3DXPoint, whereas in 2008 STMicroelectronics and Intel founded the company Numonyx (2008) devoted to the commercialization of PCM technologies. The first commercial products were introduced by Numonyx in 2008-2009 (128 Mb), followed by Samsung in 2010 (512 Mb). However, as the market was not ready for the new technology, the products were dismissed. Numonyx was purchased by Micron in 2011, and the latter started producing 1 Gb chips for some time. The first real start of the PCM market started in 2017, when the first 3DXPoint products by IMFT entered the datacenter and the consumer market. Stand-alone PCM has now achieved mass production – although volumes are not yet high enough to enable low-cost manufacturing and significant profitability – thanks to the involvement of major industrial players such as Micron and Intel.

Stand-alone MRAM. Toggle MRAM (based on magnetic field switching), has also been investigated for very long time, likely since the discovery of the giant magnetoresistance effect in 1989. R&D and testing progressed uninterruptedly until 2006, when Freescale – a company spin-off from Motorola (the USA) in 2004 – introduced the first 4 Mb chip on the market. In 2008 Freescale spun off its MRAM activities to a new company, Everspin, which started selling a new improved version of the 1 Mb and 4 Mb toggle MRAM. These chips targeted defense, transportation, industrial automation applications requiring high reliability and competing with more mature technologies, such as non-volatile SRAM (e.g., battery-backed SRAM), and ferroelectric memory (FRAM). Given the niche-type of nature of the applications, the relatively high price/bit, and the limited density (≤16 Mb), toggle MRAM is expected to be manufactured in relatively small volumes, far below the levels achieved by flash technologies.

Stand-alone STT-MRAM. MRAM based on the spin transfer torque (STT) principle has been investigated since 1996, i.e., the year of the discovery of the STT phenomenon by IBM labs. In 2016, after more than one decade in R&D and several years of testing, Everspin began sampling the first high-density STT-MRAM chips (256 Mb, 40 nm node), and introduced them into the consumer market in early 2018. STT-MRAM has been adopted by major memory module manufacturers (e.g., IBM, Smart Modular) that are integrating the technology into their storage-solution products, such as IBM's Flash Core drives and Smart Modular's nvNITRO storage accelerators. In the first quarter of 2019, Everspin – in partnership with GlobalFoundries – has also started the pilot production of 1 Gb chips (28 nm) that could open new avenues for STT-MRAM in the enterprise storage market. However, at this stage the ramp-up of STT-MRAM sales/volumes is taking a relatively long time. It is worth noting that STT-RAM chips are sold to IDMs/OEMs that require 12-18 months for developing new products and need to succeed in attracting new customers. Given that Everspin is still the only player active in the stand-alone STT-MRAM business, it is likely that a few more years will be necessary before a veritable mass adoption with significant volume ramp-up and scale economy.

Stand-alone RRAM. Compared to PCM and (STT-) MRAM, RRAM appears to have accumulated a certain delay (about 2 years). Panasonic, in collaboration with Imec, developed and fabricated 40 nm RRAM chips in 2015 and Fujitsu announced its entry into the RRAM market during the following year with a 4 Mb chip produced in collaboration with Panasonic. Adesto (the USA), has also been shipping RRAM-based EEPROM devices even before 2016, but mainly for niche applications with density requirements up to 512 kB. The ultimate milestone for stand-alone RRAM is to compete with 3DXPoint for SCM applications. All the largest memory makers (Samsung, Micron, Western Digital, SK Hynix), have carried out R&D in this technology, but the first commercial products seem still to be far. In fact, 4 Mb is still the highest density for RRAM in the consumer market in 2019, suggesting the presence of significant challenges – likely related to reliability and yields – for density upscaling.

Embedded STT-MRAM has been in R&D for about a decade before being considered and adopted by top foundries, such as for instance Samsung Foundry, GlobalFoundries and TSMC. These companies started sampling embedded STT-MRAM in 2016-2017 using 28 / 22nm lithography processes and initiated new R&D work for scaling the technology further. According to industry sources, STT-MRAM is certainly scalable down to the 1xnm node, but whether or not it can scale to 7 or 5 nm is still up for debate (mainly due to severe technical hurdles). In early 2019, Samsung started commercial production of 28 nm embedded STT-MRAM, and Intel and TSMC should follow soon in 22 nm FinFET and 22 nm planar bulk, respectively. Thanks to the involvement of top players and leading equipment suppliers, which are providing new solutions to a number of difficult manufacturing challenges, embedded STT-MRAM is poised to become a widespread technology.

Embedded RRAM. In 2013, Panasonic launched the first MCU (8 bits), with embedded emerging NVM, consisting of a 64Kb RRAM code storage memory. After some momentum building for RRAM in 2016-2017, foundries (SMIC, UMC) have dismissed/delayed RRAM adoption and there is no clear roadmap for 28 / 22 nm, except for TSMC which is currently developing an embedded RRAM technology. For embedded applications, RRAM's ultimate milestone is its adoption in edge devices for AI. Crossbar recently demonstrated various AI applications (i.e., facial recognition), with RRAM chips, and such embedded AI RRAM-based devices could enter the market (industrial production), in a few years, likely after 2021.

Nanotube RAM (NRAM) has been developed by a US-based company, Nantero, since the early 2000s. NRAM is based on voltage-induced resistance-switching (RS) occurring in a nonwoven matrix of carbon nanotubes (CNTs) deposited via a spin-coating process. It combines the attributes of DRAM (high speed), and NAND (high-density), in a single chip and could enable new applications as a storage class memory. However, NRAM is not mentioned in the roadmap of the big five memory makers (Samsung, Micron, SK Hynix, SanDisk, and Toshiba). In August 2016, Nantero licensed its technology to Fujitsu & Mie Fujitsu (foundry), for embedded product development at 55 nm, followed by a 40 nm upgrade. The two companies have been collaborating for more than two years on the production of NRAM, yet the Fujitsu's NRAM-embedded custom LSI product is still in the development phase. Likely, difficult technical challenges are delaying the volume manufacturing of NRAM-based devices.

Embedded PCM. After being researched for more than one-decade, embedded PCM is now being developed at the 28 nm lithography node by a key player in the EU (STMicroelectronics), who is now qualifying the technology for the automotive market and is expected to introduce the first commercial products by 2021. However, at this stage STMicroelectronics is the only major player involved in the development of the technology, and there is no clear roadmap so far for embedded PCM beyond the 28 nm node, so that the future of the technology appears uncertain.

Ferroelectric Non-Volatile FET. The discovery of the ferroelectric properties of Si-doped HfO_2 at NamLab (Germany) in 2015 spurred renewed interest in ferroelectric memories, particularly on ferroelectric transistors. High-κ HfO_2 has been adopted by major IC companies (Intel, IBM) since 2006, and it is now a very well known and mastered material in the microelectronics industry. The possibility to import NVM properties to metal-oxide-semiconductor (MOS) transistors *via* a doping/annealing process is extremely appealing for working-memory applications. FMC, in collaboration with GlobalFoundries and the leading European research institutes (e.g., Fraunhofer), are now dedicated to turn the scientific discovery into a viable technology. The potential is indeed very high – given the ease of integration and the compatibility with conventional CMOS logic processes – although there are severe challenges that need to be addressed to improve the figures of merit (retention, endurance, and switching speed), at the device and at the array level.

Roadmap of market applications

Automotive electronics. Thanks to its high reliability and high-read speed, NOR flash is still the NVM solution of choice for code/data storage applications in the automotive market, particularly those requiring execute in place (XiP) functions. At the same time, SLC NAND is emerging as high-density alternative to NOR, and new NVM technologies – such as MRAM – are poised to make the first steps in the automotive market space. Stand-alone STT-MRAM (≥ 2 Gb) could compete with NOR if the price/bit will decrease below ~10 $/Gb, and this requires scaling up the production to much higher volumes than the current one (it might take several years). At the same time embedded NVM – particularly PCM and MRAM – are potential competitors to embedded Flash (eFlash) in the automotive market space for technology nodes below 28 nm. The key embedded NVM players in the automotive space are STMicroelectronics and GlobalFoundries, which could introduce the first products based on PCM and MRAM, respectively, with significant impact on the market after 2023. Noteworthy, the automotive market is well established in the EU, with key suppliers of automotive electronics, such as for instance Bosch and Continental (Germany), STMicroelectronics (France), NXP (Netherland) and Infineon (Germany).

Industrial & Robotics electronics. Industrial and robotic applications (factory automation), require memories with high reliability and often capable of operating in harsh environment. In this context, FeRAM, (NV-)SRAM and toggle MRAM are already in the market with low-density products (≤ 16 Mb) that are used in various industrial devices, among which smart meters, which is a continuously growing market (CAGR 2018-2024 ~ 9%). Emerging NVMs, in particular toggle MRAM, have a competitive advantage over incumbent technologies thanks to their superior electrical characteristics (e.g., high-speed, retention and robustness), although their price/bit is not the most advantageous. Further density scaling and cost reduction are expected to open new pathways to emerging NVMs, promoting their penetration into the industry/automation electronics markets.

Health & Care electronics / Aerospace, Defense & Security electronics. In terms of memory requirements, health & care, aerospace, defense & security applications, are very similar to the industry and factory automation case: the priority is on the memory reliability, i.e., on the minimization of the bit error rate in critical missions and harsh environments. Such applications are currently targeted by Everspin's stand-alone toggle MRAM (128 kb – 16 Mb), which provide high reliability (> 20 years of retention), and radiation hardness. In 2019, the global NV-SRAM is estimated at ~€225M and the FRAM markets is estimated to be ~€233M in 2019 (that is a total of ~€458M in 2019).

Mobile phones. Emerging NVMs – particularly embedded STT-MRAM – are potential candidates for cache-memory applications in processors for mobile devices (smartphones & tablets). Cache memories require high endurance and high speed, but a relatively low density – up to 256 Mb for last-level (LL) caches – is sufficient. SRAM technology is used today but could be replaced/complemented by embedded STT-MRAM, which is expected to become mature for LL caching by 2023. It is worth noting that SRAM's memory cell factor (# of F^2), worsens as miniaturization advances. For example, the memory cell area of a 6-transistor SRAM can be as high as 550 F^2 at 7 nm, but only 150 F^2 at 40 nm. STT-MRAM provides a remarkable advantage over SRAM, i.e., higher density (3x) together with non-volatility and low-power consumption. Remarkably, STT-MRAM is manufactured during the back-end of the line (BEOL) steps with a cost adder corresponding to approximately of 2-3 additional mask layers and could be used at the same time to replace eFlash (14-16 additional mask layers), leading to a memory technology unification in embedded systems. The penetration of emerging NVM into mobile systems will require several years (likely more than five years) for further optimization and integration, but if successfully implemented into LL caches (eventually for replacing eDRAM), could bring to a significant impact. In the long-term (>10 years), magnetic memory technologies, such as spin-orbit torque (SOT-)MRAM, could reach performance levels compatible with L1/L2 caches and have even higher impact on the mobile memory segment.

Telecommunication infrastructures. The rollout of the 5th generation (5G) wireless technology in the coming years will be critical for the future market expansion of NVM on telecommunication infrastructures. Indeed, the rise of 5G not only will trigger the explosion of the 5G chipset market – which is expected to reach more than €8-9 billion by 2024 – but will also dramatically boost the stand-alone memory demand (including stand-alone NVM).

PC & data processing. Data centers and PCs are the end-market segments targeted by the SCM technologies. Since 2017, Intel has commercialized low-latency solid-state drives (SSDs), and storage accelerators based on the 3DXPoint technology jointly developed with Micron at IMFT. These products were conceived for both enterprise storage and client applications. Their sales enabled the take-off of the emerging NVM market. In 2019, Intel has introduced novel persistent memory modules (Optane DIMMs) targeting the datacenter market, e.g., for in-memory databases and real-time analytics applications. The technology started already to have a non-negligible impact on the market (hundreds million euros revenues in 2018). If the manufacturing costs/volumes will be effectively lowered/increased in next technology generations – leading to net profitability – the market could grow rapidly up to several billion euros by 2024 with critical impact level.

Audio & Video / Home appliances. Companies involved in the emerging NVM business consider to some extent to develop new IC products for house appliances and audio/video applications. For instance, Samsung has been working on memory buffers for display drivers' ICs where embedded STT-MRAM could replace SRAM due to competitive advantages arising from higher densities (3x) together with non-volatility and thus low power consumption. For similar reasons, Sony and Samsung have been also working on STT-MRAM memory buffers for CMOS image sensors, suggesting a possible penetration of emerging NVM in the imaging equipment market. Assuming an efficient technology development by such major players, a significant impact could start being observed from the early 2020s.

Data analytics / Big data. Data analytics (especially real-time analytics) and big data applications will largely benefit of SCM technologies (e.g., Optane DIMMs), for implementing in-memory databases, as mentioned in points (7-8). In these applications, it is very convenient to have large amount of data residing directly in the working memory (typically DRAM), in order to avoid detrimental data transfer from storage drives. In this framework, persistent memory modules based on stand-alone emerging NVM are poised to have a significant-to-critical impact in the forthcoming decade.

Smart Systems (Home / Mobility / Energy). Smart houses, smart cars (autonomous vehicles), smart objects, etc., all make use to some extent of AI algorithms, e.g., for voice/image recognition. As discussed in section 2 ("Synergies with other emerging technologies"), new memories are particularly appealing for these applications, as they provide new efficient methods for implementing neural networks. RRAM and PCM are being intensively investigated to this purpose. Although still in R&D, the first promising prototypes have appeared and could start having an appreciable impact into AI memory market within the next 5 years.

Wearables. The proliferation of the internet of things (IoT) has led to growing interest in portable and wearable technologies. These typically require low-power electronic chips with wireless communication functions. Several companies consider the wearable electronics market as the entry point for embedded emerging NVM: the latter provide significant advantages over incumbent technologies in terms of power consumption, density and cost (particularly over eFlash for nodes ≤ 28 nm). Key players, like GlobalFoundries and TSMC are already active in this front and the first products are expected soon to enter the market.

Technology Roadmap - Maturity of the emerging non-volatile memories technologies at the global scale

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Stand-alone PCM	Industrial production							Massive production													
Stand-alone MRAM	Industrial production											Massive production									
Stand-alone STT-MRAM	Tests & prototyping						Industrial production						Massive production								
Stand-alone RRAM	R&D			Tests & prototyping			Industrial production								Massive production						
Embedded STT-MRAM	R&D						Tests & prototyping			Indus. prod.		Massive production									
Embedded RRAM	R&D			Tests & prototyping								Industrial production				Massive production					
Nanotube RAM	R&D						Tests & prototyping					Industrial production				Massive production					
Embedded PCM	R&D							Tests & prototyping				Industrial production				Massive production					
Ferroelectric Non-Volatile FET	R&D											Tests & prototyping				Indus. prod.		Massive production			

Source: Yole Développement, 2019

Penetration rate of Non-Volatile Memories - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production

N°		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		Electronic Segment																				
1	Automotive applications	No significant impact											Small impact					Medium impact				
2	Industrial & robotics applications	No significant impact											Small impact					Medium impact				
3	Health & Care applications	No significant impact											Small impact					Medium impact				
4	Aerospace applications	No significant impact											Small impact					Medium impact				
5	Defense & Security applications	No significant impact											Small impact					Medium impact				
6	Mobile phones applications	No significant impact														Small impact					Med. impact	
7	Telecommunications infrastructures applications	No significant impact											Small impact					Medium impact				
8	PC & data processing applications	No significant impact			Small impact					Medium impact					Critical impact							
9	Audio & Video applications	No significant impact											Small impact					Medium impact				
10	Home appliances applications	No significant impact											Small impact					Medium impact				
		Crossed segments																				
1	Data analytics / Big data	No significant impact			Small impact					Medium impact					Critical impact							
2	Smart home	No significant impact											Small impact					Medium impact				
3	Smart mobility	No significant impact											Small impact					Medium impact				
4	Smart energy	No significant impact											Small impact					Medium impact				
	Wearables	No significant impact											Small impact		Medium impact			Critical impact				

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: Yole Développement, 2019

Impact of emerging NV Memories by end-user electronic applications in 2023

	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Small	Small	Medium	No	Small	Small	Small	Small	Critical	Small	Small

Corresponding quantitative impact of emerging NV Memories in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
6	85	644	7 540	85	344	1 853	0	300	5 687
				Professional PC	Consumer PC	Industrial & Robotics electronics, Automotive electronics, Telecommunication infrastructures, Aerospace/ Defense/Security electronics, Audio & Video, Health & Care electronics and Home appliances	-	IT market service providers	Industrial equipments industry, automotive industry and Aerospace/ Defense/Security industries

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of emerging NV Memories in 2023

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. Mainstream memories (NAND & DRAM)

Main industry players in the World for mainstream memories (NAND and DRAM) in 2018

N°	Company	Nationality of capital ownership	World estimated annual efforts dedicated to memory technologies		Position in the electronic value chain
			R&D expenses (M$)	R&D employees	
1	Samsung Electronics*	South Korea	3,900	> 10,000	Components + Systems (IDM)
2	SK Hynix	South Korea	3,124	> 10,000	Components + Systems (IDM)
3	Micron	The USA	2,140	> 10,000	Components + Systems (IDM)
4	Western Digital	The USA	2,400	> 10,000	Components + Systems (IDM)
5	Toshiba**	Japan	2,640	> 10,000	Components + Systems (IDM)
6	Intel	The USA	820	> 10,000	Components + Systems (IDM)
7	Nanya	Taiwan	148	1,000-5,000	Components + Systems (IDM)
8	Winbond	Taiwan	179	1,000-5,000	Components + Systems (IDM)
9	Macronix	Taiwan	141	1,000-5,000	Components + Systems (IDM)
10	Cypress***	The USA	364	1,000-5,000	Components + Systems (IDM)

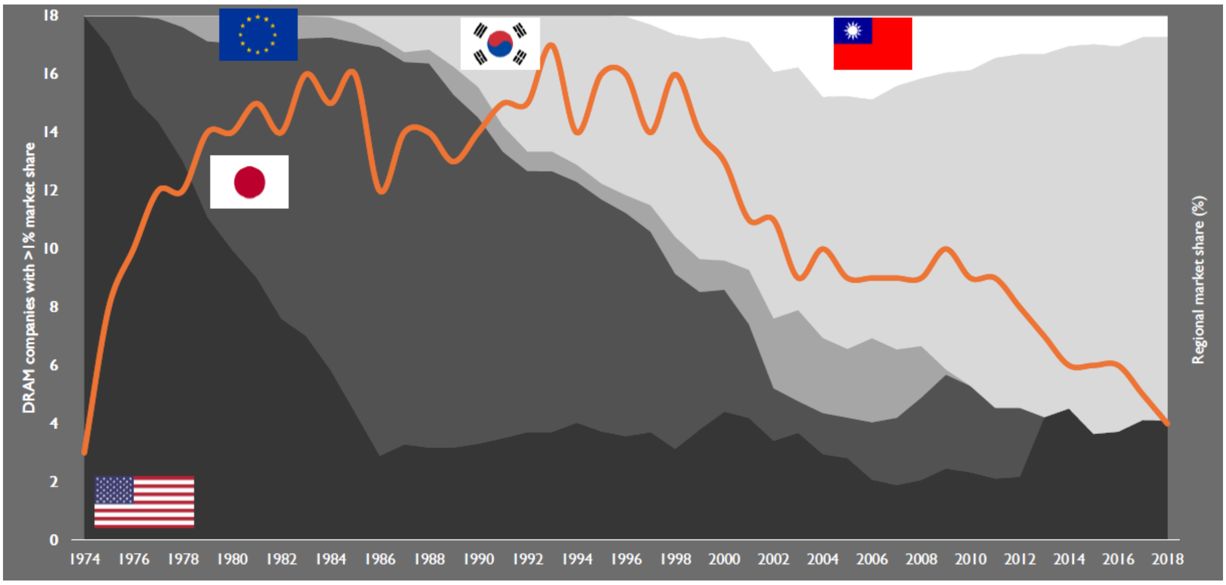
Notes. (*) Estimate by Yole Développement based on available R&D data in financial reports. (**) Figures indicated for Toshiba are from 2017. R&D data for Toshiba are available for the fiscal year (FY) 2016 and FY 2017 (ended in March 2016 and 2017, respectively). They refer to the total R&D expenses of the company (including HDD) before the sale of the memory unit. In June 2017, Toshiba split off its memory business (including SSD). In 2018, Toshiba's memory business was sold to a consortium including Apple, SK Hynix, Dell and Seagate. (***) In late 2018, Cypress and SK Hynix entered into a new Joint Venture for NAND flash. The JV has started its activities in April 2019 under the name SkyHigh Memory and focuses on SLC NAND chips. The JV is 60% owned by SK Hynix and 40% owned by Cypress, and it has its headquarters in Hong Kong. In June 2019, Infineon Technologies (Germany) announce it will acquire Cypress for an enterprise value of €9.0 billion.

Source: Yole Développement, 2019

Country analysis.

South Korea (Samsung, SK Hynix), and the USA (Micron, Intel and Western Digital), hold together almost 90% of the combined NAND and DRAM markets, followed by Japan (Toshiba), and Taiwan (Nanya, Winbond, Powerchip, etc.), respectively holding 7% and 3%. The current state of the market is the result of a progressive consolidation process that drastically reduced the number of the memory players as a consequence of more and more challenging technology-manufacturing processes within an extremely competitive business environment. In the graph below, the DRAM industry provides an example of this dynamic of consolidation, from a maximum of 16 players in the 1990s to only 3 players nowadays. The DRAM consolidation took more than 30 years, as new participants tried to enter the market, supported by distressed suppliers and government-backed capital.

DRAM consolidation process: Number of DRAM companies with >1% market share (left axis) and market shares by countries (right axis)



Source: Memory Research by Yole Développement, 2019

Stand-alone memory industry players.

The memory market is currently dominated by South Korean companies, i.e., Samsung and SK Hynix. In the stand-alone business, they hold more than 60% of the combined NAND and DRAM markets. The US players (Intel, Micron, and Western Digital), have altogether ~25% of the market, followed by Japan (Toshiba), and Taiwan (Winbond, Nanya, Macronix, and others) (See the pie charts below, left).

Following the stop of Qimonda's activities in 2009, the EU has no longer taken active part in the challenging NAND and DRAM businesses. Moreover, the EU contributes to only ~5% of the NAND and DRAM consumption[9], whereas the USA and China purchase most of the memory chips (see the pie charts below, right). Automakers in the EU often import from memory providers in Asia, with the aim of reducing operational cost and increasing the production level. In the coming years, the growing memory demand from the European automotive market and from the increasing number of the European hyperscale datacenter infrastructures will be driving the growth of memory sales in the EU. Besides memory chip manufacturing, it is worth mentioning the presence of a few memory-module integration companies in the EU, such as GoodDRAM (formerly Wilk Elektronik, Poland) selling DRAM modules and NAND products (e.g., SSDs, flash cards), as well Swissbit (Switzerland), which has been developing highly reliable NAND-based products for more than 20 years.

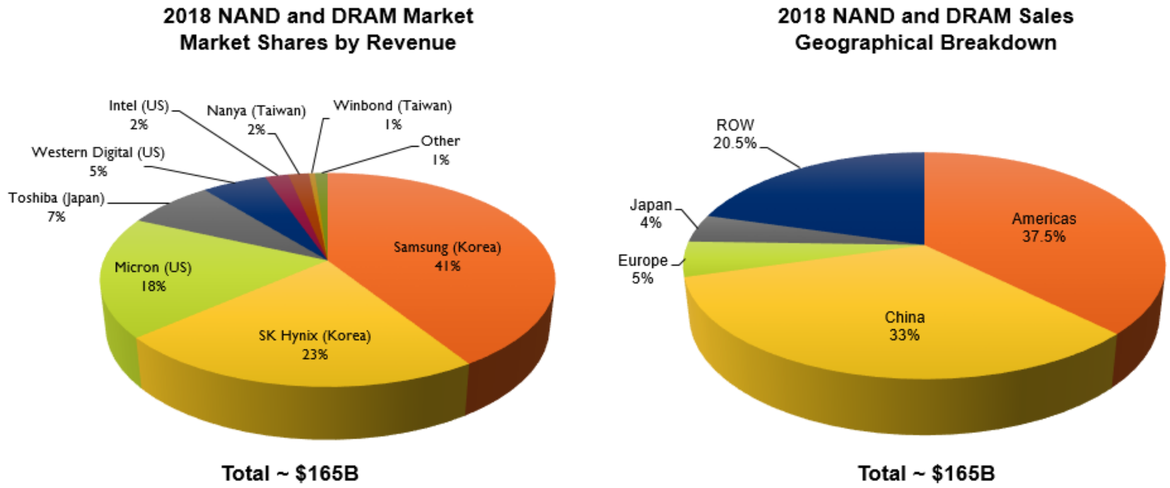
Nowadays, China is responsible for one third of the worldwide NAND and DRAM consumption, and so far, it had to rely upon imports. Since 2014-2015, central and local governments in China, in partnership with many private players, are investing billions of dollars to develop a local semiconductor memory ecosystem. The objectives are:

- Bridging the gap between domestic production and consumption;
- Reducing the dependency on the supply of global memory companies;
- Fulfilling the huge memory-chip demand in strong growth segments like mobile/wireless, consumer, servers, AI, IoT, and automotive.

[9] It means only 5% of the NAND and DRAM produced are directly shipped to the EU. It does not mean that in terms of consumption of final goods & services, 5% of the NAND and DRAM are used in the EU. Indeed, a lot of NAND and DRAM might for instance be shipped to China, then integrated in a Cyber-Physical System, and then shipped to the EU as a final good.

In the NAND business, Yangtze Memory Technologies Co. (YMTC), is the most likely to succeed out of all the publicly known Chinese memory players thanks to significant financial backing from government investment funds and a head start on R&D and manufacturing.

Stand-alone memory market (NAND+DRAM): top players and geographical breakdown



Methodology notes: The sales geographical breakdown (right) is based on the country of origin of the company that purchases the memory chips (e.g., sales to Apple are counted in the Americas segment although Apple buys memory chips for its phones manufactured in China).

Source: Yole Développement, 2019

On the other hand, DRAM in China is still in the technology-development phase. DRAM manufacturing is incredibly difficult, and it will likely take a while longer for China to become competitive with the leaders of the industry. Stand-alone NOR will remain the most solid memory business in China thanks to a well-developed local supply-chain system. In the coming years, a possible relaxation of the China-US trade tension might open up new opportunities for China to acquire key companies across the memory supply chain, which could reinforce China’s position in the semiconductor memory industry.

B. Emerging Non-Volatile Memories

Country analysis

The USA. In the emerging NVM business, American players (Micron and Intel), are currently leading the market with their 3DXPoint phase-change technology. GlobalFoundries is getting ready with 28 / 22 nm processes for embedded emerging NVM and is soon expected to enter the ramp-up phase. A number of American IP companies, such as Everspin, Avalanche, Spin Memory (MRAM), Crossbar and Adesto (RRAM), Nantero (NRAM), have clearly triggered the development of new memory technologies and strongly promoted their commercialization via strategic alliances with major IC manufacturers.

South Korea. Samsung is the main player for embedded emerging NVM, as it was the first company to announce the commercial production of IC products based on STT-MRAM.

China. The Chinese/Taiwanese major foundries (TSMC and UMC), are also getting ready with 28 / 22 nm processes for embedded emerging NVM and are soon expected to enter the ramp-up phase.

Japan. Japan has also taken active part in the emerging NVM business, especially with Panasonic and Fujitsu. These two companies were among the first companies to introduce ≥1 Mb stand-alone RRAM chips. So far, Toshiba has pursued important R&D activities, but has not yet commercialized products with PCM, RRAM or STT-MRAM.

France & Italy. With a long history in the R&D of PCM technologies, STMicroelectronics is playing a key role in the production and commercialization of microcontrollers (MCU), based on 28 nm embedded PCM, mainly targeting the automotive market.

Main industry players in the World for emerging NV Memory technologies in 2018

N°	Company	Nationality of capital ownership	World estimated annual efforts dedicated to emerging memory technologies		Position in the electronic value chain
			R&D expenses (M$)	R&D employees	
1	Intel	The USA	< 500	> 10,000	Components + Systems (IDM)
2	Micron	The USA	< 500	> 10,000	Components + Systems (IDM)
3	Samsung	South Korea	< 500	> 10,000	IC components (Foundry & IDM)
4	GlobalFoundries	The USA	< 500	> 10,000	IC components (Foundry)
5	TSMC	Taiwan	< 500	> 10,000	IC components (Foundry)
6	UMC	Taiwan	< 200	> 10,000	IC components (Foundry)
7	STMicroelectronics	France / Italy	< 100	> 10,000	Components + Systems (IDM)
8	Fujitsu	Japan	< 100	> 10,000	Components + Systems (IDM)
9	Panasonic	Japan	< 100	> 10,000	Components + Systems (IDM)
10	Everspin	The USA	24	> 50	IP (fabless company)
11	Avalanche	The USA	< 20	> 30	IP (fabless company)
12	Spin Memory	The USA	< 20	> 30	IP (fabless company)
13	Adesto	The USA	< 20	> 50	IP (fabless company)
14	Crossbar	The USA	< 20	> 30	IP (fabless company)
15	Nantero	The USA	< 20	> 30	Components + Systems (IDM)

Source: Yole Développement, 2019

Emerging NVM players

The first stand-alone 3D XPoint (PCM) products - Optane SSDs and storage accelerators - were introduced by Intel in early 2017, and persistent-memory modules (Optane DIMMs), are now making inroads in the datacenter market. Indeed, Intel's dominant position in the enterprise-processor business has been the key for the take-off of the emerging NVM market. In the forthcoming years, Micron is also expected to launch products based on the 3D XPoint technology (i.e., QuantX), and other major players (e.g., Samsung, SK Hynix), could enter the race with similar SCM technologies.

In terms of RRAM, low-density (≤ 4 Mb) chips have already been commercialized by Fujitsu and Panasonic (Japan), as well as by Adesto (USA). For stand-alone MRAM, Everspin (USA) is currently the undiscussed market leader. It is the only supplier of toggle MRAM (≤ 16 Mb), for applications requiring high reliability (e.g., industrial, medical, etc., but also the NVSRAM market), and is the only player shipping high-density (≥ 256 Mb) spin transfer torque (STT) MRAM for enterprise storage applications. 1 Gb chips (28 nm) are currently in pilot production at GlobalFoundries.

In the embedded memory business, the major foundries (TSMC, GlobalFoundries, Samsung, UMC), as well as integrated device manufacturers (e.g., Intel and STMicroelectronics), are developing or ramping up the production of 28 / 22 nm technology processes based on emerging NVM to be integrated in MCUs/SoCs.

Yole Développement is expecting that STT-MRAM will be the first to takeoff in the coming years and will lead the embedded emerging NVM market. This is thanks to the strong involvement of several top players (see the table below), and to the support of key equipment suppliers – such as Applied Materials and Lam Research (US), Canon, Tokyo Electron and Hitachi (Japan) – and testing companies – e.g., Hprobe (France) and Advantest (Japan) – that are providing new solutions to the difficult technical challenges hampering the mass adoption of MRAM. RRAM companies, such as Crossbar (the USA) and Weebit (Israel), have already demonstrated practical AI applications (i.e., facial recognition at the edge), where RRAM helps address performance and energy challenges by delivering lower power, faster read, and byte-addressable writes.

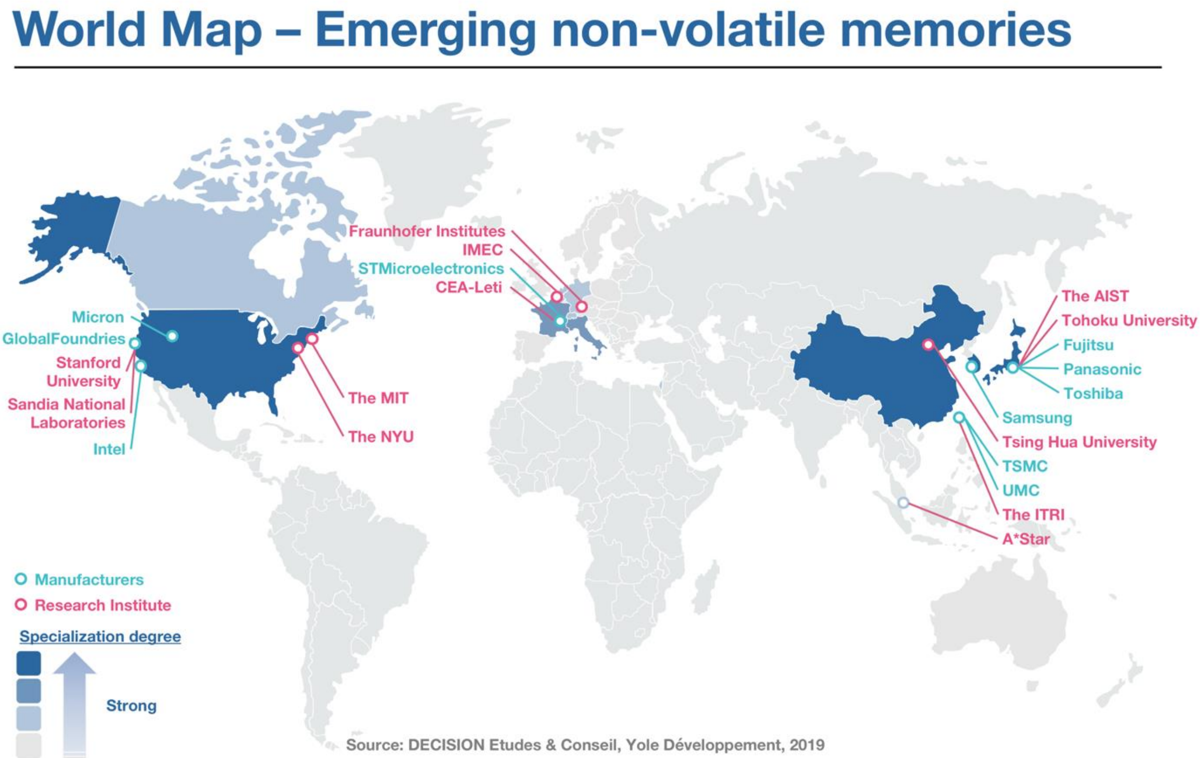
At the same time, IBM is actively researching PCM for AI networks for several years, carrying out part of its R&D activities in Zurich, Switzerland, with labs dedicated to neuromorphic architectures, analog computing devices, new materials and non-von Neumann computing with crossbar arrays of emerging NVM cells.

Partnership established by key players (foundry / IDM and design / fabless) involved in the embedded NVM business

Foundry / IDM	tsmc	GLOBALFOUNDRIES	SAMSUNG	UMC	intel	ST life.augmented	*Others / To be announced*
RRAM Players	Bulk 22nm (sampling)			Panasonic Bulk 28/22nm (in development)	22nm FinFET (in development)		CROSSBAR 28/22nm
(STT-)MRAM Players	TDK 22nm bulk (sampling)	EVERSPIN 22nm FD-SOI (sampling)	IBM 28nm FD-SOI (mass production)	avalanche technology 28/22nm bulk (in development)	22nm FinFET (sampling)		SPIN MEMORY APPLIED MATERIALS arm 28/22nm
PCM Players						28nm FD-SOI (sampling)	

Source: Yole Développement, 2019

Finally, a number of European research institutes and universities are already developing RRAM and PCM devices for AI neuromorphic networks and in-memory computing (CEA-Leti, IMEC, Fraunhofer Institutes). Since mid-2019, several research and industrial partners in the EU are working together in the framework of the European project TEMPO (Technology & hardware for nEuromorphic coMPuting), a three-year research program led by CEA-Leti of France and the Fraunhofer Group of Germany. FeRAM and FeFETs, developed by Ferroelectric Memory Company (FMC, Germany) in collaboration with top semiconductor companies (e.g., GlobalFoundries) – are in the list of technologies under investigation for application in neural networks. Based on patents of the former memory manufacturer Qimonda, FMC makes use of techniques and materials (high-κ dielectrics, e.g., HfO_2) that are well established in the semiconductor industry with the aim of enabling a viable technology for fast and non-volatile memories targeting DRAM replacement.

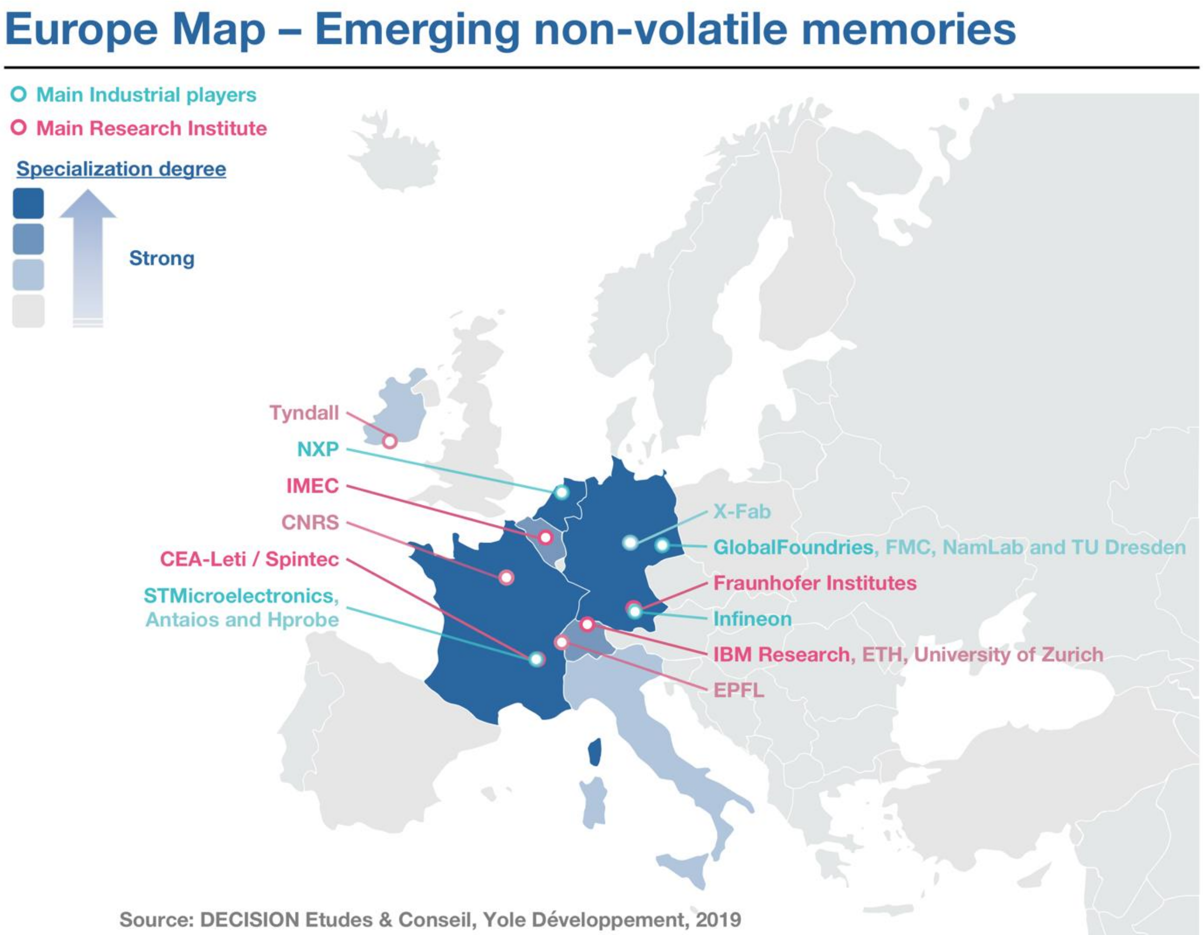


C. European players

In the EU, several high-quality research institutes are carrying out forefront research in the field of emerging non-volatile memories (see the list in the table below).

It is worth highlighting the activities of **IMEC** (Belgium) and **Spintec** (France) that have enabled significant advances in magnetic memory technologies, including STT-MRAM and SOT-MRAM. Imec started research activities on MRAM in 2012 and is the leader of the *MRAM alliance*, a research consortium that involves 5 major partners, including Micron, TSMC, Western Digital, Sony, and GlobalFoundries. Various MRAM start-up companies were born in France – in the Grenoble area – following key scientific discoveries at Spintec, namely Antaios (dedicated to SOT-MRAM development), Hprobe (focusing on fast testing tools for MRAM in the presence of magnetic fields), Crocus (formerly involved in MRAM and now dedicated to magnetic sensors), and Evaderis (formerly developing embedded MRAM, before closing its activities in July 2018).

Finally, important progress has been made in the field of ferroelectric memories thanks to the efforts of Ferroelectric Memory Company (**FMC**) that has initiated the development of FeFETs *via* key collaborations through the EU, e.g., with GlobalFoundries (Dresden) and the Fraunhofer Institute (Germany).



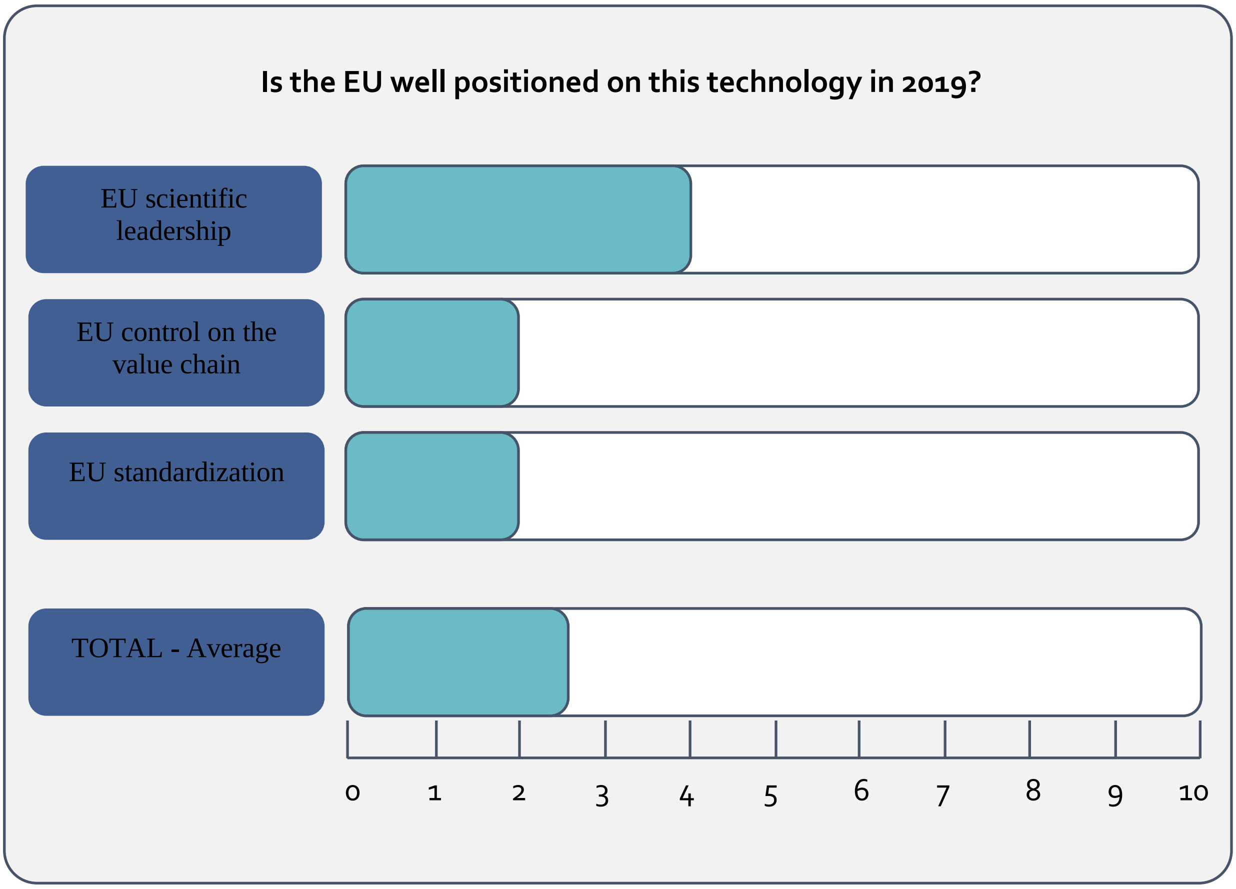
Main R&D centers in the EU (and Switzerland), for emerging non-volatile memory materials & devices in 2018

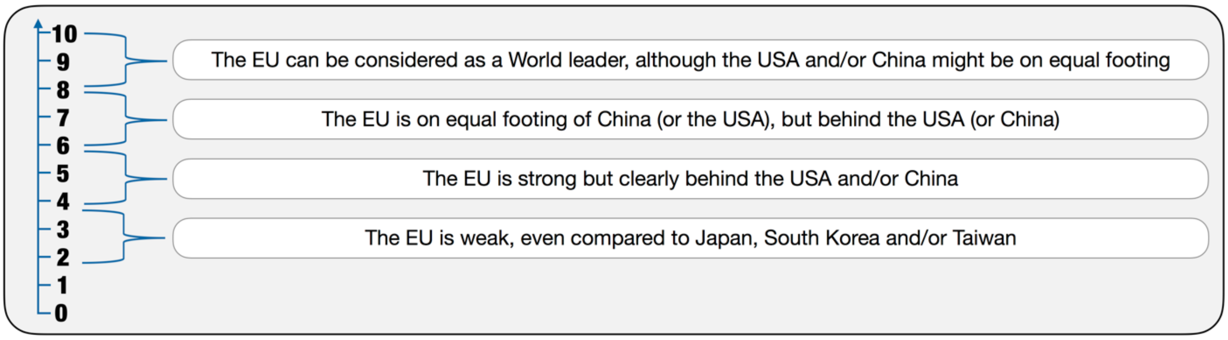
N°	Type of player	Company	Nationality of capital ownership	World estimated annual efforts dedicated to emerging memory technologies		Country location of the main R&D center	City location of the main R&D center	Position in the electronic value chain
				R&D expenses (M$)	R&D employees			
1	Industry Player	STMicroelectronics	Switzerland	< 100	> 10,000	France	Crolles	Components + Systems (IDM)
2	Industry Player	GlobalFoundries	Germany	< 100	> 10,000	Germany	Dresden	Electronic supplier/integrator
3	Industry Player	Infineon	Germany	< 100	> 10,000	Germany	Neubiberg, etc.	Components + Systems (IDM)
4	Industry Player	NXP	Netherlands	< 100	> 10,000	Netherlands	Eindhoven	Components + Systems (IDM)
5	Industry Player	X-FAB	Germany	< 20	> 1,000	Germany	Erfurt	IC components (Foundry)
6	Research Institute	IMEC	Belgium	< 20	> 1,000	Belgium	Leuven	Materials, electronic systems
7	Research Institute	CEA-LETI	France	< 20	> 1,000	France	Grenoble	Materials, electronic systems
8	Research Institute	Fraunhofer	Germany	< 20	> 1,000	Germany	Munich, Berlin, etc.	Materials, electronic systems
9	Industry Player	IBM Research	Switzerland	< 20	> 50	Switzerland	Zurich	Materials, electronic systems
10	Research Institute	Spintec	France	< 10	> 50	France	Grenoble	Materials, electronic systems
11	Industry Player	Antaios	France	< 2	> 5	France	Grenoble	IP (fabless company)
12	Industry Player	Hprobe	France	< 2	> 5	France	Grenoble	Tools (equipment supplier)
13	Industry Player	FMC	Germany	< 2	> 5	Germany	Dresden	IP (fabless company)
14	Research Institute	CNRS	France	< 2	> 10,000	France	Paris	Materials, electronic systems
15	Research Institute	NamLab	Germany	< 2	> 20	Germany	Dresden	Materials, electronic systems
16	Research Institute	TU Dresden	Germany	< 2	> 20	Germany	Dresden	Materials, electronic systems
17	Research Institute	University of Zurich	Switzerland	< 2	> 20	Switzerland	Zurich	Materials, electronic systems
18	Research Institute	ETH	Switzerland	< 2	> 20	Switzerland	Zurich	Materials, electronic systems
19	Research Institute	EPFL	Switzerland	< 2	> 20	Switzerland	Lausanne	Materials, electronic systems
20	Research Institute	Tyndall	Ireland	< 2	> 20	Ireland	Cork	Materials, electronic systems

Source: Yole Développement, 2019

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

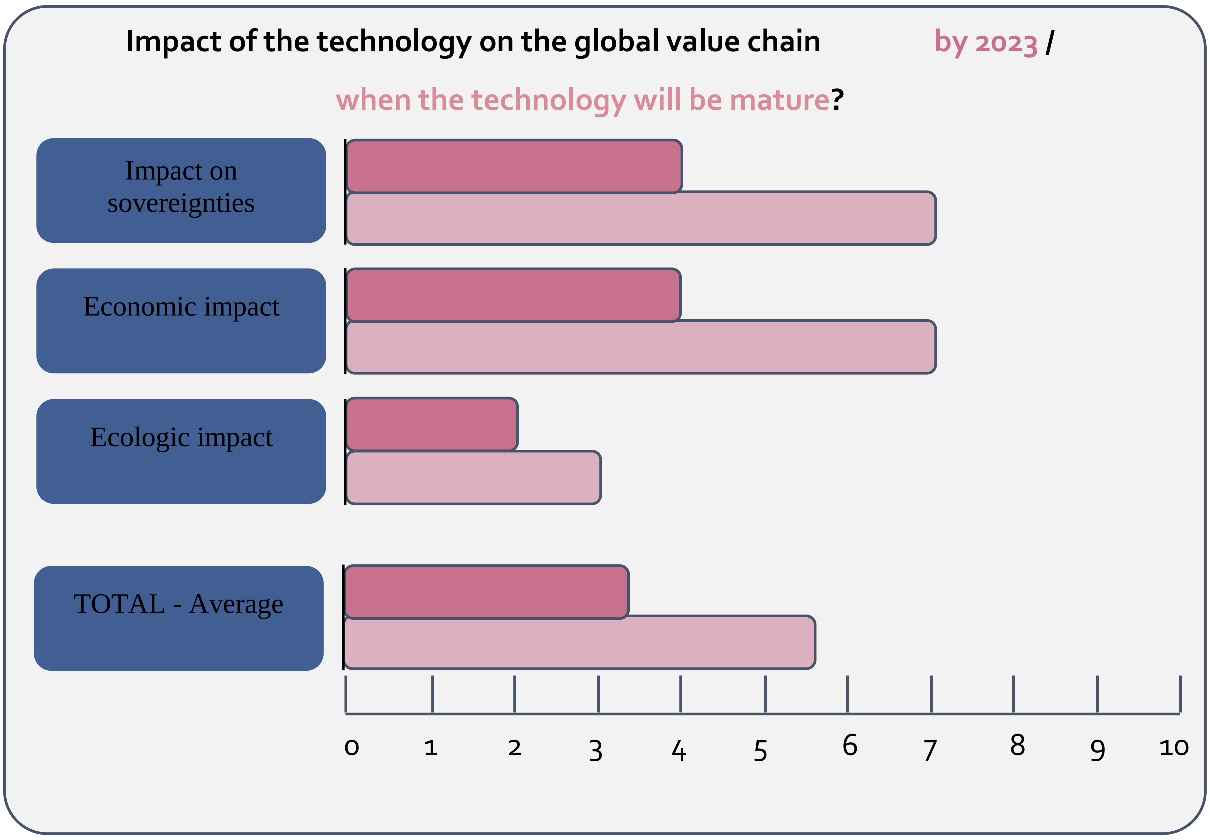
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The European research institutes described in the previous section, have made possible for the EU to achieve scientific excellence in emerging non-volatile memories, with a relatively large number of patents filed in the technology areas of PCM, RRAM, STT/SOT MRAM, and on emerging NVM-based neuromorphic computing. The excellence of the EU research is not only documented by several outstanding scientific publications, but also by the presence of various start-up companies that are developing new memory technologies, starting from discoveries that occurred in academic or industrial research institutes.

However, the EU cannot be considered as the world scientific leader in emerging NVM and related AI applications, due to the presence of strong competitors. The main US research institutes (e.g., IBM Research, the Stanford University, the MIT, the Sandia National Laboratories, the NYU, etc.), are at the forefront of innovations in these areas, followed by a number of leading laboratories in Japan (e.g., the Tohoku University, the AIST), Taiwan (e.g., the ITRI), Singapore (e.g., A*Star), as well as in China (e.g., the Tsing Hua University).

EU control on the value chain

NAND and DRAM represent about 97% of the stand-alone memory market, i.e., an impressive €133 B market in 2018. It is worth noting that memory revenues account for nearly 30% of the worldwide semiconductor revenues (€456 B in 2018). In this space, the EU players are less present, and therefore have to rely on supplies from other countries, making the position of the EU in the memory supply chain very vulnerable. For emerging non-volatile memories, besides rare cases (e.g., STMicroelectronics develops embedded PCM), the EU is carrying out remarkable technology-development activities but will be obliged to establish strategic alliances with foreign players on the manufacturing. For instance, NXP (Netherlands), uses Samsung Foundry services for manufacturing MCUs with embedded STT-MRAM.

Standard analysis

Most of the standardization activities in emerging NVM are currently focused on SCM technologies, particularly on protocols, interfaces and controllers for Intel's Optane drives and persistent memory modules. The latter require specific NVDIMM protocols that are developed by international organizations, such as for instance JEDEC (an independent semiconductor engineering trade organization/standardization body comprising all major semiconductors European companies), and the Storage Networking Industry Association (SNIA) that has more than 160 unique members, 3,500 active contributing members and over 50,000 IT end users and storage professionals worldwide.

Impact on sovereignties

By the 2030s, emerging Non-Volatile Memories will become key memories used for computing applications requiring high processing capabilities (that is most of emerging computing applications), both in embedded and stand-alone applications. The rise of the emerging NVM market will occur progressively during the 2020s. Therefore, mastering the production of these NVM in the EU territory and / or by European players is a clear and important issue to prevent a risk of technological vulnerability. The rise of protectionism can also lead to a situation where non-European players and / or states might refuse to deliver such products to the EU, placing the EU in a less competitive position towards its competitors.

Economic impact

The estimated sales of emerging Non-Volatile Memories in 2023 is €6B. As discussed in previous sections, the economic impact of emerging non-volatile memories in various market segments for the time range beyond 2020 can be significant and sometimes even critical (professional PCs). The EU would surely benefit of the economic impact generated by emerging NVM, but this required a good positioning within the global business.

Ecological impact

Memory technologies are not immediately related to an ecological impact. The adoption of low-power emerging NVM for AI applications, as well as the implementation of efficient in-memory computing systems, could help minimizing energy consumption in data centers, which are nowadays important consumers of energy (3% of the global electricity was used in data centers in 2018).

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to rise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, as for the other emerging components offering better energy consumption performance, the ecological impact might be very significant or null depending on the uses made by the consumers and the states.

C. Conclusion

Since the exit of Qimonda in 2008-2009, **the EU has no longer taken active part in the semiconductor memory business**. The major EU semiconductor companies (NXP, Infineon and STMicroelectronics), have not participated in the memory market for the last decade and the EU has lost the possibility to compete in this technology area. Nowadays, it would be **extremely challenging for the EU to enter the memory business** and try reducing the gap/delay with leading companies (Samsung, SK Hynix and Micron). NAND and DRAM are indeed very complex technologies to design and manufacture, and the delay accumulated versus leading players is now too large for the EU to acquire market shares in a reasonable time.

China is currently on a similar venture: the Chinese government has established the China Integrated Circuit Industry Investment Fund (CICIIF) or "Big Fund" in September 2014, which planned to spend more than $150 billion over 10 years (that is around €125 M per year over the 2014-2024 period), to stimulate developments in semiconductor design and manufacturing. Noticeably, the EU does not consume the same amount of memory chips (~5% vs. ~33% of the World consumption), so that establishing a local memory industry might not seem as vital as in the case of China. The latter is also facing import restrictions in the context of the to the US-China trade war. In 2019, with hundreds billion dollars of investments and several years of intense activities, China is still struggling to launch an effective commercial production of memory chips and is facing a technology delay of approximately 2 years versus the leading South Korean players (Samsung and SK Hynix).

Emerging NV Memories could be an interesting opportunity for the EU to reacquire a certain influence on the memory market. New technology developments initiated within the EU – such as ferroelectric transistors (FMC) or novel spintronic memories (Spintec, Antaios, IMEC) – should be encouraged and carried out energetically within the European boarders. If successful, they could trigger new business opportunities and strengthen the position of the EU within the supply chain.

In the stand-alone emerging NVM business, the EU players are far behind leading US players, i.e., Intel and Micron, who already entered volume production and commercialization of their PCM-based 3D XPoint technology. The emerging NVM stand-alone market is driven primarily by SCM, which started in 2017 for both client and enterprise storage applications and is expected to reach several billion euros in 2023. At the same time, embedded emerging NVM technologies are adopted by major foundries/IDM, including Intel, Samsung, TSMC, GlobalFoundries, UMC and STMicroelectronics. STMicroelectronics has a relatively long experience in the PCM field (two decades of investments and the joint venture Numonyx with Intel that led to the commercialization of 128 Mb stand-alone PCM devices), and thus it is currently the main EU industrial player that could support the development of the emerging NVM industry in the EU. This is already leading to competitive advantage in embedded memory applications, but it could be exploited further in next-generation commercial products.

Overall, the emerging NVM market is still at the early stages. As a consequence, entering this field would be not only feasible (contrarily to the NAND/DRAM case), but also convenient for the EU. It would both lead to an influence on the memory marked (a €138 B business in 2018) and strengthen the position of the EU within the semiconductor supply chain. To this purpose, it appears important that local technology developments related to magnetic, ferroelectric, phase-change and resistive memories, would be adequately funded by the EU. Promising R&D activities and start-up companies are already present in most of the EU member states, as discussed in the previous sections, and could be the starting point to turn the existing scientific leadership of the EU into an effective technology/market leadership. Moreover, emerging NVM are being regarded as promising components of neural networks for AI applications based on in-memory computing, which are becoming more and more popular in our society. Hence, entering the emerging NVM business, would also allow the EU to strengthen its positioning within the growing AI market.

E. Photonic Interconnection Networks

i. Definition

Photonic Interconnection Networks is a scientific and technological field which is crucial for the transmission of data at high-speed rate, connecting devices on long distances, medium distances (such as in data centers), and even short distance (such as within the inter-chip or chip scale).

Distributed computing over the distance have been already exploited for massive parallel computing where data rate limitations were overcome by the fragmentation of huge data in many parts. This approach was enabling large-scale computing from a limited number of purposes and research centers. However, recent progresses in the data-rate with up to Tb/s per channel give the promise of remote and high-capacity computing thanks to photonics interconnect networks.

Photonic interconnection networks are segmented in three fields:

- **Short-distance interconnects** such as chip-scale, chip-to-chip and core-to-core interconnections in processors, are moving towards the optical domain, motivated by the request for higher energy efficiency, bandwidth density and reduction of cost-per-bit for large-scale Data Center and High-Performance Computing. The employment of copper interconnections is becoming obsolete due to the losses of the wires, their parasitic capacitance, pin count constrains and crosstalk. The transfer to photonic technologies still requires further integration and cost reduction. The development of this sector is closely related to integrated photonics and especially silicon photonics and silicon interposers which are key solutions that will boost further the deployment at a massive level. Photonics short distance interconnects may disrupt the current architecture of computers.

- **Medium-distance interconnects** for distributed computing. Medium distance interconnects links are from few meters to few 10 km. They are currently available at the smallest scale into optical active cable (10 Gbps per link) and can be extended further for optical backplanes and machine-to-machine interconnects. They are also key technology into Data Center networks where increased data-rates are required. Ongoing developments are going toward two directions: both the increase in data rates (multi-Tbps per channel), and their cost and size drastic reduction. A key force from this domain may be expected from the trend to get this interconnection data rate accessible at the personal devices level, such as with optical active cable. It is then possible to envisage novel way of computing for the domestic appliance and robotics systems. Applications are also foreseen in automotive, remote surgery, security monitoring, etc.

- **Long-distance links** such as metro or long-haul interconnections are accompanying the trend in communication between individual users and objects. Photonics is providing high capacity connection for low-cost and energy efficient devices with high throughput.

ii. Synergies with other emerging technologies

Communication networks (IoT & 5G). Photonic interconnection networks might be combined with IoT communication networks and 5G networks to raise the speed and the density of the data transferred.

Big data analysis: Synergies with AI algorithms, HPC & Neuromorphic computing. Photonic interconnection networks might play a great role in the development of big data analysis while being combined with AI algorithms, HPC and / or neuromorphic computing, leading to applications in every end-user segment, but especially in the professional and consumer PC market and in the mobile phone market.

Integrated photonics plays a central role in making these devices and systems robust, compact and cheaper.

iii. Technology roadmap: Maturity levels and expected impacts by application area

The Photonics Interconnects Networks that will mainly contribute to the overall effort to disrupt computing and cyber-physical systems are clearly short and medium distance interconnects. Their progress is depending on efforts to make them more and more integrated, with a general trend towards Silicon Photonics or Hybrid Photonics on Silicon Interposers.

Medium distance interconnect. The research and development direction in Medium Distance (which is currently the most significant and structured technology) are:

- Super-DWDM (Dense Wavelength Division Multiplexing) -with the adoption of advanced modulation format- and finer selective optical switches;
- Multicore fibbers;
- Multi-modulation multi-channel formats;
- Coherent communications;
- The rise of both the capacity per channel (above 40 Gbps) and the overall link capacity (above 1 Tbps). The next evolution is to develop a 400 G optical port over a single fiber across 500 m at less than $1 per gigabit and with power < 5 mW / Gb

The main breakthrough which is expected, however, to contribute to further computing approaches are within HPC and smart home appliances (thanks to personal cables).

Short distance interconnect.

The development of short distance interconnects relies on the integration of the optical source with Silicon through hybrid and molecular bonding approach, or eventually monolithic integration which is still exotic. The development of short distance interconnect therefore depends on the willingness of the semiconductor players to invest to adapt their industrialization processes to this technology.

Yet, in the scenario of large integration of short distance interconnect by the semiconductor industry, short distance interconnects should impact every electronic end-user segment and especially the ones sensitive to high-speed and high-processing capacities (that is professional & consumer PC and mobile phones).

Technology Roadmap - Maturity of the technology at the global scale and by application area

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
	Technology	Maturity level of the technology																									
	Short distance Interconnects (intra-chip)	R&D															Tests & prototyping						Industrial production				
	Medium distance Interconnects (for distributed computing)	R&D										Tests & prototyping					Industrial production						Massive production				
N°	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																									
1	Automotive applications	No significant impact																					Medium impact (short distance interconnects)				
2	Industrial & robotics applications	No significant impact																					Medium impact (short distance interconnects)				
3	Health & Care applications	No significant impact																					Small impact (short distance interconnects)				
4	Aerospace applications	No significant impact																					Small impact (short distance interconnects)				
5	Defense & Security applications	No significant impact																					Medium impact (short distance interconnects)				
6	Phones applications	No significant impact																					Critical impact (short distance interconnects)				
7	Telecommunications infrastructures applications	No significant impact															Small impact (medium and long distance interconnects)						Medium impact (short distance interconnects)				
8	PC & data processing applications	No significant impact															Medium impact (medium distance interconnects in professional PC & HPC)						Critical impact (short distance interconnects)				
9	Audio & Video applications	No significant impact																					Medium impact (short distance interconnects)				
10	Home appliances applications	No significant impact																					Small impact (short distance interconnects)				
N°	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																									
1	Data analytics / Big data	No significant impact															Medium impact (medium distance interconnects)						Critical impact (short distance interconnects)				
2	Smart home	No significant impact															Medium impact (medium distance interconnects)						Medium impact (short distance interconnects)				
3	Smart mobility	No significant impact																					Medium impact (short distance interconnects)				
4	Smart energy	No significant impact																					Significant impact (short distance interconnects)				
5	Wearables	No significant impact																									

At the global scale, each technology is defined through four different stages of maturity.

- **R&D:** Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- **Tests & prototyping:** Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- **Industrial production:** Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- **Massive production:** Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

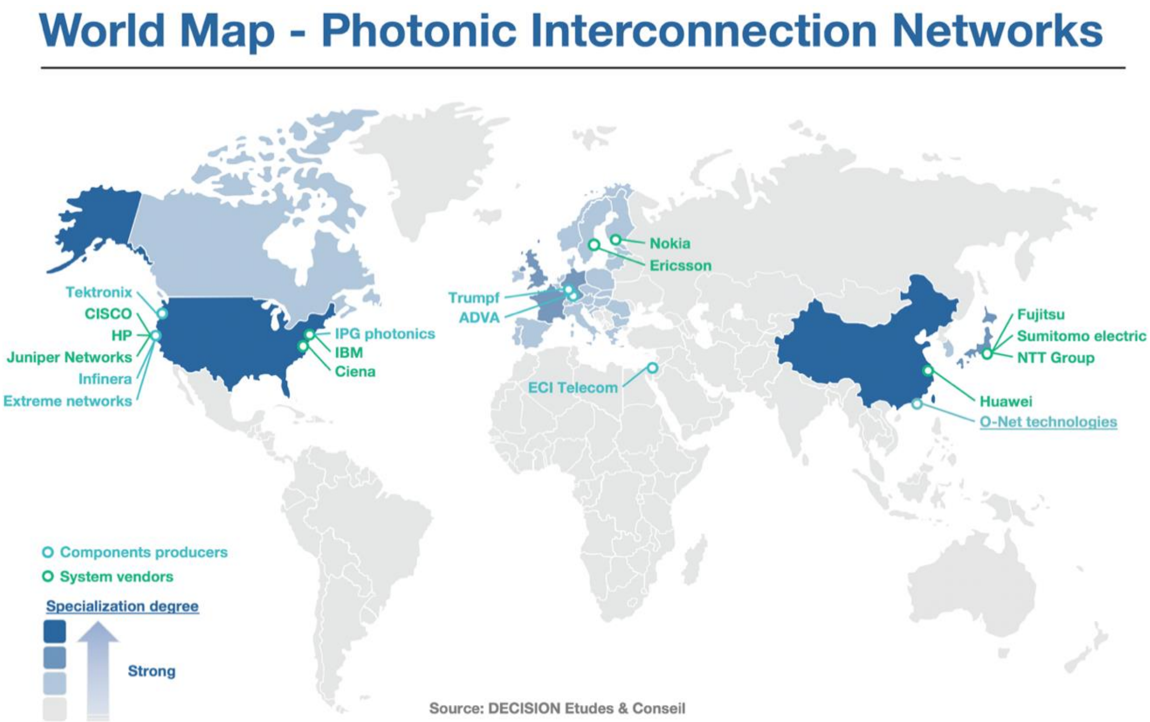
…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

The ecosystem of photonic interconnects is composed of public research programs, large research & industry players allocating research expenses and a significant number of start-ups developing prototypes. The world map below provides an overview of some of the main industrial players involved in medium and long-range interconnection networks:



In the EU, most of the players involved are members of the European Photonics Industry Consortium (EPIC, 500 members), and / or of Photonics21 and / or of the European Conference on Optical Communication.

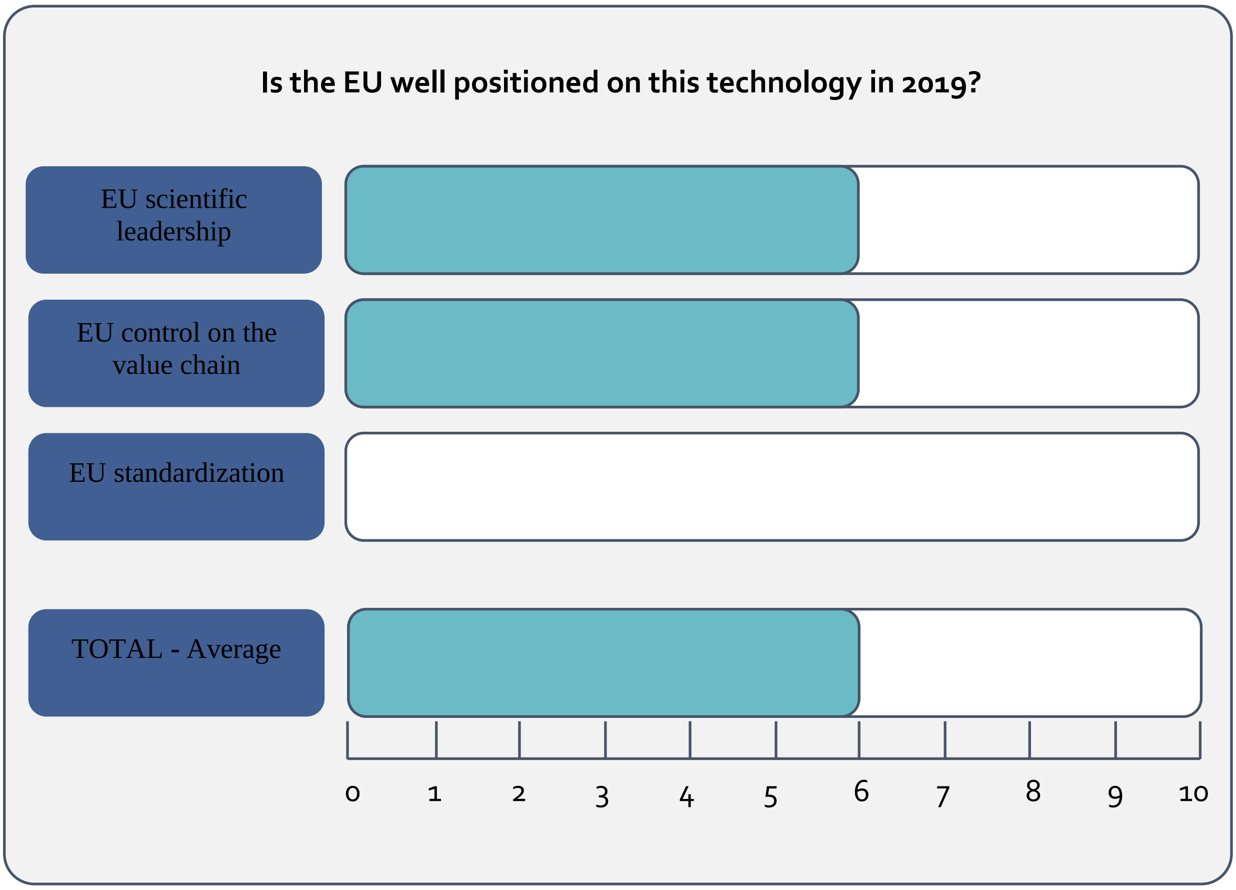
EU projects such as the PASSION project to develop future metropolitan communication networks, regroup EU players involved in photonic interconnection networks R&D:

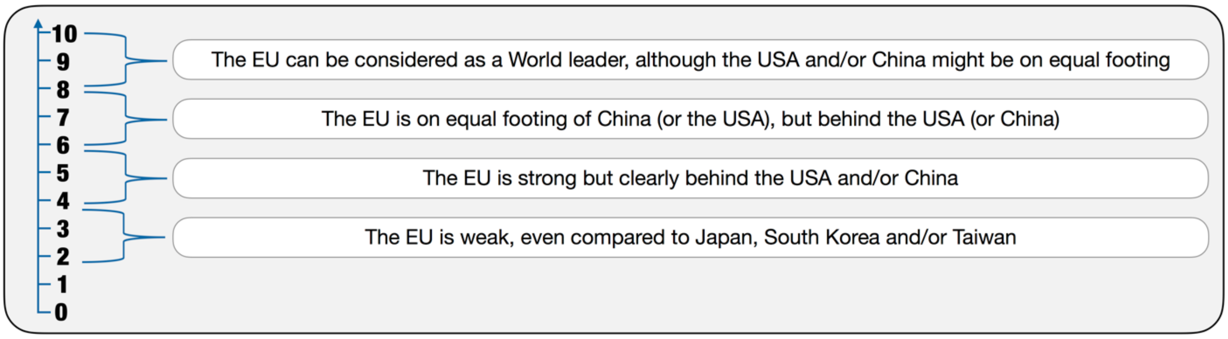
- In Spain, players such as the Centre Tecnològic de Telecomunicacions de Catalunya, VLC Photonics (a spin-off company of the Universitat Politecnica de Valencia) and Telefónica Investigación y Desarrollo (TID, the innovation business unit of Telefónica);
- In Italy, players such as Politecnico di Milano, SM Optics (SMO, part of SIAE Microelectronics Group, funded from a spinoff of Alcatel-Lucent);
- In the Netherlands, players such as the Technische Universiteit Eindhoven and Effect photonic (highly integrated (on InP) optical communications products based on its Dense Wavelength Division Multiplexing (DWDM) optical System-on-Chip technology, spin-off of the technical university of Eindhoven);
- The VTT Technical Research Centre of Finland;
- VERTILAS GmbH (VERT), a spin-off from the Technical University of Munich (TUM);
- Etc.

The players involved in the research for photonic computing are also often involved in the research for short distance interconnection networks (see the associated chapter).

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

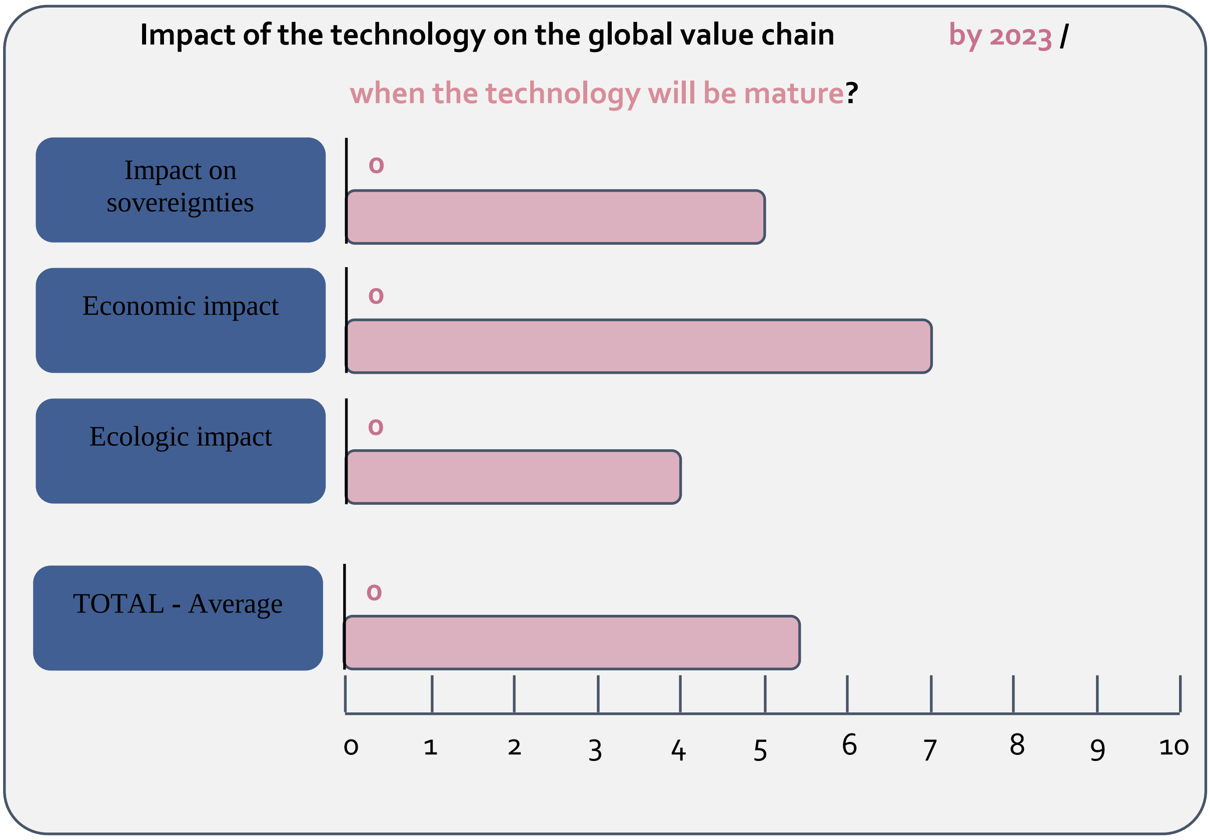
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.
- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.
- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The USA has an advantage for now, but China is investing heavily and catching up. The EU is far behind in terms of industrialization and China has the advantage compared to the EU in this regard. Most of the American companies have volume production in Asia and China. Japan is the other main competitor.

The R&D in the EU is lower than in the USA and China in terms of budget, so that a gap is being formed, even if the initial R&D and knowledge were stronger in the EU.

EU control on the value chain

The EU has a rather good control on the value chain (most parts of the chain are present in the EU territory), thanks to several world leaders in integrated photonics (such as ST Microelectronics and III-V foundries).

The only exception is the end-system level which is less strong: IT networks, dominated by American players such as Cisco and by Chinese players to a lesser extent.

The European Union also suffers from a low capacity to produce in high volumes. The European Union is very strong to produce small and medium series, with innovative technologies, but as soon as the volumes are much larger, there is a transfer to Asia and China.

Nevertheless, some very high value-added foundries continue to hold the market on the European side. There is also a tendency from Chinese players to invest in production facilities in the EU.

Standard analysis

No standard is clearly set up in regarding the most recent innovations in photonics interconnection networks. This lack of standardisation, which can be seen as a drawback, is actually a great opportunity as standards may be seen as freezing the innovation and dynamic of the sector. It is therefore an opportunity for a great variety of players at the same time in data centers and the arrival of disruptive options.

Impact on sovereignties

Photonics Interconnects Networks are an enabling technology. Sovereignty maybe affected by the restricted access to III-V materials which are under control for safety and military reasons. The sovereignty is currently protected by the existence of key players in the EU that guarantee the availability on the European ground. However, it is a fragile ecosystem in a tough economic battle with great US and Asian competitors. For instance, the American company Finisar is currently buying the German player II-VI Laser Enterprise. After this merger, Finisar will still have subsidiaries in Europe, but no pure European player will be able to compete directly with this American player.

Economic impact

The economic impact estimation is directly driven by the number of connected devices, which will be exponentially growing within the coming decade with the development of IoT.

Ecological impact

The only ecological impact of photonic interconnection networks might occur through positive impact on the energetic yield of computing devices.

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, the positive ecological impact of photonic interconnection networks is entirely conditioned on the used made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if photonic interconnection networks are used to develop ever new and more consuming applications, then the ecological impact will be null at best.

F. Integrated photonics

i. Definition

Integrated Photonics (also named Photonic Integrated Circuits - PICs), is a branch of photonics in which waveguides and devices are integrated onto the same substrate, to process light signals similarly to how electronic integrated circuits process electronic signals. Integrated photonics circuits can be optical integrated circuits or optoelectronics integrated circuits.

- **Optical integrated circuits**. In an optical integrated circuit, the light is directly manipulated without optoelectronic conversion, thus reducing the required conversion time and the related power consumption compared to an optoelectronic integrated circuit;

- **Optoelectronics integrated circuits**. An integrated Photonics circuit exploiting optoelectronics devices is, however, at the moment the mainstream approach: more mature both at the R&D and industrial level, leading the electronics and photonics convergence.

Integrated Photonics are mainly fabricated from III-V materials or silicon.

Among the main standard function, one can find:

- Photonic Signal Processing, where high bandwidth and zero-delay processing is allowed paving the way to high multi-GHz processing frequencies;
- High resolution correlation and convolution functions in parallel at high-speed to be used in coprocessors;
- Arbitrary Waveform generators;
- Filtering: high-frequency selectivity at microwave frequencies, high stopband attenuation, high skirt selectivity, and operation with a large FSR (interference mitigation filters, high-skirt selectivity bandpass filters, high FSR filters);
- D/A and A/D conversion, together with Sampling;
- Beamforming networks;
- Real-time spectrum analysis.

The great majority of optical integrated circuits includes the following architectural/technological solutions:

- **Optical logic gates for optical microprocessors**: logic gates crystal's cavities which confine a resonant frequency allowing the light to pass through (according to its length and refractive index). A high light intensity can modify the refractive index of the cavity allowing it to transmit light, or vice versa. Onto this principle are realizable all kinds the optical logic gates, fundamental for the creation of all-optical microprocessors;

- **Photonic memories**: Recrystallization of phase-change materials, on an integrated waveguide, induced by optical pulses, has been shown effective for implementing non-volatile photonic memories.

Integrated photonics lead for instance to the production of photonic sensors which can identify chemical or biochemical gases from air pollution, organic produce, and contaminants in the water. They can also be used to detect abnormalities in our blood, such as low glucose levels, and measure biometrics like our pulse. Photonic integrated circuits can be designed as comprehensive and ubiquitous sensors with glass/silicon and embedded via high-volume production in various mobile devices.

ii. Synergies with other emerging technologies

Photonic computing & photonic interconnection networks. Integrated Photonics might integrate photonic computing and photonic interconnection networks to reach lower-cost and higher compacity. These technologies can also replace standard electronics functions with optical ones in case of performances gap.

Big data analysis: Synergies with emerging algorithms, HPC & Neuromorphic computing. Integrated photonics might play a significant role in the development of big data analysis while being combined with AI algorithms, HPC and / or neuromorphic computing, leading to applications in every end-user segment, but especially in the professional and consumer PC market and in the mobile phone market. For instance, deep neural networks are being accelerated via arrays of programmable photonic elements. The need for high-bandwidth and low-latency communication in HPC and data centers is fulfilled by integrated Si photonic components, etc.

Organic and molecular electronics. Molecular logic gates consist of molecules that perform logic operations on one or more physical/chemical inputs (which change the structure of the molecule), and return a single output, based on spectroscopy (commonly of a fluorescence signal which switches in wavelength, at a change of the inputs). Integrated photonic is a necessary building block of these systems, allowing the readout of the computation. Conversely, organic compounds and molecules provide an interesting substrate, which can be advantageous to build photonic circuits, providing further scalability. The field has evolved to moleculators, which consist of molecules able to perform combinatorial/sequential operations.

iii. Technology roadmap: Maturity levels and expected impacts by application area

As shown in the table below, the integrated photonics market accounted for €3 B in the World in 2018 and should reach €12 B, with an impressive estimated Compound Annual Growth Rate (CAGR), of 29% per year over the 2018-2023 period.

Integrated Photonics market (B€)

	2018	2019	2020	2021	2022	2023	CAGR 2018-2023(%)
Integrated photonics market	3	4	6	7	9	12	29 %

Source: Yole Développement, figures of 2019 translated in euro by DECISION and adapted to meet the global methodology of the report.

Integrated photonics (or PICs), is built from many different materials, on custom manufacturing platforms. These include Silicon (Si), Indium Phosphide (InP), Silica (SiO2), Lithium Nibate (LiNbO3), Silicon Nitride (SiN), polymer or glass. The motivations for PICs are numerous, including smaller photonic dies, higher data rates, lower power consumption, lower cost per bit of data and better reliability compared to legacy optics. InP is the most used but the silicon photonics segment will be the most fast-growing segment over the next five years.

Silicon Photonics is a sub category of photonic integrated circuits leveraging semiconductor manufacturing infrastructures to combine different photonic functionalities on the same chip, although lasers still use InP. They integrate multiple (at least two) photonic functions and can be considered as the optical equivalent of electronic ICs. Silicon photonics has an impressive estimated Compound Annual Growth Rate (CAGR), of 45% per year over the 2018-2023, as despite a technical difficulty to get light in and out compared to other materials, it is the best option for electronic/optical integration at the smallest size. Indeed, to make the change of technology milder and less expensive, industrial players are fostering fabrication tools already used for electronic circuits in existing fabrication facilities. The following roadmap from Yole Développement shows the links between the current PICs materials and market applications.

Photonic Integrated Circuits (PIC), materials overview

		LONG HAUL	DATA CENTRES INTERCO	5G WIRELESS ACCESS NETWORK	AUTOMOTIVE	SENSORS	MEDICAL
Applications		LONG HAUL	DATA CENTRES INTERCO	5G WIRELESS ACCESS NETWORK	AUTOMOTIVE	SENSORS	MEDICAL
Examples of products		Coherent optical transceivers AWG Modulators	Optical transceivers (100G/400G) Embedded optics (200G) Switches Splitters	Optical transceivers (28G)	Optical transceivers for intra cars interconnects	Lidars Gas sensors	OCT Blood analysis
Typ. wavelength		1310 – 1550 nm	1310 – 1550 nm	1310 – 1550 nm	700nm+	900 – 7000+nm	400 – 1500 nm
PIC materials	*Si*	■	■	■	■	■	■
	InP	■	■			■	
	SiN					■	
	Polymer	■					
	Glass		■			■	
	Silica	■	■				
	LiNbO3	■					

Source: Yole Développement, Silicon Photonics and Photonic Integrated Circuits 2019 report

In the maturity level of the technology indicated in technology roadmap, the industrial production which is indicated to have been started in 2015 corresponds to the first production of InP-based and Silicon photonics PICs. Si Photonics and InP PICs are the two PIC segments that will drive the growth of market applications over the 2020s. During the 2020s, Si photonics will integrate other PIC materials as Si uses mature manufacturing platforms but will also use other materials as performance improves. Options include InP for lasing, germanium (Ge) for photo detection, LiNbO3 for modulation, glass for interconnect, etc. The following roadmap from the AIM Photonics Academy of the MIT provides a vision of the next technology development up to 2030.

Technology	Status
2015-16	
GaAs Lasers	VCSEL arrays commercially deployed in datacom
InP Lasers	Edge emitter arrays commercially deployed in telecom
Ge-on-Si Lasers	Research demonstration by several labs
Ge-on-Si Detectors	Fully waveguide integrated, commercially deployed
Waveguides	Si, SiON, SiN commercially deployed
SiP/SoC Assembly Technology	Electronics, but not photonics
Si Photonic Integration	Commercially deployed in cable and board assemblies
2017-20 Projected	
Ge-on-Si Lasers	Early market entry
Ge-on-Si Detectors	Pervasive commercial deployment
Waveguides	Pervasive commercial deployment, single channel
SiP/SoC Assembly Technology	Early 2.5 D deployment
Si Photonic Integration	Pervasive commercial deployment: cables and boards
2020-25	
Waveguides	Pervasive commercial deployment: WDM
SiP/SoC Assembly Technology	Pervasive commercial deployment: cables and boards
Si Photonic Integration	Emerging chip-to-chip intra-package
Beyond	
SoC Assembly Technology	Embedded in distributed circuit/system architectures
Si Photonic Integration	Transceiver-less: embedded electronic-photonic synergy

Source: The AIM Photonics Academy, the MIT

Main applications of integrated photonics[10]

- Data Centers Interconnects (DCI) for Data centers (Professional PCs) and telecommunication infrastructures. The use of integrate photonics in data centers (Professional PCs) and telecommunication infrastructures is the most promising application of integrated photonics on the short-run. PICs are progressively replacing vertical cavity surface emitting lasers (VCSELs) for increasing bandwidth and distance in data-communication networks. PICs are used for high data rate transceivers (100G and above) in coherent or non-coherent mode. The demand is driven by the rising number of data transiting through data centers coupled with the development of 5G in telecommunication infrastructures.

  In recent years, strong R&D effort has been put into the embedded optics approach to have photonic dies as close as possible to the electronics on the board in the server. Today, development of co-packaged Application-Specific Integrated Circuits (ASICs) and optics for switches anticipates future data center architectures and reduces power consumption.

  For instance, regarding telecommunication infrastructures, using the GHz precision signal processing of photonic integrated circuits, radiofrequency (RF) signals can be manipulated with high fidelity to add or drop multiple channels of radio, spread across an ultra-broadband frequency range. In addition, a photonic integrated circuit can remove background noise from an RF signal with unprecedented precision, which increases the signal-to-noise performance and enable new benchmarks in low-power performance.

- Big data analysis. As integrated photonics will impact big data analysis thanks to synergies with emerging algorithms, HPC and neuromorphic computing, integrated photonics should have an (at least small), impact on the same applications as the one mentioned on the chapters on AI algorithms, HPC and neuromorphic computing;

- Embedded electronics (automotive electronics, industrial & robotic electronics and to a lesser extent aerospace and health & care electronics). Integrated photonics offers great performances under extreme temperature or environment, with great reliability. In particular, the ability of photonic sensors to reconstruct 3D images in detection and ranging applications leads to their growing adoption in ADAS and biomedical imaging applications.

  - ADAS applications: Photonic sensors are being more and more used in ADAS applications (for instance, Intel, Rockley Photonics, SiLC and Blackmore are planning to use their PIC platforms for LIDAR applications). However, the prospects of market success are still uncertain for LiDARs as they should probably be displaced by a combination of other approaches like radar and imagers and the success of autonomous vehicles is still uncertain because of technical challenges, regulations and strategic changes from car makers. The market volume for LIDARs is still in thousands of units, not millions (in any case, far less than for data centers);

  - Smart wearables. Integrated photonics can lead to the design of smart wearables which employ optical sensors to track vital signals such as heart rate, blood pressure and body temperature. It is, furthermore, capable of non-invasively analyzing the composition of body fluids (blood oxygen and glucose levels). The development of stretchable optoelectronic devices is of utter importance in this field: the research focuses on optoelectronic devices (polymer light-emitting diodes and organic photodetectors) directly integrated on the skin (in a tattoo-like fashion), which has been shown able to allow both sensing and display functionalities.

Silicon photonics, in particular, can be considered at the maturity level of the electronics industry in the 1980s and there are still challenges to overcome. The future steps to address are:

- Si Photonic integration on the same chip of optics items and electronics items (drivers, logic, etc.). See for instance the ongoing research from the AyarLabs (the USA), and Sicoya (Germany);

[10] See the "Silicon Photonics and Photonic Integrated Circuits 20119" report from Yole Développement, published in April 2019.

- Integration of optical sources on Silicon at low cost and massive production;
- Progressive development of all the optical integrated circuit functions (logic gates and memory);
- Miniaturization of the product, moving towards organic substrates;
- Progress toward wafer level and 3D packaging, including e.g., Silicon Interposers;
- Design and software: specific software is required for photonics with pre-defined models;
- Supply chain maturation similar to the semiconductor supply chain.

Technology Roadmap - Maturity of the technology at the global scale and by application area

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Maturity level of the technology		Tests & prototyping										Industrial production								Massive Production		
N°	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
1	Automotive applications	No significant impact					Small impact					Medium impact								Critical impact		
2	Industrial & robotics applications	No significant impact					Small impact					Medium impact								Critical impact		
3	Health & Care applications	No significant impact					Small impact					Medium impact										
4	Aerospace applications	No significant impact					Small impact					Medium impact										
5	Defense & Security applications	No significant impact					Small impact					Medium impact										
6	Phones applications	No significant impact												Small impact								
7	Telecommunications infrastructures applications	No significant impact					Small impact					Medium impact										
8	PC & data processing applications	No significant impact												Small impact								
9	Audio & Video applications	No significant impact												Small impact								
10	Home appliances applications	No significant impact																				
N°	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
1	Data analytics / Big data	No significant impact					Small impact					Medium impact					Critical impact					
2	Smart home	No significant impact												Small impact								
3	Smart mobility	No significant impact					Small impact					Medium impact										
4	Smart energy	No significant impact												Small impact								
5	Wearables	No significant impact												Small impact								

At the global scale, each technology is defined through four different stages of maturity.

- **R&D:** Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- **Tests & prototyping:** Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- **Industrial production:** Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- **Massive production:** Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

Impact of integrated photonics by end-user electronic applications in 2023

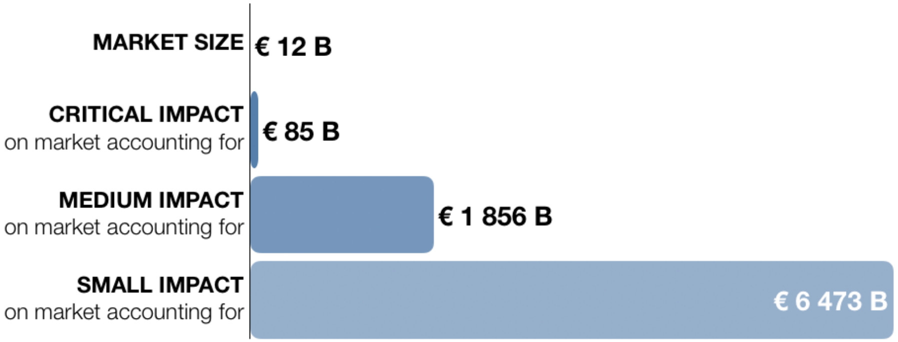
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Medium	Small	Small	Medium	Medium	Small	Medium	Small	No	Medium

Corresponding quantitative impact of integrated photonics in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
12	85	1 856	6 473	85	1 556	786	0	300	5 687
				Professional Computer	Automotive electronics, Industrial & Robotics electronics, Defense & Security electronics, Heath & Care electronics, Telecommunication infrastrctures	Mobile phone, Consumer PC and Audio & Video applications	-	IT market service providers	Industrial equipments industry, automotive industry and Aerospace/ Defense/Security industries

*** Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency**

Estimated economic impact of integrated photonics technologies in 2023



Source: DECISION Etudes & Conseil

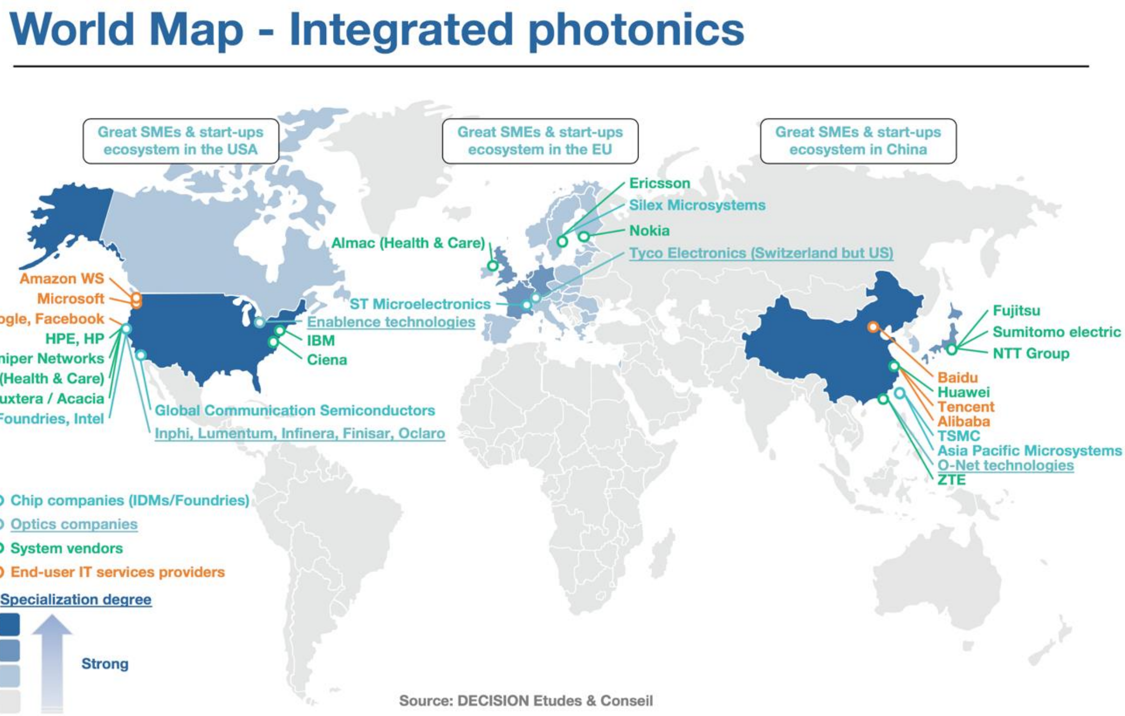
iv. Main players in the World and in the EU

Integrated photonics is already quite mature, with industrial players already marketing products. In the EU, most of these players are members of the European Photonics Industry Consortium (EPIC, 500 members), and / or of Photonics21.

Hyperscale networking companies like the GAFAMI (and to a lesser extent the Chinese BATX), are today the driving force for the deployment of PICs. They are currently setting up interconnected networks with local data centers at the nodes of the mesh. The GAFAMI are ahead of the traditional telecom players in investment, setting up their own long-haul and undersea networks for DCI. Until recently, they were relying on traditional telecom players for long-distance transmission. Since 2018, large hyperscale companies are now highly investing in long-haul DCIs.

Major foundries and IDMs are being more and more involved, such as TSMC and GlobalFoundries. For smaller MEMS foundries like Silex Microsystems, APM (Asia Pacific Microsystems), and VTT (in Finland), having Si photonics processes is a way to fill their fab, as some processes are very similar, like Cisco/Luxtera's MEMS capping.

The world map below shows some main players of the integrated photonics value chain:



The USA benefits from great ecosystem of SMEs and start-ups investing in integrated photonics. Luminate is the world largest accelerator program for optics, photonics and imaging enabled applications, based in New York. Light matter and Ayar Labs are two relevant American start-ups.

The EU also benefits from a strong ecosystem of SMEs and start-ups investing in integrated photonics, such as:

- In the Netherlands:
  - PhotonDelta is a public-private partnership in the EU consisting of a network of companies and high-qualified knowledge institutes;
  - Tipps (Netherlands) is a specialized solution provider for PIC (Photonic Integrated Circuits) evaluation & packaging by supplying dedicated and mid-range volume packaging services.

  - Among the other SMEs from Netherlands, one can find EFFECT Photonics, Bright photonics, Smart photonics, Lionix International, etc.

- In France: Teem Photonics, Sentea, Scintil Photonics, etc.

- LIGENTEC (Switzerland) provides Silicon Nitride Photonic Integrated Circuits;

- Sicoya in Germany, Pilot Photonics in Ireland, Optoscribe in the UK, Caliopa in Belgium (recently bought by Huawei), etc.

Among the main R&D centers in the EU, one can find the IMEC in Belgium, the CEA Leti and the III-V lab in France, the National Photonics Research Labs and the Fraunhofer Heinrich Hertz Institute in Germany, the TU/e Institute for Photonic Integration in the Netherlands, the Irish Photonic Integration Center… Among the main R&D centers abroad, one can find the American MIT, the Japanese PETRA (Photonics Electronics Technology Research Association), the South Korean ETRI (Electronics and Telecommunications Research Institute), etc.

Focus on Silicon Photonics

The Si photonic market only involves a few players, the main being concentrated in the USA: Luxtera/Cisco, Intel, Acacia and InPhi.

- Founded in 2001, Luxtera, now part of Cisco, is the historical pioneer, with almost 2M Quad Small Form-Factor Pluggable (QSFP) transceivers shipped since starting volume production in 2009;

- Intel introduced a silicon photonics QSFP transceiver that supports 100G communications in 2016. In only a few years, Intel has become the number two suppliers for silicon photonics-based optical transceivers. The company now ships a million units of the product per year into data centers. Intel's 400G products are expected to enter volume production in late 2019;

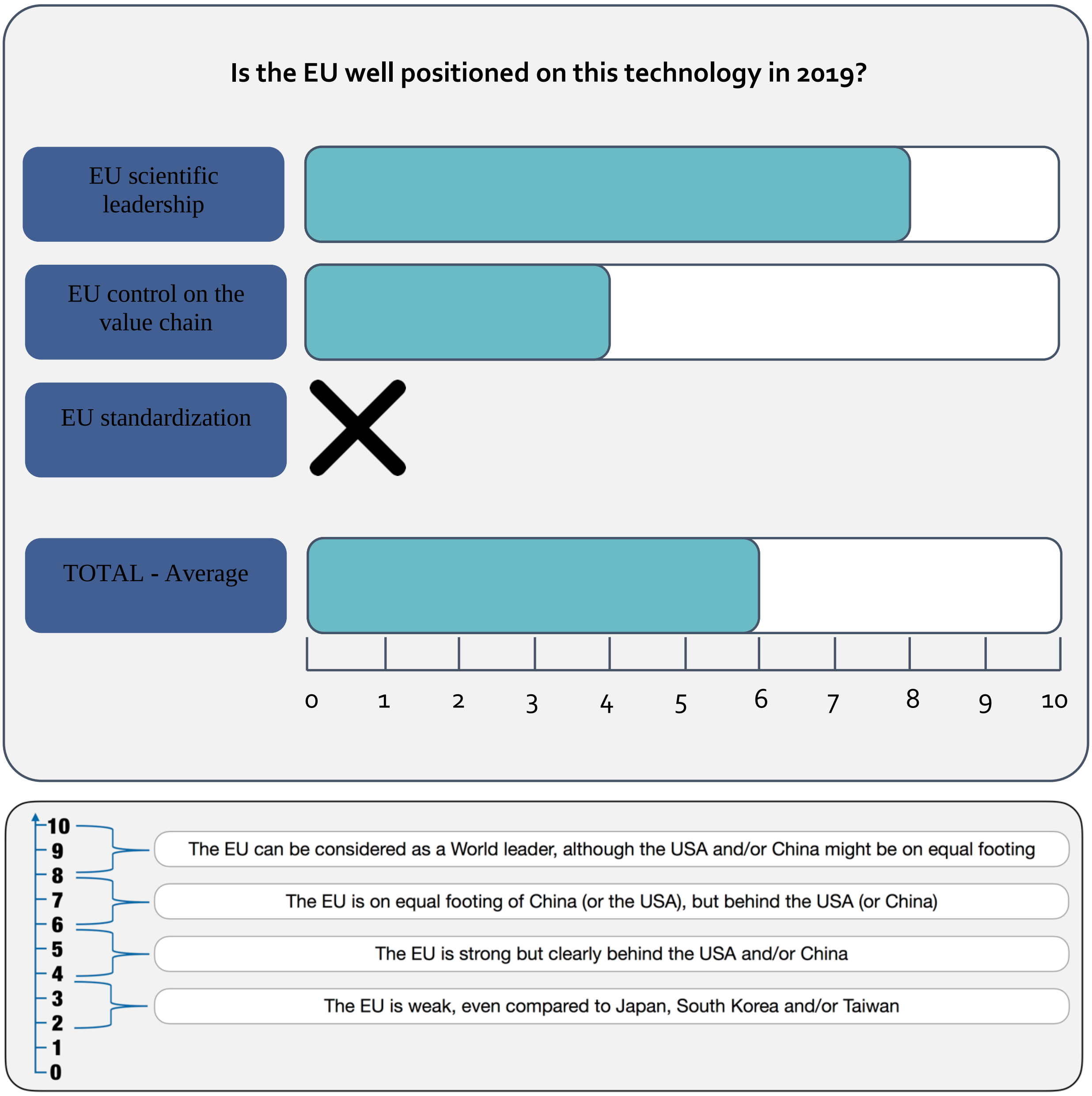
- Acacia announced the shipment of more than 100,000 modules 400ZR in total for coherent optics by 2022.

Moreover, many new start-ups are being created and more foundries are involved from the IC and MEMS industries. Finally yet importantly, there is always a big R&D effort worldwide with many industrial contracts in North America, Europe and Japan. Therefore, this market is on its way to industrial maturity and very large volumes.

The recent involvement of large integrated circuit foundries, such as TSMC's relationship with Luxtera, and GlobalFoundries with Ayar Labs, are very encouraging signs showing the big promise for silicon photonics.

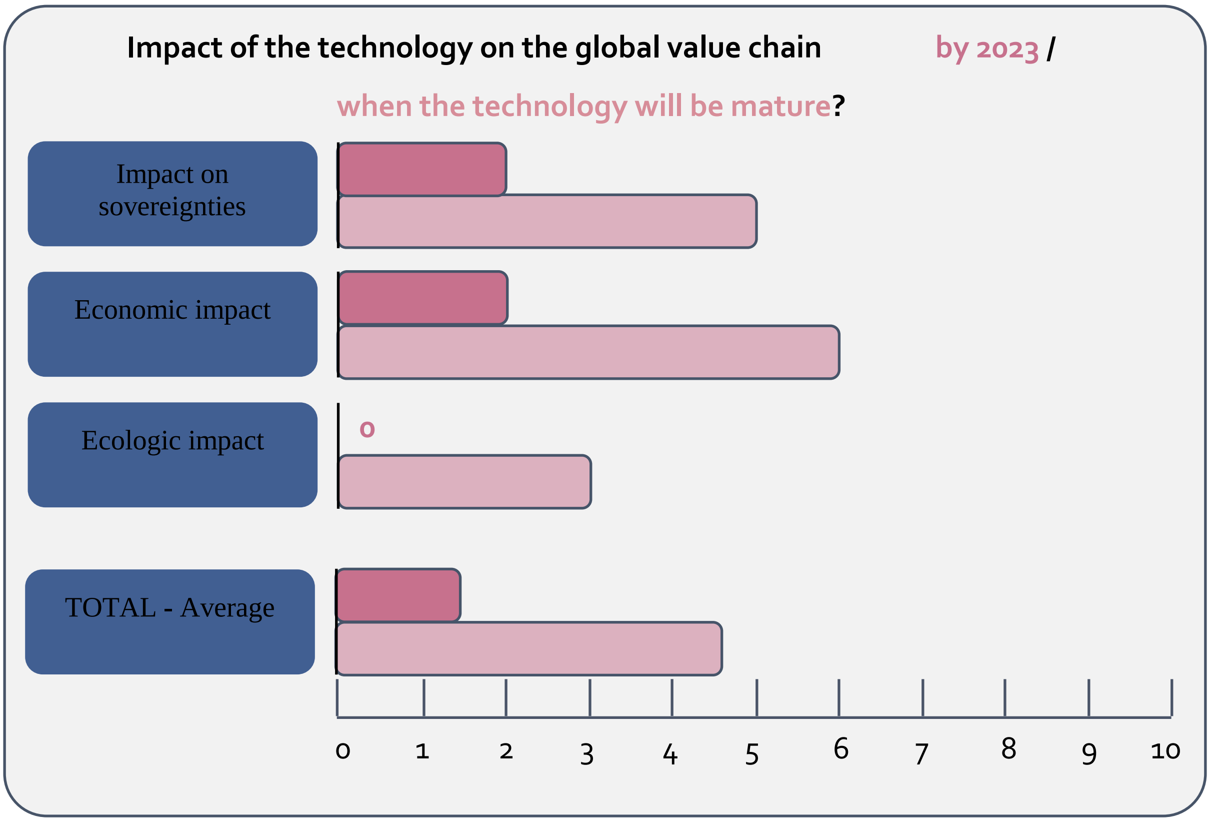
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

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EU scientific leadership

The USA has an advantage for now, but China is investing heavily and catching up. The EU is far behind in terms of industrialization and China has the advantage compared to the EU in this regard. Most of the American companies have volume production in Asia and China.

The R&D in the EU is lower than in the USA and China in terms of budget, so that a gap is being formed, even if the initial R&D and knowledge were stronger in the EU.

Yet, the EU remains one of the most advanced regions for the scientific development of integrated photonics (pure R&D and knowledge). The European Research Agenda has included the field efficiently and clusters have emerged to facilitate the opening of research and production facilities to the industry (Examples: Pixfab and ePixnet).

EU control on the value chain

The European platform of technology supported by H2020 is quite efficient to boost an R&D and industrial transfer tissue toward innovative SMEs and start-ups. However, the EU suffers from a shortage of industrial players at the level of integrated photonics applications (telecoms infrastructures, IT networks), the main EU players being Atos, Nokia and Ericsson.

Standard analysis

There is no standardization of the field of integrated photonics.

Impact on sovereignties

The impact on sovereignties is limited. It occurs as integrated photonics is an enabling and embedded technology. Thus, if all the production were to be located outside the EU, the EU would become dependent from foreign countries for some interesting applications sometimes important for sovereignty such as telecommunications infrastructures and a few Defense & Security applications (military communications, but integrated photonics will also be essential to photonics quantum computing and therefore to Quantum Communication Infrastructures QCI).

While it is possible to buy it outside the EU, the material that can be used and the application that can be exploited in can justify restrictions on the commercialization (ITAR regulations).

Economic impact

The estimated market value of integrated photonics in 2023 is €12B. The broader economic impact is significant but limited compared to other technologies as the main foreseen applications are in telecommunications infrastructures and IT infrastructures (servers, HPC, etc.). However, integrated photonics has the potential to penetrate on the long-run other embedded segments (Industrial IoT, automotive, health & care), and consumer markets through optical active cables (with current developments), further fiber to the home and fiber into the home applications (more prospective).

Si photonics, in particular, is not yet fully mature. We have reached the tipping point thanks to a convergence of early adopters mastering this technology and requests from GAFAMs, but there are still very few suppliers, as mentioned above. However, a lot of new start-ups are being created and more foundries are involved from the IC and MEMS industries. One reason for large IC foundries such as TSMC to develop Si photonics approach could be linked to a future co-packaged switch approach. The data center architecture is evolving from pluggable to more co-packaged optics, with Microsoft and Facebook working on this topic, and “Top of the Rack” switches could disappear. This means that switches could be co-packaged with the optics at the server level. In this case, volumes will be boosted as the number of switches is very high, in the range of millions of units. For smaller MEMS foundries like Silex, APM and VTT, having Si photonics processes is a way to fill their fab, as some processes are very similar, like Cisco/Luxtera’s MEMS capping. Last but not least, there is always a big R&D effort worldwide with many industrial contracts in North America, Europe and Japan. So, this market has a long-term potential (more than 5 years), for industrial maturity and very large volumes.

Ecological impact

There is no specific ecological impact of integrated photonics except an indirect impact through an improvement in terms of energy efficiency.

2. Emerging architectures in Micro and Nano components (MNE)

An **emerging electronic architecture** consists in a new way of thinking, designing and assembling algorithms and devices, including all aspects from the device to the user interface. The current architectures used in More Moore technologies for decades are indeed based on the Von Neumann approach (or Princeton architecture), corresponding to stored program computers in which an instruction fetch, and a data operation cannot occur at the same time because they share a common bus. The Rebooting Computing international initiative has been launched by the IEEE in 2009 in order to coordinate international effort to build new computing architectures. In this study, "Rebooting computing" is therefore a synonym of "emerging architectures". On the programming side, new communities are also emerging devoted to programming approaches such as approximate and probabilistic programming which are also directly related to the design of dedicated hardware.

The two main emerging architectures are currently:

- **Neuromorphic computing (also named bio-inspired computing)**.
- **Quantum computing**.

Other approaches in rebooting computing. Quantum computing and neuromorphic computing occupy a special place as the number of teams and the financial means to pursue these efforts are much higher than for any other approaches. Yet, other important but less funded research and development efforts exist which may also lead to a radical change in the way AI algorithms (read complex and data intensive algorithms) will be implemented in the future.

A. Neuromorphic computing

i. Definition

Neuromorphic computing is taking inspiration from biological system to study cognition and to design computing machines. The principle is to mimic neurons with special hardware units and to organize these units to provide computing devices able to learn and compute. Neuromorphic computing can be described as the development of non-von Neumann hardware architectures for simulating ANNs[11] or biological neural systems.

This field addresses the whole spectrum of computing: from the physical phenomenon supporting the computation to the software stacks necessary to operate the system. It encompasses the type of computing elements, the way they are organized, and the nature of the signal used to exchange the numerical signals (pulses, electrical wave, fixed point representation). The combination of these three elements defines the neuromorphic computing machine and its computing capability.

Initially the approach was used to understand better natural cognition. At the beginning, simple assemblies of artificial neurons were used to demonstrate the ability to perform learning and classification (Hopfield networks), with a limited set of simple computing elements. This idea and the power of current computing machines have ignited the rebirth of "AI" by envisioning more complex systems based on the same principle (multi-layer perceptron, convolutional neural networks, etc.), but expressed in forms which could be computed on machines such as GPUs. Yet, neuromorphic computing machines are not only effective to handle machine-learning algorithms, but also optimization algorithms, inference algorithms and graph search algorithms.

Spiking Neural Networks (SNN), is an emerging field of research in Neuromorphic computing, aiming to replace Artificial Neural Networks (ANN). ANNs are characterized by a single, static, continuous-valued activation. Yet biological neurons use discrete spikes to compute and transmit information, and the spike times, in addition to the spike rates, matter. SNNs replicate spikes and are thus more biologically realistic than ANNs. SNNs have two main advantages:

- Regarding biological research, SNNs are arguably the best viable option if one wants to understand how the brain computes at the neuronal description level;
- In terms of electronic industrial application, SNNs might have better low-power efficiency than standard neuromorphic hardware.

However, training deep SNNs remains a challenge. Spiking neurons' transfer function is usually non-differentiable, which prevents using backpropagation. Therefore, SNNs still lag behind ANNs in terms of accuracy. The gap is slowly decreasing, and can even vanish on some tasks, while SNNs typically require many fewer operations and are the better candidates to process spatiotemporal data.

[11] "Artificial neurons" are not reflecting at all the complexity of real ones but are rather only imitating a few key characteristics of real neurons.

ii. Synergies with other emerging technologies

AI algorithms. For historical reason the neuromorphic approach is very much related to machine-learning algorithms and especially Deep Neural Networks (DNN), although these algorithms are not necessarily implemented on neuromorphic machines (in fact, most of the implementation are currently made on farms of GPUs). Neuromorphic computing may also be used to run optimization and inference algorithms.

Innovative sensors & edge computing. Neuromorphic computing might be a great alternative to GPUs for many applications related to sensor interpretation and edge computing (especially edge AI), thanks to the low-energy consumption neuromorphic chips may offer. In this regard, other underlying technologies such as memristors are also considered and under development but with a lower Technology Readiness Level (TRL).

iii. Technology roadmap: Maturity levels and expected impacts by application area

Some prototypes have been developed in the USA (IBM, Intel, HP and Brainchip), some of which have recently reached the development phase of prototype demonstration in real environment (Technology Readiness Level 7). As a consequence, one can expect first commercialization and industrial use to occur by 2025. In other words, the market of neuromorphic computing will remain nonsignificant by 2023.

The programming approaches are still significantly varying from device to device and program to program. With True North, for example, the best results come from training a deep learning network offline and moving that program onto the chip. Others that are biologically inspired implementations like Neurogrid, for instance, are based on Spike timing-dependent plasticity.

The level of development of neuromorphic chips is currently too immature to assess clearly the potential applications of neuromorphic computing in the different end-user electronic systems. Yet, neuromorphic computing has currently three main proven applications:

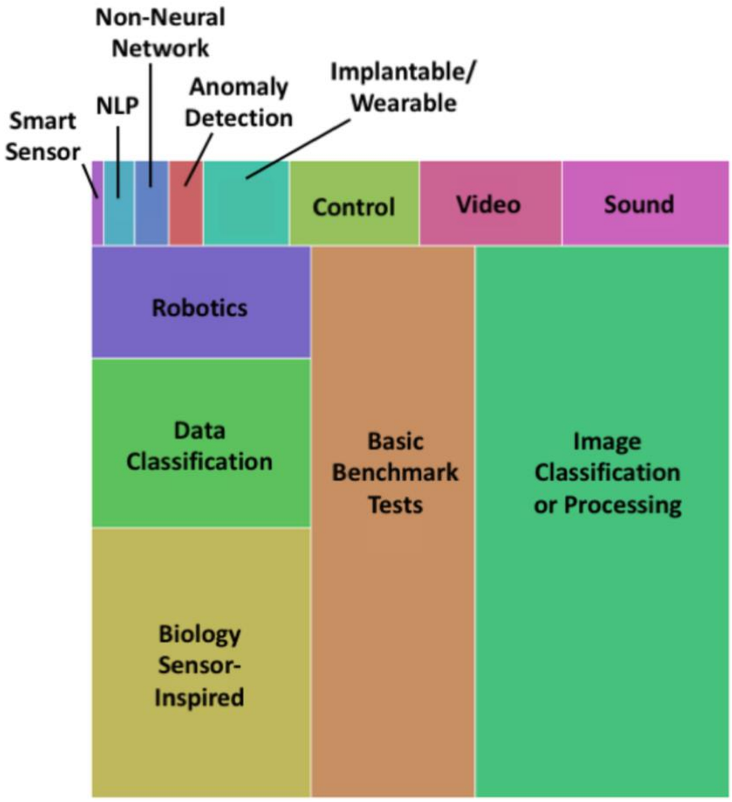
- **Applications similar to the ones of AI algorithms**, as neuromorphic chips are mostly developed to run AI algorithms (see the applications of AI algorithms). To this end, neuromorphic chips could for instance act as coprocessors on large-scale supercomputers, sitting alongside the traditional CPUs and GPU accelerators.

- **Reducing energy consumption**, with main economic impacts in edge computing, edge AI and sensor applications. Current computers are limited by the amount of power required to process large volumes of data. In contrast, biological neural systems, such as the brain, process large volumes of information in complex ways while consuming very little power. Power savings are achieved in neural systems by the sparse utilization of hardware resources in time and space. As emerging low-consumption devices, neuromorphic chips might disrupt in particular the embedded electronic markets, highly impacted by energy consumption issues: automotive, industrial & robotics, aerospace/defense/security, embedded health & care electronics, telecommunication infrastructures, and to a lesser extent mobile phone.

- **Life Science & Biology**. Neuromorphic computing is used to simulate living neural networks in research programs in life science and biology. For this reason, it might lead to innovations in the Health & Care industry.

The "Survey of Neuromorphic Computing and Neural Networks in Hardware" published in 2017 by the IEEE and the DOE, provides a great overview of the current state of play of Neuromorphic computing research. Through the analysis of 2682 research papers published worldwide on neuromorphic computing over the 1988-2017 period, this study enlightens a rising interest of the research community for neuromorphic computing since the late 2000s. The diagram below shows the classification of the 2682 research papers by application fields. The size of the boxes corresponds to the number of works in which a neuromorphic system was developed for that application.

Breakdown of neuromorphic computing applications



Source: IEEE, US Department of Energy

As shown in this diagram, the first applications of neuromorphic computing should occur in the professional PC segments (servers, cloud computing), and in the Audio & Video segments. Neuromorphic computing should also impact AI-type applications of embedded segments: Automotive (ADAS, Infotainment), Robotics electronics, Health & Care electronics as well as Aerospace/Defense/Security applications. Defense & Security applications should take more times to be commercialized in line with the technical and ethical issues posed by the use of autonomous functions which might hurt people.

Technology Roadmap – Maturity of the technology at the global scale and by application area

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	Maturity level of the technology	R&D									Tests & prototyping				Industrial production							
N°	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
1	Automotive applications	No significant impact													Small impact							
2	Industrial & robotics applications	No significant impact													Small impact							
3	Health & Care applications	No significant impact													Small impact							
4	Aerospace applications	No significant impact													Small impact							
5	Defense & Security applications	No significant impact																		Small impact		
6	Phones applications	No significant impact																				
7	Telecommunications infrastructures applications	No significant impact																				
8	PC & data processing applications	No significant impact													Small impact							
9	Audio & Video applications	No significant impact													Medium impact							
10	Home appliances applications	No significant impact																				
N°	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
1	Data analytics / Big data	No significant impact													Medium impact							
2	Smart home	No significant impact																				
3	Smart mobility	No significant impact													Small impact							
4	Smart energy	No significant impact													Small impact							
5	Wearables	No significant impact													Small impact							

At the global scale, each technology is defined through four different stages of maturity.

- **R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6**
- **Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9**
- **Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)**
- **Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies**

The impact of the technology on each end-user segment is described as:

- **A critical impact;**
- **A significant impact;**
- **No significant impact;**

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

Neuromorphic chips remain at the stage of prototyping and test. Yet, the most dynamic projects in neuromorphic computing are in the USA. The EU can be considered as in second position along with China, although European programs such as the SpiNNaker programs seem very late compared to US programs. Japan is also investing significantly in neuromorphic computing, mostly through research programs of R&D players (universities, research laboratories), and oriented towards robotics applications. Canada, Switzerland, Australia and South Korea are other significant players. The map below shows the main countries, R&D players and industrial players involved in neuromorphic computing.

The USA. In the USA, the main public organisations involved is the DARPA (with the SyNAPSE program, developing low-power electronic neuromorphic computers that scale to biological levels. The DARPA also released a prototype of drone using a neuromorphic chip), the IARPA and the Department of Energy (DOE).

The main research laboratories involved are the HRL Laboratories (associated to the SyNAPSE program and the FRANC program), the Sandia National Laboratories (HAANA program leading to memristors prototypes), the University of Stanford (Neurogrid project, started in 2008 and based on CMOS technologies). “The Next platform” program, launched by the Oak Ridge National Laboratory, is another relevant project based on a neuromorphic architecture called NIDA, short for the Neuroscience Inspired Dynamic Architecture, which was implemented in FPGA in 2014 and now has a full SDK and tooling around it. Others American projects are more oriented toward solving challenges related to power consumption and alternative computational capabilities using the same concepts, including a 2011 effort at MIT, research programs at HP using memristors as a key to neuromorphic device creation, and various other smaller projects, including a spin-off of the True North architecture launched in 2015 in the Rensselaer Polytechnic Institute and named Carothers.

Many great American industrial players are actively involved in Neuromorphic computing research:

- IBM invests in neuromorphic chips like its TrueNorth processors and remains a little ahead in neuromorphic computing. IBM TrueNorth is part of the Synapse project from the DARPA. The objective of this bio-inspired computing full-scale project is to design a machine which is compact, lightweight, low-power and enable real-time and robust data analysis. A number of applications have been selected to demonstrate the effectiveness of the approach: Speaker recognition, sequence prediction, digit recognition, collision avoidance and mapping of optical flows. Finally, a partnership with a sensor company (iniLabs Ltd), has been established to investigate extremely low-power end-to-end vision systems;
- Intel’s Neuromorphic Computing Lab announced in July 15th, 2019, that an 8 million-neuron neuromorphic system named “Pohoiki Beach” and comprising the 64 Loihi research chips was now available to the broader research community. Loihi is a 60-mm2 chip fabricated through Intel’s 14-nm CMOS process that advances the state-of-the-art modeling of spiking neural networks in silicon. It integrates a wide range of novel features for the field, such as hierarchical connectivity, dendritic compartments, synaptic delays, and, most importantly, programmable synaptic learning rules. Running a spiking convolutional form of the Locally Competitive Algorithm, Loihi enables searchers to process information up to 1,000 times faster and 10,000 times more efficiently than CPUs for specialized applications like sparse coding, graph search and constraint-satisfaction problems.
- Qualcomm’s Zeroth platform for machine-learning is rather focused on large-scale computing/co-processing applications for Artificial Intelligence. This platform has developed a neuromorphic silicon CMOS device and the companion software environment as an interface for programmers. The Brain Corporation, a Qualcomm-backed venture, is oriented towards robotics and sensor applications.
- Other industrial players highly involved are: HP, Xilinx, and SMEs such as General Vision.
- Industrial players down the value chain are also involved:
    - Google has designed its own neuromorphic processors in 2015/2016, the TPU. These are programmable processors capable of managing "fully connected" neuron networks (interconnected neuron layers) as well as the first stages of convolutional neural networks (requiring matrix multipliers). In 2018, they announced their third generation of TPUs positioned as true multiprocessor servers. However, Google does not plan to market these processors and servers. On the contrary, it is a technology manufactured in volume in ASIC intended to equip their own data centers (Google is the first consumer of servers in the world);

- The iPhone 8 and X announced in September 2017 by Apple integrate the A11 Bionic chipset and its neuromorphic Neural Engine functionality, dedicated to the execution of deep learning applications, as for FaceID face recognition function and for speech recognition with SIRI.

The EU. The main EU initiative in neuromorphic computing is the Human Brain Project (HBP), launched in 2013 and which should end in 2023, coordinated by the EPFL (Ecole Polytechnique Fédérale de Lausanne), and regrouping 800 European researchers in 20 countries, for a total amount of €1.2 B (that is around €120M per year). The Neuromorphic Computing platform regroups the two major Neuromorphic initiatives of the HBP: The SpiNNaker machine (Manchester) and the BrainScaleS machine (Heidelberg). Within the EU, a large number of laboratories are involved in neuromorphic research, the main R&D centers being the Imec, the CEA-Leti and the Fraunhofer Institutes. In particular, the Jülich Forschungszentrum of Germany will receive a €36 M funding in 2020 by the German government to advance quantum and neuromorphic computing technologies.

In terms of industrial players, the leading semiconductor manufacturers are interested in neuromorphic computing, at least through technology monitoring (STMicroelectronics, etc.). Yet, as the first applications of neuromorphic chips will emerge in consumer applications, the European players are often less involved than the American ones. Several SMEs and start-ups exist, such as aiCTX (Switzerland).

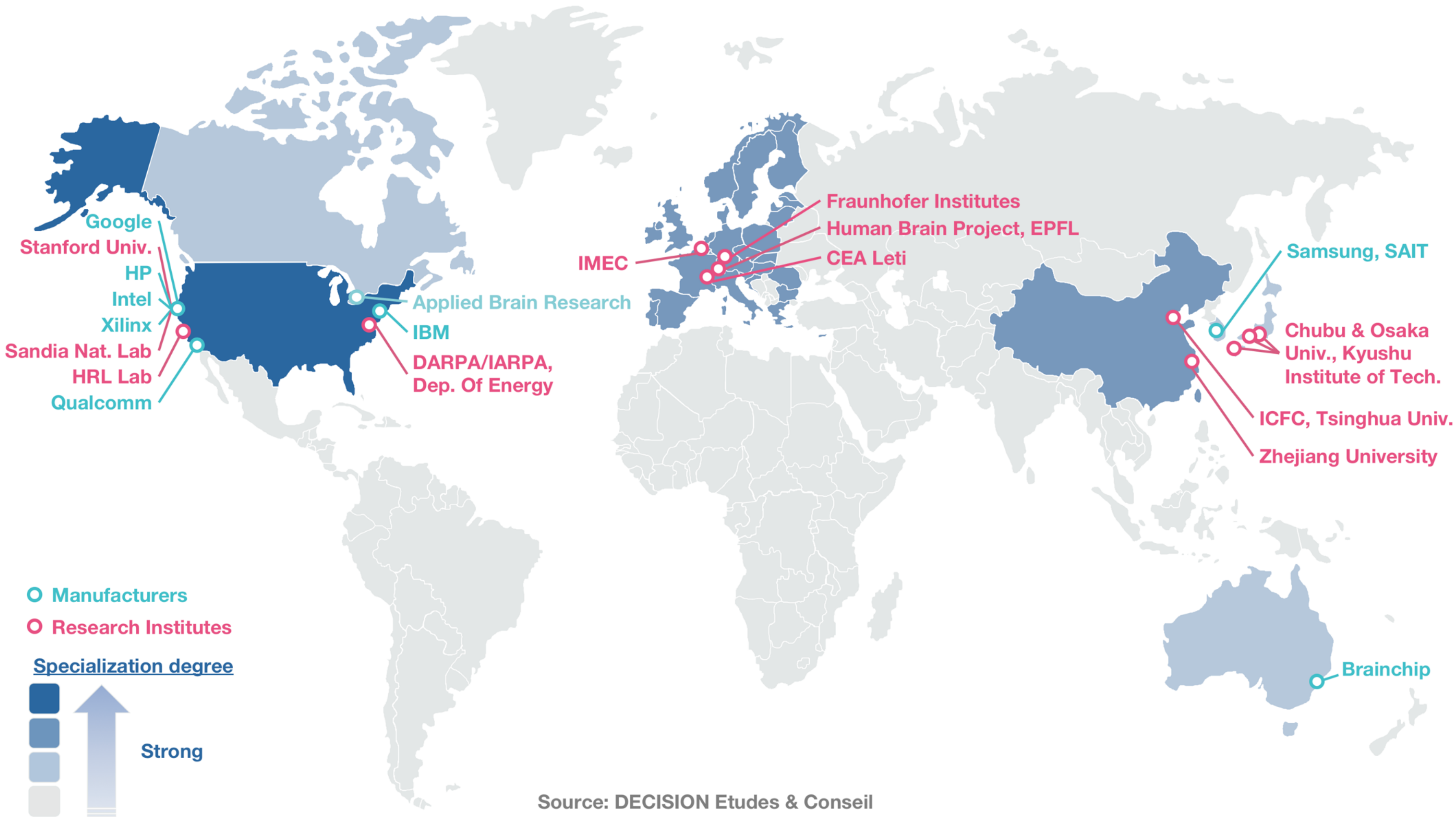
China. China is also significantly involved in Neuromorphic computing research, but in great majority through research laboratories. The main Chinese R&D centers working on Neuromorphic computing are the Zhejiang & Hangzhou Universities (that created the Darwin chip prototype based on CMOS technology), and the Beijing Innovation Center for Future Chips (ICFC), of the Tsinghua University. It was founded in 2015. ICFC's major fields of research range from low-dimensional quantum materials and devices, brain-inspired computing chips, reconfigurable computing chips, emerging memories, smart sensing microsystem to optoelectronics and flexible chips. Over the years, ICFC has grown into a team of 200 scientists and engineers and boasts the world's first nanofabrication technology open platform.

Japan. Japan is well positioned, but mostly through research programs and laboratories. The Japanese research programs are mainly dedicated to life science and biology and robotics applications. None of the main industry players involved in neuromorphic computing are in Japan. The main Universities involved in Neuromorphic research programs are the Kyushu Institute of Technology, the Universities of Chubu, Osaka, Ristumeikan, etc.

Australia. Australia is a significant player, especially through the works of Brainchip (created by a former IBM researcher) that has introduced in 2017 the first production neuromorphic computing system, using spiking neural networks. Brainchip recently unveiled the Akida Neuromorphic System-on-Chip, regrouping 1.2 million neurons and 10 billion synapses.

South Korea. South Korea is a significant player, in particular through the works of Samsung. The Samsung Advanced Institute of Technology (SAIT), has active research programs on near/in memory computing, asynchronous spiking neural networks, and other concepts to create a brain-like processor: brain-inspired learning and inference algorithms, low-power mixed signal computing architectures, and new synaptic memories.

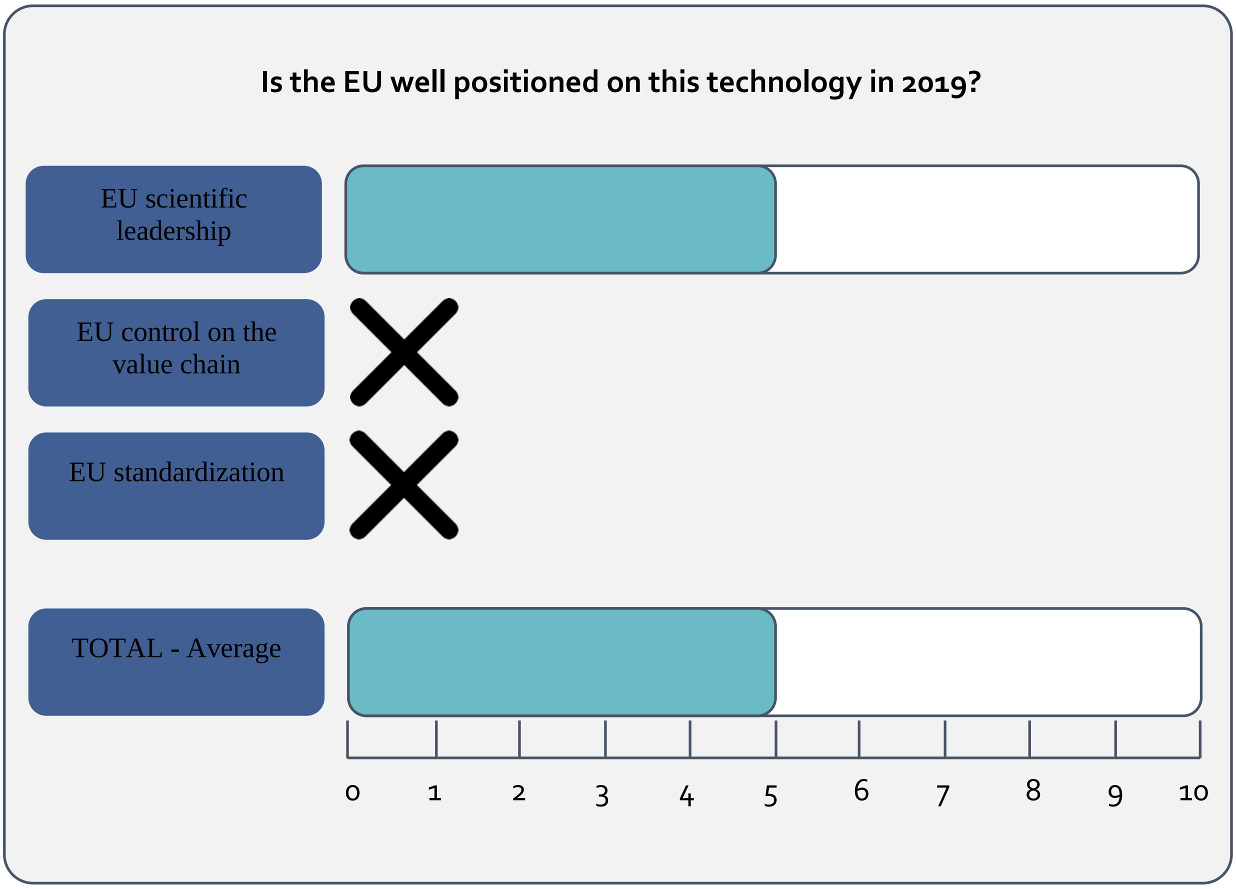
World Map - Neuromorphic computing

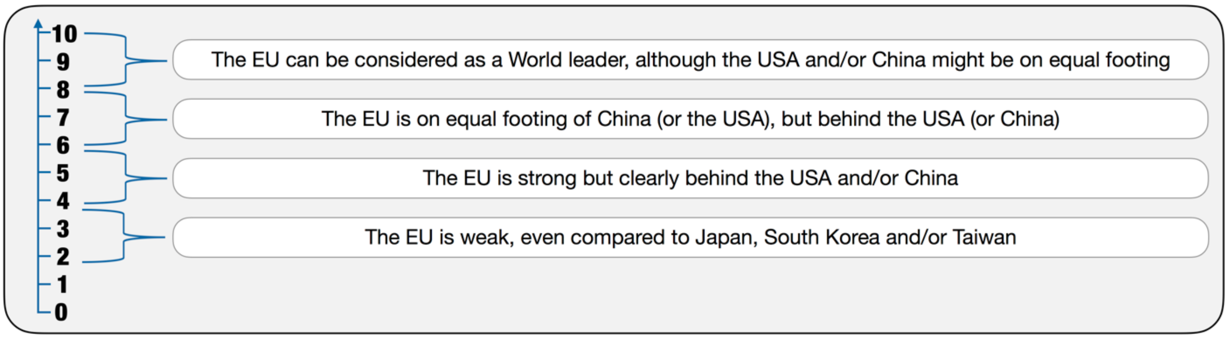


Source: DECISION Etudes & Conseil

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

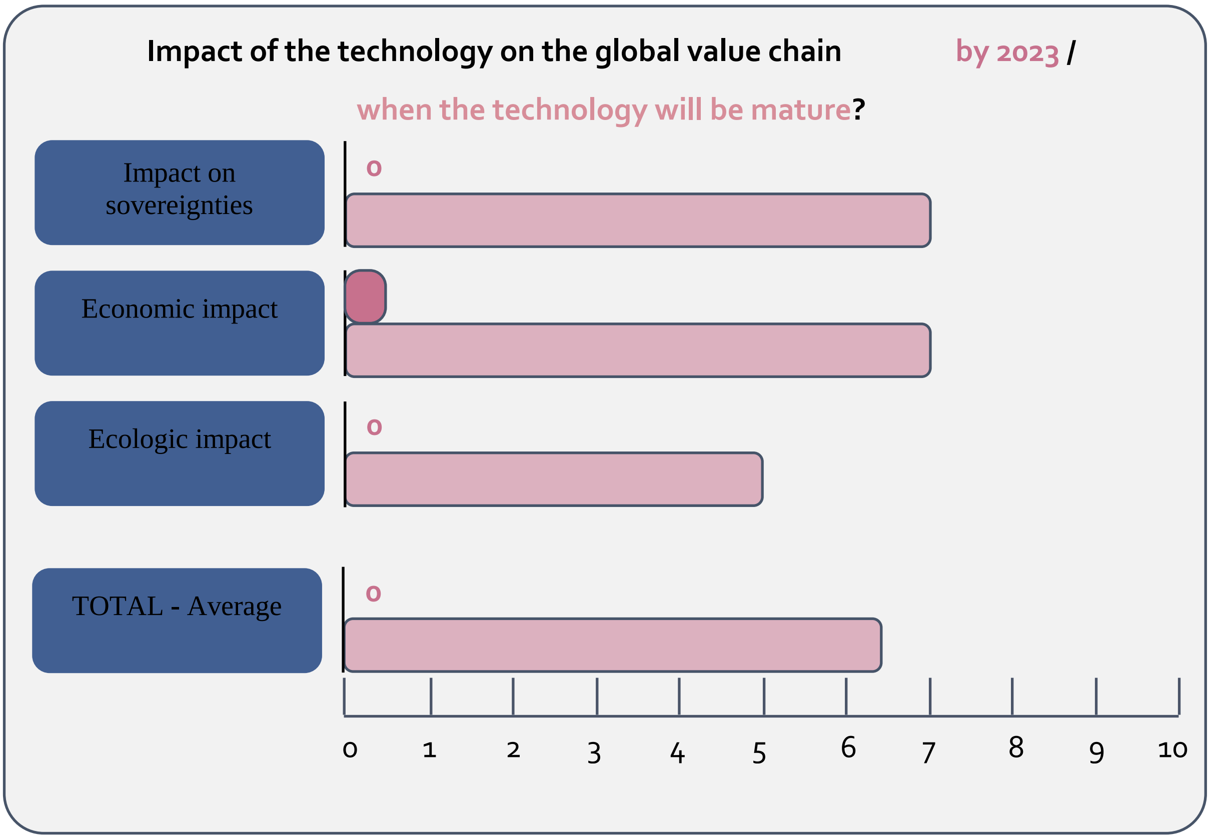
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The USA have a clear technological lead on neuromorphic computing. Yet, the EU remains in the race in second position with China, ahead of the rest of the world.

EU control on the value chain

The only neuromorphic chips that might be released on the global market by 2023-2025 would be American. As a consequence, it is likely that the EU will not have control on the value chain before 2023-2025.

Standard analysis

Neuromorphic computing is still at the stage of R&D. Only a few prototypes exist, and therefore no standards exist yet. Still, given the current situation, it is likely that the US players will be the best positioned to impose their standards at the global scale during the 2020-2030 period.

Impact on sovereignties

If neuromorphic computing chips were to be successfully introduced on the markets, they would become the key elements for computing applications requiring high processing capabilities (that is most of emerging computing applications: ADAS, 5G, etc.). A technological security risk could not be excluded if the EU were to use these chips if they were not produced in the EU territory and / or by European players. The rise of protectionism might also lead to a situation where non-European players and / or states might refuse to deliver such products to the EU, placing the EU in a less competitive position towards its competitors. In other words, the impact on sovereignty of neuromorphic computing would be 10/10 in this scenario.

Yet, such a situation is currently highly uncertain and the impact on the EU sovereignty by 2023 is forecasted to be almost null.

Economic impact

As the first neuromorphic chip should not be commercialized before 2023, the economic impact of neuromorphic computing should remain null until then. Yet, by the end of the 2040s, the potential economic impact of neuromorphic computing is very significant in almost every embedded/professional end-user electronic segment.

Ecological impact

The only ecological impact of neuromorphic computing occurs through their increasing energetic yield. As a consequence, with an equivalent level of raw materials and energy consumption, a neuromorphic chip will lead to greater speed and processing capability than a standard one.

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain theirs level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1950s.

In other words, the positive ecological impact of neuromorphic computing is entirely conditioned on the used made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if neuromorphic computing is used to develop ever new and more consuming applications, then the ecological impact will be null.

B. Quantum computing

i. Definition

Quantum computing is the use of quantum-mechanical phenomena such as the superposition and entanglement to perform computation. The main objective in the field of quantum computation is to build a quantum computer. Other objectives include the development of quantum algorithms to solve specific problems (cryptography, etc.), and the creation of interfaces between quantum computers and communication systems (mainly for secure communication purposes, see the chapter on cryptography).

The concept of quantum computation has been introduced in the seminal work of Feynman (1982) and Deutsch (1985). Shor (1997) then produced a first efficient quantum algorithm for factoring large numbers, thereby raising the game for cryptographic schemes by suggesting that a quantum computer could break them more easily (see the chapter on cryptography). Since then, the growth in research has been phenomenal on both theoretical and experimental aspects of the challenge to construct a quantum computer. Steady progress has been made over the intervening years, and there is a plethora of promising architectures on the drawing board and the laboratory bench.

There are currently two main approaches to physically implementing a quantum computer: analog and digital.

- **Digital approaches**. Digital quantum computers use quantum logic gates to perform computation.
- **Analog approaches** are further divided into quantum simulation, quantum annealing, and adiabatic quantum computation.

Both approaches use **quantum bits** or qubits. Qubits can be in a 1 or 0 quantum state. But they can also be in a superposition of the 1 and 0 states. However, when qubits are measured the result is always either a 0 or a 1; the probabilities of the two outcomes depend on the quantum state they were in.

Apart from the research on classical analog and digital approaches, a trend consists in developing software for classical computer inspired from quantum software and to mix standard hardware and software with quantum devices to perform optimization (see the works of Dwave).

Yet, quantum computing remains at the stage of pure R&D and there is currently no clear front runner in the pack. We are at a stage of development equivalent to that of classical computers before the advent of silicon chips (a mere 60 years ago). We know a lot about what a quantum computer should be able to do, and what components/technologies it may need (trapped ions, neutral atoms, photons, NV centers in diamonds, quantum dots, superconducting devices, etc.), but we have not identified the best materials to build it with, nor what it will be most useful for calculating.

Small prototypes have been built using some of the above-mentioned technologies, and some of the quantum algorithms have been demonstrated. The most advanced technologies at the moment are trapped ions and superconducting qubits. With the first one, coherent control has been achieved with up to 15 qubits. Although the control of the latter is still not at the level of the first, it has the potentiality of being scaled up much more easily. With both technologies, proof-of-principle experiments on quantum error correction have been carried out.

ii. Synergies with other emerging technologies

Photonics. The research to explore these fields is considering many different types of technologies such as quantum dots (electron or photons) to design the building blocks which will make the approach possible at different temperatures and integration scale.

Quantum cryptography. Quantum Communication is the art of transferring quantum states from one place to another. The general idea is that quantum states encode quantum information: hence quantum communication also implies transmission of quantum information and the distribution of quantum resources such as entanglement.

- From an application point of view, a major interest has been focused on Quantum Key Distribution (QKD), as this offers a provably secure way to establish a confidential key between distributed partners. This has the potential to solve long-standing and central security issues in our information-based society as well as emerging problems associated with long-term secure storage (e.g., for health records and infrastructure) and will be critical for the secure operation of applications involving the Internet of Things (IoT) and cloud networking. In the last years the field has seen enormous progress, as QKD systems have gone from tabletop experiments to compact and autonomous systems and now a growing commercial market. More generally there has been an explosion in the number of groups active in the field working on increasingly diverse physical systems. Quantum cryptography is now developing from the initial point-to-point QKD systems, towards the management of quantum-based security over many-node networks that are running in various places worldwide. Presently, technical problems are controlled well enough so that secure transmissions over a few hundred kilometers can be implemented. Indeed, in recent years, we have seen free space quantum communication over 144 km and fiber demonstrations over 300 km. However, non-trivial problems emerge for really long-distance communication (hundreds to thousands of kilometers), and in the quest for higher bit rates. If Quantum Communication is to become, on the coming 5-10 years, an established technology backing up the quantum cryptography “boxes” which are already commercialized, several scientific as well as technological gaps have to be filled;

- Quantum Random Number Generators (QRNG) are one of the most fundamentally fascinating and practically useful quantum technology applications with a direct application in QKD systems. Our information-based society consumes a lot of random numbers for a wide range of applications, e.g., cryptography, PINs, lotteries, numerical simulations. The production of random numbers at high rates is technically challenging; at the same time, given the pervasiveness of the deployment of random numbers, poor random number generators can be economically very damaging. Importantly, from a commercial perspective, higher rate and lower-cost approaches continue to be demonstrated. For example, recently it has been shown that the camera in mobile phones can be used as a QRNG, opening the door to potentially massive commercial opportunities;
- These quantum communication applications are also reliant on a wide range of component technologies: photon sources, detectors, quantum memories, and (frequency conversion) interfaces for connecting disparate systems.

iii. Technology roadmap: Maturity levels and expected impacts by application area

Quantum computing remains a field of research. Currently, no large scalable quantum hardware has been demonstrated, nor have commercially useful algorithms been released. Only the basic principles of quantum computing have been observed and the technology concepts and / or application formulated (Technology Readiness Level 1 and 2). By 2025, analytical and experimental critical functions of quantum computing should be tested through characteristic proof-of-concepts (Technology Readiness Level 3). Component and / or breadboards in laboratory environments should not emerge before the 2025-2030 period. In other words, no tangible evidence suggests the emergence of a functioning prototype over the next 10 years.

According to the DARPA (in 2019), “*Universal quantum computers with millions of quantum bits, or qubits – which can represent a one, a zero, or a coherent linear combination of one and zero – would revolutionize information processing for commercial and military applications. Realizing that vision, however, is still decades away*”. These lead many financing agencies (such as the DARPA) to adopt an approach based on supporting long-term science and to target particular problems: “*The program will identify classes of problems in combinatorial optimization where quantum information processing is likely to have the biggest impact*”.

Furthermore, evidence already exists that quantum computing will not solve NP-complete problems.

Quantum Information science currently includes the following subfields corresponding to different **applications**:

- **Quantum Computation**. Quantum computation will enable the use of AI algorithms at levels never obtained before: large-scale machine-learning, optimization, etc. quantum computing might therefore impact end-user electronic markets through AI applications (see the chapter on AI algorithms);
- **Quantum Communication**. This field might lead to the set-up of secure network solutions and innovative cryptography codes (quantum cryptography), thanks to entangle bits. Future quantum computers would also be able to decrypt retrospectively any internet communication that was recorded today (the EU is therefore setting up a Quantum Communications Infrastructure (QCI), dedicated to secure communications in the EU. The QCI should be set up by 2030);

- **Quantum Simulation**, quantum simulators may become the first short-term application of quantum computers, since with modest requirements one may be able to perform simulations that are impossible with classical computers. They could be used for a variety of purposes, e.g., to obtain an accurate description of chemical compounds and reactions, to gain deeper understanding of high-temperature superconductivity, etc. This field might lead to commercial outlets, especially in health & care (drug design);
- **Quantum Information Theory**, leading to innovation in Mathematics research. Quantum algorithms will be one of the most powerful applications of quantum computers. We know only a few examples up to date, such as Shor factoring algorithm, but new techniques and protocols are currently being developed;
- **Quantum Metrology Sensing and Imaging**. Specific quantum phenomena such as coherence and entanglement can be exploited to develop new modes of measurements, sensing, and imaging that offer unprecedented levels of precision, spatial and temporal resolution, and possibly auto-compensation against certain environmental factors, such as dispersion. It will lead to innovations in the sensors' markets;
- **Quantum Control**, consisting in controlling another quantum system.

A detailed presentation of these fields may be found in the Quantum Flagship roadmap[12].

The table below, based on a study from the Institute for Defense Analyses, provides estimates of the current market value of the few existing quantum applications in quantum metrology sensing & imaging and quantum communication. The current market value of quantum applications does not exceed €3 B worldwide and can be estimated at €1-2 B.

Technology	Estimated market (M€)
Quantum metrology Sensing & Imaging	
Atomic clocks	60-600
Gravimeters and other atomic interferometers	<60
Atomic magnetometers	60-600
Magnetoencephalograpghy	60-600
Quantum communications technologies	
Quantum Key Distribution	60-600
Quantum random number generators	<60
Quantum computation & simulation	
-	0
TOTAL quantum	**350 - 2500**

Source: DECISION Etudes & Conseil, based on estimates from IDA Science & Technology Policy Institute « Assessment of the Future Economic Impact of Quantum Information Science, 2017 ».

The main future directions of research are the following:

- Coherence time / Decoherence. The main issue is that the performance and reliability of quantum devices depend on the length of time the underlying quantum states can remain coherent. If you wait long enough, interactions with the environment will make the state behave like a conventional classical

[12] The Quantum Flagship is the third large-scale research and innovation initiative of this kind funded by the European Commission. It started in October 2018.

system, removing any quantum advantage. Often, this coherence time is significantly short, which makes it difficult to perform any meaningful computations;

- Further development of all current technologies to understand their limitations and find ways around them;
- Assessment of the capabilities of different technologies for being scaled up;
- Optimization of the performance of error-correcting codes, by both increasing the error threshold and decreasing the overhead of required qubits;
- Investigation of new ways of performing quantum computation, in particular based on self-correcting codes (as they appear in topological systems);
- Development of new quantum algorithms and search for problems where quantum computers will be required;
- Development of quantum complexity theory and its application to many body physics;
- Building interfaces between quantum computers and communication systems;
- Development of quantum-proof cryptography to achieve forward-in-time security against possible future decryption (by quantum computers) of encrypted stored data.

Technology Roadmap - Maturity of the technology at the global scale

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	Maturity level of the technology											R&D										
N°	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
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N°	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production																				
1	Data analytics / Big data											No significant impact										
2	Smart home											No significant impact										
3	Smart mobility											No significant impact										
4	Smart energy											No significant impact										
5	Wearables											No significant impact										

At the global scale, each technology is defined through four different stages of maturity.

- **R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6**
- **Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9**
- **Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)**
- **Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies**

The impact of the technology on each end-user segment is described as:

- **A critical impact;**
- **A significant impact;**
- **No significant impact;**

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

This roadmap corresponds to the restrictive definition of quantum computing (that is a quantum chip). Yet, specific applications in communication and sensing already exists and will have significant impacts on specific markets in the coming years (mostly in secure communications).

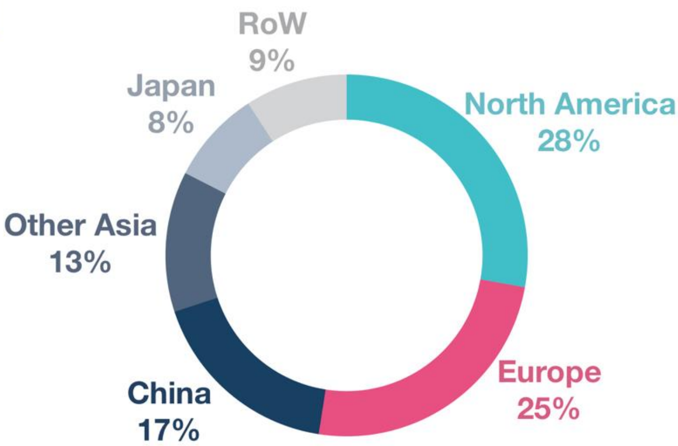
Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

The world map below summarizes the main countries, industrial and research players in 2019. Quantum remains in the field of pure R&D. The table below summarizes the estimated public and private R&D expenses in 2018 by region of the world. Europe is in second position behind North America.

Quantum public & private R&D spending

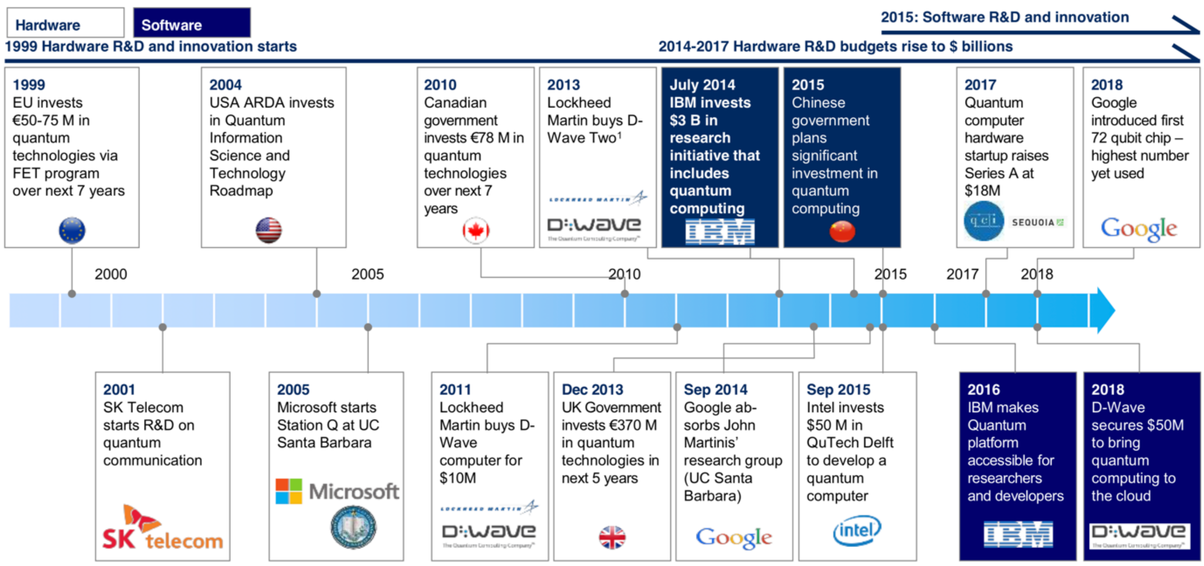
Region	2018 (B€)
North America	1,8
Europe	1,6
China	1,1
Other Asia & Pacific	0,8
Japan	0,5
Rest of the World	0,6
World	6,3



Source: DECISION Études & Conseil, based on public R&D spending (sum of public support programs), and private R&D spending (sum of R&D expenses dedicated from main companies involved), estimates also in line with existing public reports.

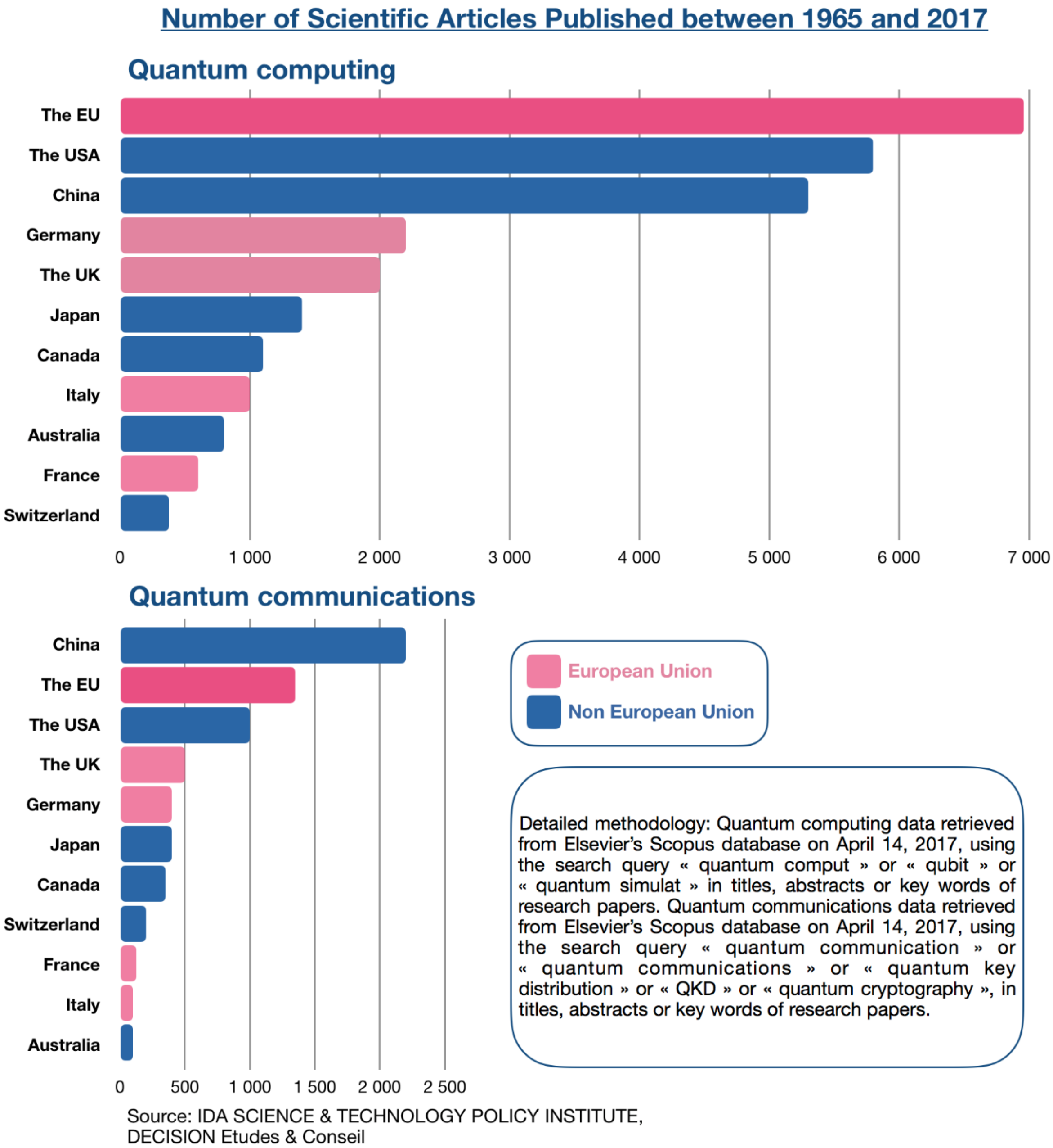
As shown in the figure below, the massive uptake of industry interest and funding in the field of quantum computing only occurred since 2014.

Some of the main initiatives in Quantum R&D over the 1999-2019 period



Source: INSEAD

One important aspect about this technology is the emergence many start-up companies. A detailed list of quantum start-ups can be found there.



The USA. In the United States, R&D expenses in quantum technologies exceed Europe and China in quantity, thanks to an unrevealed density of public & private laboratories on quantum, the presence of great industrial players to manage a future industrialization process (IBM, Intel, Microsoft, etc.), and the greatest internal market for computer applications. Among the main public programs, one can find the National Strategic Computing Initiative, the National Quantum Initiative Act and the SBIR (Small Business Innovation Research), a component of the Small Business Act.

The main public research institutions involved are the DARPA (through many programs: QuASAR, ONISQ, etc.)[13], the IARPA (Through 5 main programs: LogiQ, QEO, CSQ, MQCO and QCS), the NSA (confidential co-

[13] In particular, the DARPA policy consists in supporting long-term science (such as quantum), in a step-by-step approach (identifying near-term particular problems and solving them the one after the other). In this spirit, the Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ) program aims to exploit quantum information processing before fully fault-tolerant quantum computers exist. This effort will pursue a hybrid concept that combines intermediate-sized quantum devices with classical systems to solve a particularly

programs with Lockheed Martin on the implementation of the Shor algorithm to decrypt RSA types public key protected communications and to protect sensitive communications with quantum cryptographic keys), but also the US Air Force and the Office of Naval Research (on quantum cryptography), the Army Research office, the NASA (with the QuAIL laboratory founded in 2013 with Google & Dwave), the Quantum Institute of the Los Alamos National Laboratory (LANL), and universities such as the MIT and the University of California, Santa Barbara.

The current leaders in quantum private R&D are American. Google has designed the biggest quantum processor (72 qubits) and its quantum processor Sycamore has proved in October 2019 being able to perform a specific computing operation more than 1000 times faster than all the supercomputers that have tried the same operation. IBM has designed the second-biggest quantum processor (50 qubits), and Intel has designed the third-biggest quantum processor (50 qubits). Furthermore, in 2019, IBM has presented its first commercial circuit-based quantum computer: System One from IBM Q. Other key industrial players are Microsoft, Rigetti, Raytheon, Honeywell, etc.

Canada. Canada ranks among the world's leading nations in quantum research, building on investments of more than $1 billion in the past decade alone, corresponding to around €83 M per year. In a recent evaluation of worldwide quantum research efforts published in the Economist, McKinsey and Co. ranked Canada 5th globally in total annual expenditures on quantum science and 1st among G7 nations in per capita spending on quantum research. The main Canadian research players are the University of Waterloo & its Institute for Quantum Computing (IQC), and the University of Sherbrooke. The main industrial player is Dwave (one of the world leaders, marketing its hardware since 2000), and Xanadu is a remarkable start-up (designing and integrating quantum silicon photonic chips into existing hardware to create truly full-stack quantum computing).

The EU. In many of these activities, European research has played a leading role and has established a strong set of world-leading centers. According to McKinsey, over 50 percent of academic papers in this field were coming from European scholars over the 2013-2015 period. Over the 1996-2016 period, the EU invested of cumulated amount of nearly €550 M (that is around €30 M / year). In 2018, the EU has launched the Quantum Flagship, a €1 billion program, 10-year endeavor (that is around €100 M / year). The UK and Germany seem to be the two European leading countries in quantum research. Yet, the EU clearly suffers from a lack of great industrial players of the digital industry (GAFAMI / BATX equivalents).

- **The UK** is very well positioned with a lot of projects and has been one of the first European players to invest significantly in quantum computing. The UK National Quantum Technology Programme (UKNQT), is a £270 million investment over the 2014-2019 period (that is €60 M / year), by the UK government to establish a quantum technology industry in the UK (and especially building a quantum computer demonstrator, the Q20:20 engine, which demonstrates a networked, hybrid light-matter approach to quantum information processing). Regarding the coming years, the British Government has announced in 2018 that €89 M will be given to four UK-based world-leading quantum technology development centers over the 2018-2022 period to create new technologies for diverse applications (that is €22-23 M / year). The UK Defence Science and Technology Laboratory (DSTL) is separately investing €30-35 M per year in quantum R&D. The main research centers are the University of Oxford with the Networked Quantum Information Technologies Hub (NQIT) and the QuOpaL program financed by Nokia & Lockheed Martin, the University of Cambridge (centre for Quantum Information and Foundations), the Universities of Glasgow, York, Bristol, etc. Yet, no great British industrial players seem significantly involved in quantum research;

challenging set of problems known as combinatorial optimization. This program also identifies classes of problems in combinatorial optimization where quantum information processing is likely to have the biggest impact. This policy is similar to the approach of Dwave, a company that makes combinatorial optimization in order -for instance- to solve a routing problem for a huge taxi fleet and optimizing in real time the overall journey time for those thousands of taxis with thousands of different destinations (a specific short-term solution for a specific problem).

- **Germany** is well positioned with a lot of projects. In particular, the German government has announced a €650 M plan to support quantum R&D over the 2018-2022 period (that is €160-170 M per year). Two research institutes are particularly involved in quantum computing research: The Max Planck Institute for Quantum Optics (MPQ), and the Institut für Quanteninformation of Aix La Chappelle. Several great German industrial players are involved in quantum research, but mainly through technology monitoring (Bosch, Infineon, etc.);

- **France.** In terms of scientific knowledge, France regroups some scientists that have made the greatest advances in quantum research (Alain Aspect, Serge Haroche, Philippe Grangier and Michel Devoret), line with research institutes such as the CNRS and the Universities of Orsay/Saclay. The French investments are spread into diverse laboratories, institutes and programs, such as the ANR, the CEA-Leti, the INAC, the Institut Néel, the SIRTEQ project, Quantonation, the INRIA, the IQUPS (Ingénierie Quantique à l'Université Paris-Saclay), the Paris Center for Quantum Computing (PCQC), etc. The only noticeable French industrial player is Atos / Bull, which might be considered as the European leading industrial player in quantum computing. The European player Airbus is involved through technology monitoring;

- **Belgium.** Belgium is invested in quantum research, in particular through the IMEC.

China. China can be considered as the second main country in terms of quantum research, at a level comparable to the EU (with less remarkable R&D advances but with more industrialization capabilities). Yet, China remains significantly behind the USA in terms of investments and industrial & laboratories ecosystem. Quantum is one of the scientific priorities announced by Xi Jinping in 2015. Among the greatest investments, China is building a National Laboratory for Quantum Information Sciences, a massive multi-location national-level quantum laboratory. The BAQIS (Beijing Academy of Quantum Information Sciences), is one of the main beneficiaries, along with the main Chinese universities: the Tsinghua University, the University of Science & Technologies (USTC), etc.

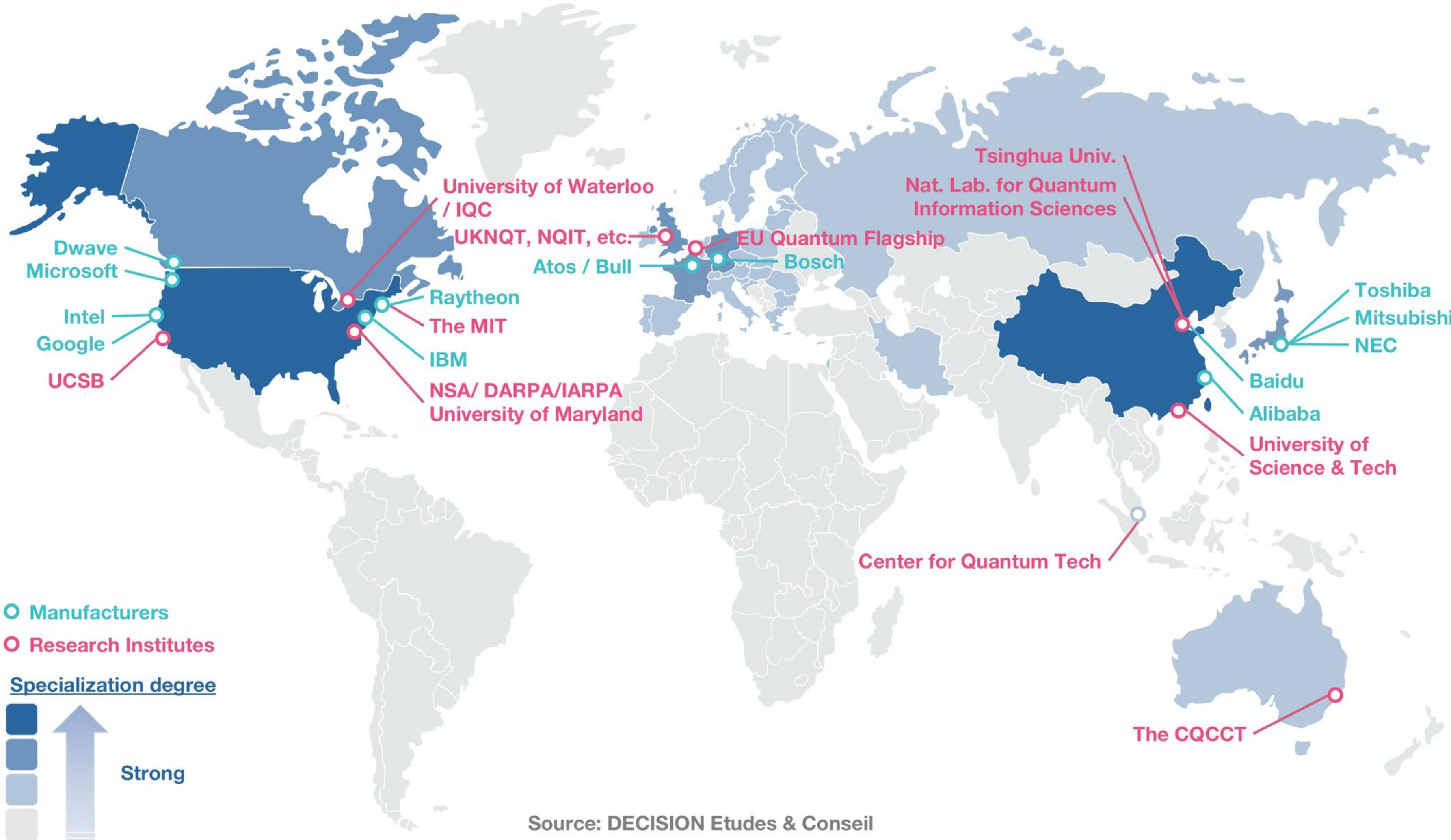
Great Chinese industrial players like Alibaba, Baidu and ZTE are investing heavily in quantum computing, too. Alibaba has launched a cloud computing service that lets people experiment on quantum processors, mirroring similar efforts by US companies such as IBM and Rigetti.

Japan. Japan is also along the main countries involved in quantum research worldwide, with several significant industrial players involved: Fujitsu, NEC, Toshiba, Mitsubishi, Hitachi and NTT (Nippon Telegraph and Telephone). The main research centers are the NICT (National Institute of Information and Communication Technologies), and the National Institutes for Quantum and Radiological Science and Technology (QST), launched in 2016 and with a total annual budget of more than €400 M (but mainly focused on quantum metrology sensing & imaging).

Australia. The National Innovation and Science Agenda is funding research on quantum for an amount of $ 820 M over the 2015-2019 period (that is around €170M per year). In other words, Australia is a significant player of the world quantum research, despite its small size (such as Canada). The main research players involved are the Center for Quantum Computation and Communication Technology (CQCCT), the Centre for Quantum Software and Information of the University of Technology Sydney (which collaborate with the IARPA), and the UNSW (University of New South Wales). Yet, no significant Australian industrial players are involved in quantum research, only start-ups.

Singapore. The Singapore Center for Quantum technologies has an annual budget of more than €12M since 2007.

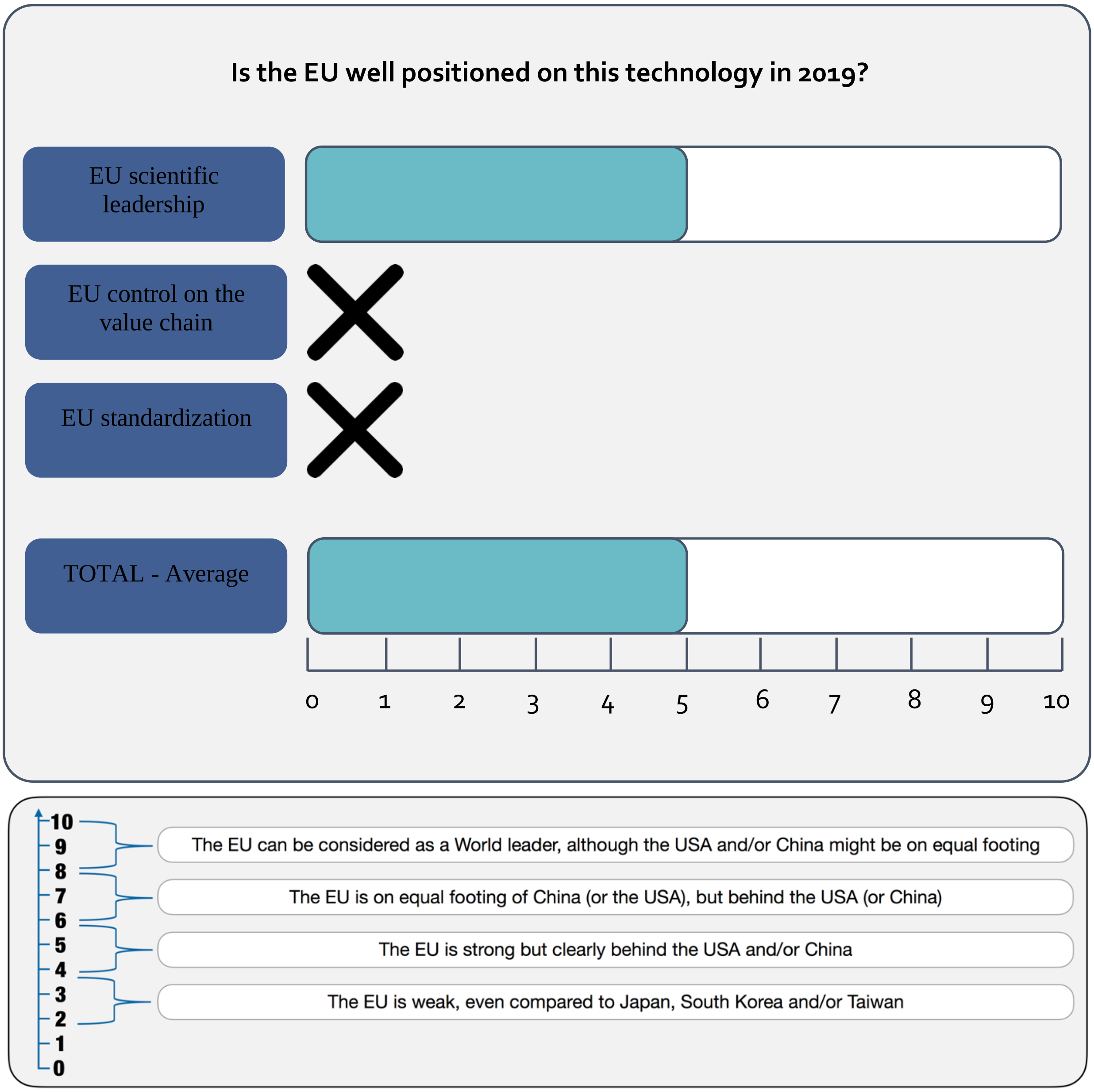
World Map - Quantum computing



Source: DECISION Etudes & Conseil

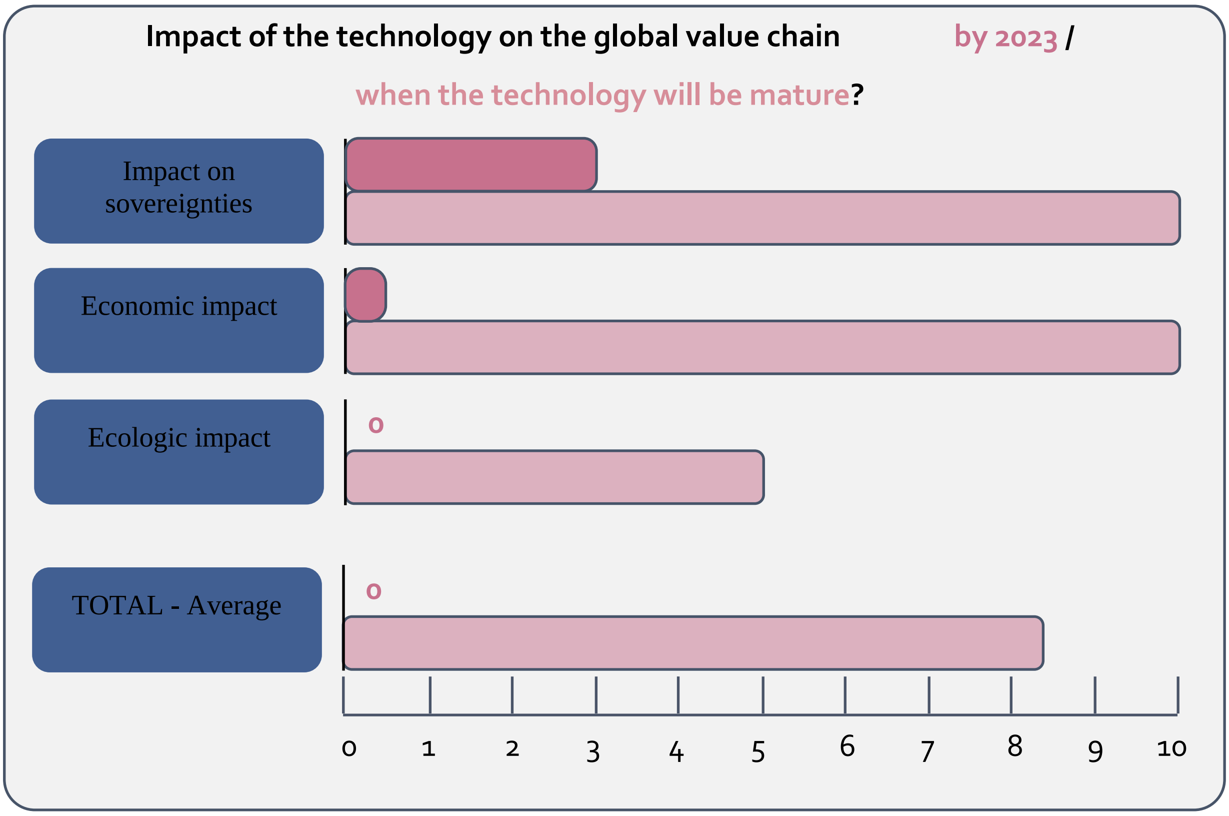
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU can be considered in second position, significantly behind the USA but on a relatively comparable position with China. Japan and Canada are the two other main competitors, in third position. Finally, Australia, South Korea, Switzerland, Russia and Singapore can be considered as significant countries. The EU is in very good position in terms of pure R&D quantum innovations, but a relative dispersion of the efforts (spread over many laboratories), and mainly from a lack of industrial players able to orientate the research towards marketable applications. China can be considered as in the opposite situation, significantly investing in quantum research for less than twenty years but supported by great industrial players. The USA combines both advantages, with a great and historical ecosystem of private and public laboratories and great industrial players significantly involved in quantum research.

EU control on the value chain

This criterion is irrelevant as this technology is insufficiently mature.

Standard analysis

No standards exist as this technology is insufficiently mature.

Impact on sovereignties

If quantum computing chips were to be successfully introduced on the markets, they would become the key elements for computing applications requiring high processing capabilities (that is most of emerging computing applications: ADAS, 5G, etc.). A technological security risk could not be excluded if the EU were to use these chips if they were not produced in the EU territory and / or by European players. The rise of protectionism might also lead to a situation where non-European players and / or states might refuse to deliver such products to the EU, placing the EU in a less competitive position towards its competitors. In other words, the impact on sovereignty of quantum computing would be 10/10 in this scenario.

Yet, such a situation is currently highly uncertain and the impact on the EU sovereignty by 2023 is forecasted to be null.

Economic impact

The commercialization of a quantum chip is currently highly uncertain as components and / or breadboards in laboratory environments should not emerge before the 2025-2030 period. No tangible evidence suggests the emergence of a functioning prototype over the next 10 years. The economic impact of quantum computing should therefore remain null until then. Yet, by the end of the 2040s, the potential economic impact of quantum computing might be equivalent to the one of the current More Moore technologies.

Specific applications (quantum sensing, quantum communications), already represented a world market of €2-3B in 2018, and these applications should gain in importance within the next five years (especially quantum communications for critical communications).

Ecological impact

The only ecological impact of quantum computing occurs through their increasing energetic yield. As a consequence, with an equivalent level of raw materials and energy consumption, a quantum chip will lead to greater speed and processing capability than a standard one.

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, the positive ecological impact of quantum computing is entirely conditioned to the use made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if quantum computing is used to develop ever new and more consuming applications, then the ecological impact will be null.

C. Photonic computing

i. Definition

Photonic computing is a field that envisages realizing complex computing through the inherent specific properties of optics and photonics. It relies on interactions of light (from one or more sources, such as lasers or diodes), with a non-linear system, in order to perform complex computations. Attainable bandwidths and speeds are larger than those reached with electrons, thanks to the inherent speed and parallelism of processes involving light.

Photonic computing allows performing operations that are unfeasible using traditional electronics because of their complexity, power consumption or speed, random number generation (especially in the field of cryptography), or pattern recognition ability.

The field has emerged in the early 2000s and currently regroup three main categories:

1. **Chaos-based photonic computing**. Chaos-based communication uses optoelectronic or optical devices and exploits non-linearity (e.g., saturation…), of components, or the instabilities of oscillators, in order to improve the computational complexity, to lower the power consumption and / or to reinforce the security of data transmission at a physical level;

2. **Photonics reservoir computing**. As an evolution of Artificial Neural Networks (ANNs), this concept is based on realizing neural networks of reservoir computers through opto-electronics or optical systems in order to overcome the time delay of computing and training of electronic systems. Those systems are explored generally for pattern classification problems (speech and image recognition), time series prediction and in communication;

3. **Quantum optics**. Quantum optics consists in combining the semi-classical (reflection/transmission) and quantum-mechanical (quantum states) principles of light to provide a way towards the quantum computer. Various quantum properties can be utilized in conjunction of different particles, polaritons, spintronic and plasmonic. The two main uses of quantum optics are Quantum Random Number Generation (QNRG), and quantum simulation. QNRG is used in cryptography for encrypted data transmission through Quantum Key Distribution. Quantum simulation is used to simulate materials or chemical compounds (in particular in drug design).

Optical data processing is another aspect of light that can be considered as a way to enhance and modify the paradigm of computing. However, optical data processing relies on a more classical approach and is therefore classified and straightforward dependent on Photonics Integrated Systems.

ii. Synergies with other emerging technologies

Cryptography & Identification-Authentication. Chaos-based photonic computing is mainly used in cryptographic applications. Quantum optics may also lead to great innovations in quantum cryptography through QNRG.

Neuromorphic computing & emerging algorithms. The design of photonic reservoir computing is a promising emerging field of neuromorphic computing. Brain-Inspired Computing can also exploit photonic materials in order to mimic biological synaptic plasticity (that is the ability of photonic materials to change their efficiency of transmitting light based on the intensity of incoming light). Neuromorphic architectures developments are among the most promising innovations to perform emerging algorithms and particularly machine-learning algorithms.

Quantum computing. Quantum optics is a promising emerging field of quantum computing: in particular, quantum communication, quantum cryptography and quantum simulation.

iii. Technology roadmap: Maturity levels and expected impacts by application area

The maturity level of Photonic Computing is diverse for each of the three main divisions (Chaos, Neural Computing, Quantum Computing). Basically, it is still at a research level (except for the Optical Quantum Key distribution which entered the industrial production 15 years ago), but it seems a mandatory pathway towards Artificial Intelligence development (see the chapter on emerging algorithms).

The following roadmap provides an overview of the impact of photonic computing on the end-user applications, through:

- Security applications of chaos-based photonic computing and quantum photonics;
- AI applications of photonics reservoir computing in mobile phones, audio & video, smart home and data analytics.

The economic impacts of quantum photonics should be largely greater by 2030-2050 as the maturity of the technologies will rise.

Technology Roadmap - Maturity of the technology at the global scale and by application area

<table>
<tr><th colspan="2"></th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><th colspan="2">Technology</th><th colspan="21">Maturity level of the technology</th></tr>
<tr><td colspan="2">Quantum optics</td><td colspan="21">R&D</td></tr>
<tr><td colspan="2">Chaos-based photonics computing</td><td colspan="5">R&D</td><td colspan="10">Tests & prototyping</td><td colspan="6">Industrial production</td></tr>
<tr><td colspan="2">Photonics reservoir computing</td><td colspan="5">R&D</td><td colspan="10">Tests & prototyping</td><td colspan="6">Industrial production</td></tr>
<tr><td colspan="2">Quantum Key Distribution</td><td colspan="6">R&D</td><td colspan="3">Tests & prototyping</td><td colspan="6">Industrial production</td><td colspan="6">Massive production</td></tr>
<tr><th>N°</th><th>Electronic Segment</th><th colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="15">Small impact</td><td colspan="6">Medium impact</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="15">No significant impact</td><td colspan="6">Small impact</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="15">No significant impact</td><td colspan="6">Small impact</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="21">No significant impact</td></tr>
<tr><th>N°</th><th>Crossed segments</th><th colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
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</table>

At the global scale, each technology is defined through four different stages of maturity.

- **R&D:** Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- **Tests & prototyping:** Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- **Industrial production:** Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- **Massive production:** Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

Impact of photonic computing by end-user electronic applications in 2023

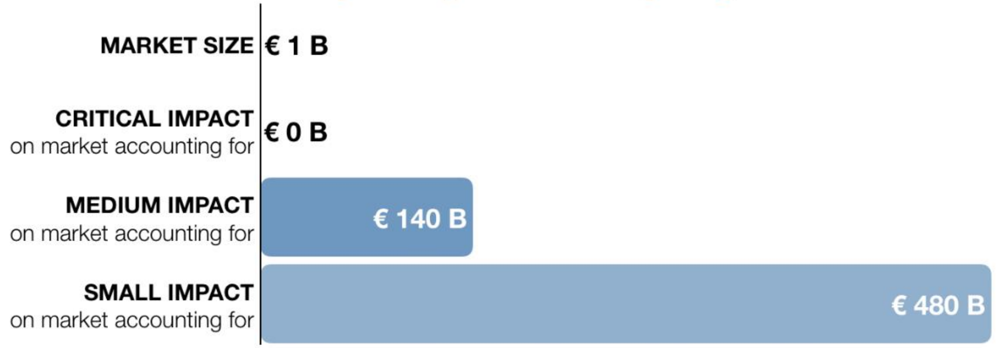
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	No	No	No	No	No	Small	No	No	No	No	No

Corresponding quantitative impact of photonic computing in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
1	0	140	480	0	0	20	0	140	460
				-	-	Cybersecurity applications (cryptography)	-	Video games & consoles	Medical diagnoses and mobile applications market

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of photonic computing in 2023

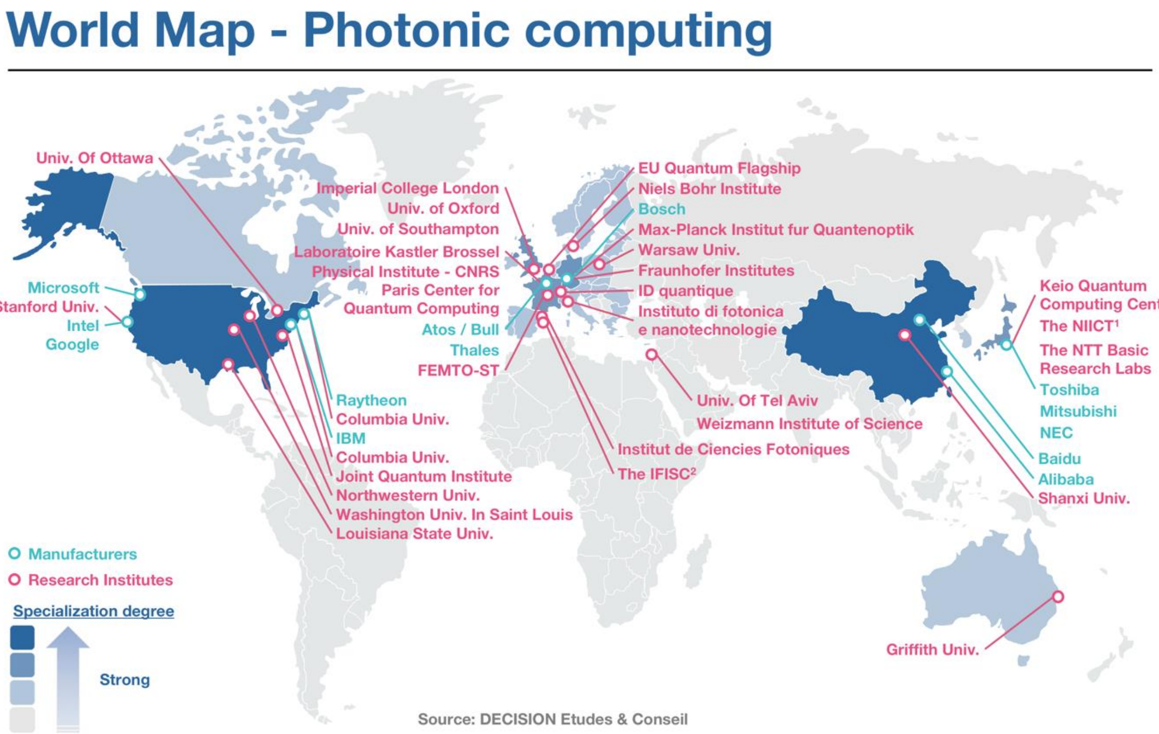


Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

Except for the sub-application of Quantum key Distribution, no products are commercialized yet. The ecosystem of photonic computing has strong synergies with the ecosystem of quantum computing. It is composed of public research programs, large research and industry players allocating research expenses and a significant number of start-ups developing prototypes.

The world map below provides an overview of some of the main R&D centers and industrial players involved in Photonic Computing R&D:



[1]NIICT: National Institute of Information and Communication Technology

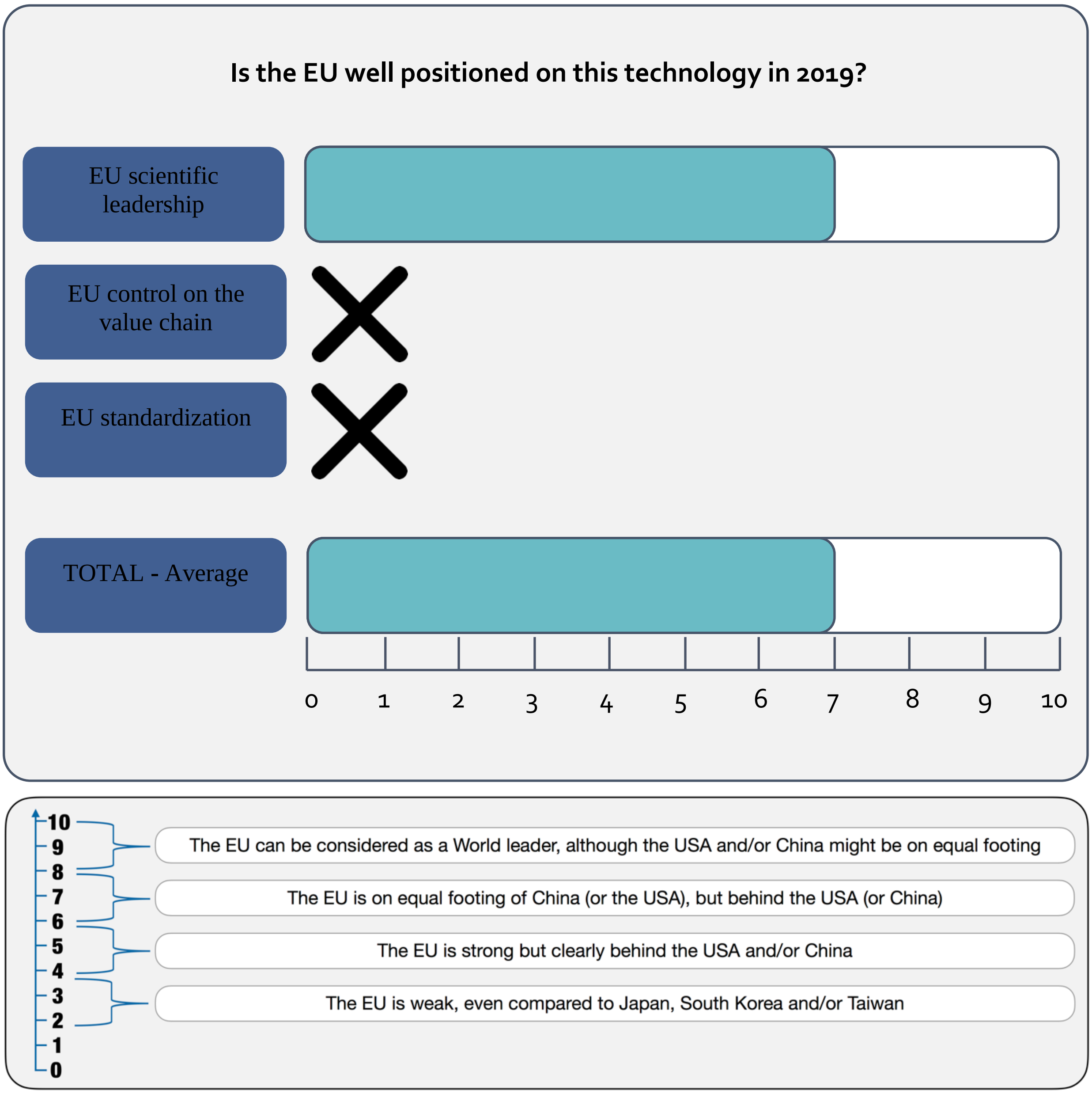
[2]IFISC: Instituto de Fisica Interdisciplinar y Sistemas Complejos

The EU benefits from a great ecosystem of SMEs and start-ups investing in Quantum Computing R&D, such as:

- LightOn (France): Using light to perform computations of interest to Machine-learning / AI (France);
- Quandela (France): Working mainly on photon sources;
- Optalysys (the UK). Optalysys can offer something unique in the AI space: a scalable processor that can perform end-to-end, full-resolution processing of multi-megapixel image and video data, or contextually pre-process data for boosting the performance of existing Convolutional Neural Network (CNN)-type models for high-resolution data applications (from the University of Cambridge);
- Lightmatter: Development of photonic chip-based Optical AI technology, financed by Google Ventures. (Boston – USA);
- Lightelligence: A subsidiary of OSRAM (Germany).

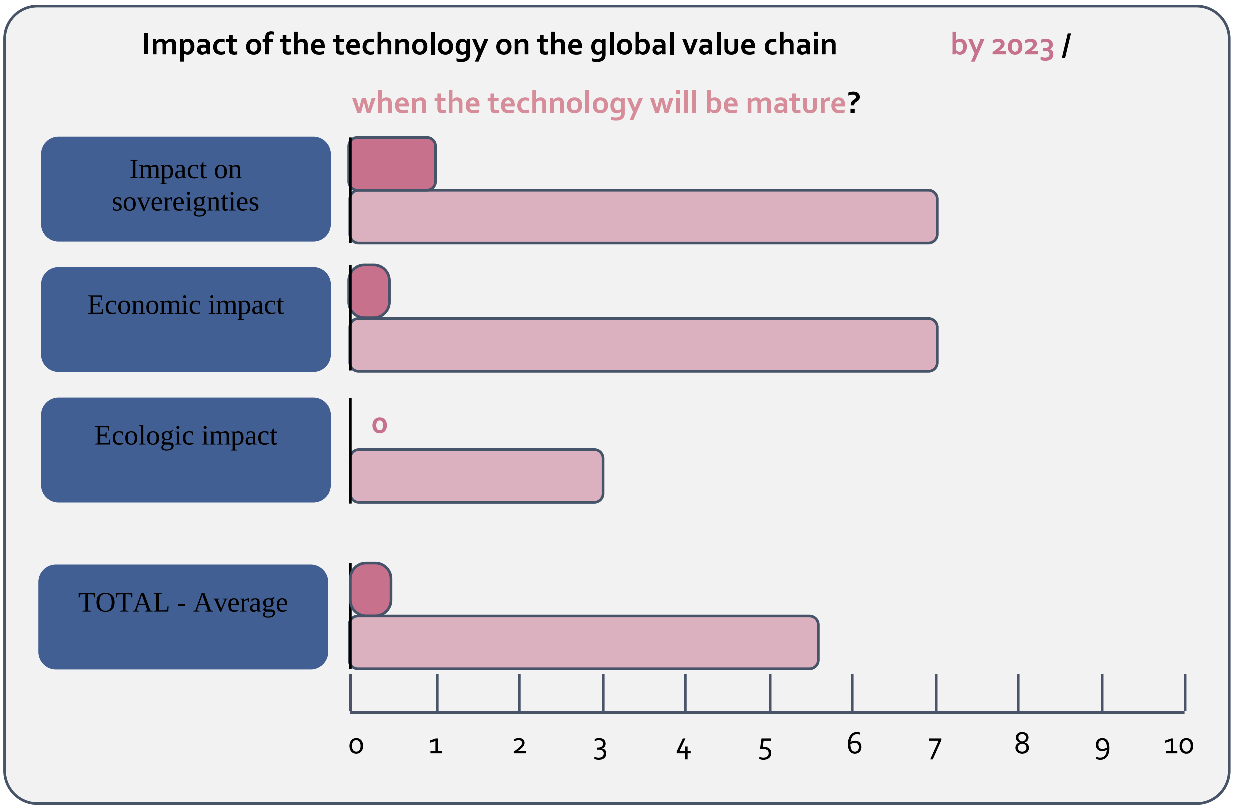
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



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- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU has a large scientific potential in the field, with key labs renown at the international scale.

EU control on the value chain

The value chain is not complete yet. Large companies, SMEs and start-ups are present in the EU, mainly through technology monitoring.

Standard analysis

Standardization is missing at this stage in the World due to the early stage of development of quantum computing.

Impact on sovereignties

Photonic computing is a very disruptive technology, especially in the field of cybersecurity, which is sovereignty concern for Europe.

Economic impact

Cybersecurity is the main application where an economic impact is expected over the next five years (Quantum optics, Quantum key distribution), representing a market of around €1B in 2018. However, on the long run, the development of photonic computing will have a key industrial impact as the need in such high-capacity computing will diffuse from highly centralized systems downward to building and personal computing.

Ecological impact

The majority of the sub-technologies of photonic computing should lead to lower power consumption. Therefore, the only ecological impact of photonic computing might occur through its positive impact on the energetic yield of computing devices.

Yet, in this situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, the positive ecological impact of photonic computing is entirely conditioned to the use made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if photonic computing is used to develop ever new and more consuming applications, then the ecological impact will be null at best.

D. Other approaches in rebooting computing

i. Definition

Quantum computing and neuromorphic computing occupy a special place as the number of teams and the financial means to pursue these efforts are much higher than for any other approaches. Yet, other important but less funded research and development efforts exist which may also lead to a radical change in the way emerging algorithms (that is complex and data intensive algorithms), will be implemented in the future.

The limit drawn between quantum, neuromorphic computing and photonic computing on one side and "other approaches" is, of course, quite arbitrary. For example, "PUMA, a neuromorphic circuit based on memristor" has been included in this section "other approaches" while it may well be considered as state-of-the-art neuromorphic circuits. Idem for 2DPE (computation with Two-dimensional Electron Photo Electro-spectroscopy), that may well be considered as a branch of quantum computing.

Below are presented some of the most relevant other approaches in rebooting computing.

A. Approximate computing

Definition. Approximate computing (and storage) is based on the intuitive observation that while performing exact computation or maintaining peak-level service demand require high amount of resources, allowing selective approximation or occasional violation of the specification can provide disproportionate gains in efficiency. For example, for k-means clustering algorithm, up to 50% energy saving can be achieved by allowing classification accuracy loss of 5 per-cent (Chippa et al. 2014).

Applications. As Approximate computing (AC), exploits the gap between the level of accuracy required by the applications/users and that provided by the computing system, AC has the potential to benefit a wide range of applications/frameworks e.g., data analytics, audio & video analysis, machine-learning, etc.

Sub-applications / Intermediate applications.

- <u>Approximate computing with software</u>: Precision scaling, loop perforation, load value approximation, skipping tasks in memory accesses, combining multiple inexact program versions, using inexact or faulty hardware, using voltage scaling, reducing branch divergence in SIMD architectures, using neural network-based accelerators, approximating neural networks, etc.

- <u>Approximate computing with low-level hardware</u>: Approximating SRAM memory, eDRAM and DRAM memories, non-volatile memories, approximating computing techniques for GPUs and / or for FPGAs, etc.

Challenge. Several large-scale software of today have been written in conventional language which assume precise operations and storage. Facilitating development of code that fully exploits the inexact hardware and approximation strategies while also meeting quality expectations requires a powerful and yet, intuitive and simple programming language. Significant work is required to transform today's research-stage programming frameworks for AC into mature and robust code development platforms of tomorrow.

B. Probabilistic CMOS (PCMOS)

Definition. Probabilistic complementary metal oxide semiconductor (PCMOS) is a semiconductor manufacturing technology invented by Pr. Krishna Palem of Rice University and Director of NTU's Institute for Sustainable Nano-electronics (ISNE). The technology hopes to compete against current CMOS technology. PCMOS-based system on a chip architecture was shown to be gains that are as high as a substantial multiplicative factor of 560 when compared to a competing energy-efficient CMOS-based realization on applications based on probabilistic algorithms such as hyper-encryption, Bayesian networks, random neural networks and probabilistic cellular automata.

Applications. Probabilistic algorithms such as hyper-encryption, Bayesian networks, random neural networks and probabilistic cellular automata.

Challenge. Extending the technology to real size problems.

C. Stochastic computing

Definition. In stochastic computing, originally proposed by B.R. Gaines in 1969, numbers are represented as a bit stream of "0"s and "1"s, called stochastic bit streams. In theory, stochastic bit streams have an infinite length. However, as in practice they are finite, this introduces an uncertainty in the representation. Also, the stochastic bit streams can be seen as a neuron-like system.

Applications.

- One main advantage of SC is to modify the precision of the computation since it is directly related to the length of the stochastic bit streams. This way, using very short stochastic bit streams allows to achieve fast (sometimes imprecise) computation. As a consequence, Stochastic Computing is mainly used for applications where process variations and soft errors are not a big problem.

- The main interest of stochastic computing is to reduce energy consumption as it allows performing robust and low-cost computing and represent a cheap alternative to conventional processors.

Therefore, the main related applications might be found in edge computing (in particular for remote communication in IoT networks), and more generally in embedded electronic applications (automotive, industrial & robotics, aerospace/defense/security, embedded health & care and telecommunication infrastructures).

Challenge. By design the method is only valid for low-precision computation. It is unclear if it can compete with standard processor when the need for precision increases. However, it may be competitive to sample probability distribution as in this case a single “1” is necessary.

D. Alternative based on physical phenomena

1.1 Random matrix

Definition. In machine-learning, one can also use optics to speedup computing. For example, some specific part of the computing can be done using analog optic devices in order to get a faster computation. Random projections allow to reduce the dimensionality of certain problems. However, it requires a random matrix. Using light going through several layers of scattering material provides random matrices. This technique is currently developed by the start-up LightOn. A first Optical Processing Unit (OPU) has been built. This method provides a very large number of random matrices at high speed.

Applications. Applications are related to machine-learning. It has been shown that filtering the inputs with random matrices (i.e., obtaining a new input by multiplying the input vector by a random matrix), greatly improve the learning performances.

Challenge. As it is just one component of a learning tool chain it as to be included in a bigger system.

1.2 Computing by Observable

Definition. Computing by Observable is a transformative novel area in computing both because of the technology (coherent information transfer by ultrafast laser addressing of engineered quantum dots, QD, arrays), and because of the specialized parallel processing of large amounts of information. The power of the machine is directly related to the number N of quantum states one can address optically: today 3. If n < N^2 then the machine could compute integer functions having their input values in $[0, 1 \cdots 2^{\mathrm{n}}[$. In this case, $2^{2^{\mathrm{n}}}$ is on the same order as the number of binary functions the device can address i.e., almost all binary functions having n bits words as input. For each of these functions, the machine can compute in parallel the result of all its 2^{n} inputs. Optically addressing quantum systems with N reasonably big (100) will allow the making of SIMD machines orders of magnitude faster than the current GPU.

Applications. The device could theoretically implement very powerful SIMD (Single Instruction Multiple Data), machines and could replace GPUs in any application while being several orders of magnitude faster.

Challenge. They are many difficulties building quantum dots allowing a greater number N of addressable quantum states. The architecture of such machine is still in its infancy has well as the software stack necessary to program but it may be a way out as it is in principle more powerful than a conventional machine based on q-bit and could in principle run at room temperature.

1.3 Reservoir computing

Definition. Reservoir computing is a framework for computation that may be viewed as an extension of neural networks. Typically, an input signal is fed into a fixed (random) dynamic system called a reservoir and the dynamics of the reservoir map the input to a higher dimension. Then a simple readout mechanism is trained to read the state of the reservoir and map it to the desired output. The main benefit is that training is performed only at the readout stage and the reservoir is fixed. Liquid-state machines and echo state networks are two major types of reservoir computing.

Applications. These machines facilitate the learning of deep neural networks. They can therefore be used for the same application: classification, time sequence identification, reinforcement learning, etc.

Challenge. The experimental validations of the approach are numerous. It is, however, difficult to justify/predict theoretically the obtained results.

1.4 Using memristor to make inference in DNN

Definition. Memristor crossbars are circuits capable of performing analog matrix-vector multiplications, overcoming the fundamental energy efficiency limitations of digital logic. They have been shown to be effective in special-purpose accelerators for a limited set of neural network applications. A PUMA (Programmable Ultra-efficient Memristor-based Accelerator), is an example of architecture of memristor for Machine-learning Inference.

Applications. The related applications are the one of machine-learning algorithms: image recognition, machine translation, language modeling, etc. For such applications, PUMA achieves up to 2,446× energy and 66× latency improvements for inference compared to state-of-the-art GPUs. Compared to an application-specific memristor-based accelerator, PUMA incurs small energy overheads at similar inference latency and added programmability.

Challenge. While the technology changes, the key issues behind using DNN remains: it is very data intensive with a poor ability to explain /compose the results.

1.5 Spintronics

Definition. Spintronics is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices.

Applications. Bayesian inference is an effective approach for solving statistical learning problems, especially with uncertainty and incompleteness. However, Bayesian inference is a computing-intensive task whose efficiency is physically limited by the bottlenecks of conventional computing platforms. As a consequence, an emerging field of research consists in using a spintronics based stochastic computing approach for efficient Bayesian inference[14].

E. Probabilistic Programming (PP)

Definition. On the digital side, a Bayesian Computing Machine (BCM) has been proposed that can be adapted to several applications, from AI to signal processing, and has been successfully tested on FPGA. Furthermore,

[14] See "Stochastic Spin-Orbit Torque Devices as Elements for Bayesian Inference" (Yong Shim, Shuhan Chen, Abhronil Sengupta & Kaushik Roy), and Spintronics based Bayesian Inference System with Stochastic Computing (SPINBIS, Xiaotao Jia, Jianlei Yang, Pengcheng Dai, Runze Liu, Yiran Chen and Weisheng Zhao).

at transistor level, spintronic can push probabilistic hardware forward due to its intrinsic probabilistic properties. Therefore, the p-bit (probabilistic bit) can be used as a building block for Bayesian inference hardware.

Challenge. Many efforts are currently done to develop better and faster PP languages. Hence, the list of new PP languages is growing. Some examples are Church, Venture and its newer version Gen, Anglican, Pyro, Edwards with a newer version Edwards released in 2018 and Stan. This long list shows the interest and the potential of PP. However, whereas on the software side research is currently moving forward at a fast pace, developments on the hardware side are still slow. Nonetheless, a few concepts have been presented in the literature (Bayesian inference on analog signals which can be seen as a hardware accelerator for belief propagation, etc.).

ii. Synergies with other emerging technologies

The “other approaches” also target emerging algorithms (learning, optimization, inference) and address the post Moore era. They are often linked to new material and use special physical properties as means to solve otherwise difficult (time and energy-wise) problems.

iii. Technology roadmap: Maturity levels and expected impacts by application area

These other approaches remain fields of research. Currently, only the basic principles have been observed, the technology concepts and / or application formulated, and first proof-of-concepts experimented (Technology Readiness Level 1-2-3). No tangible evidence suggests the emergence of a functioning prototype over the next 10 years.

Technology Roadmap - Maturity of the technology at the global scale and by application area

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	Maturity level of the technology											R&D										
N°	Electronic Segment											Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production										
1	Automotive applications											No significant impact										
2	Industrial & robotics applications											No significant impact										
3	Health & Care applications											No significant impact										
4	Aerospace applications											No significant impact										
5	Defense & Security applications											No significant impact										
6	Phones applications											No significant impact										
7	Telecommunications infrastructures applications											No significant impact										
8	PC & data processing applications											No significant impact										
9	Audio & Video applications											No significant impact										
10	Home appliances applications											No significant impact										
N°	Crossed segments											Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production										
1	Data analytics / Big data											No significant impact										
2	Smart home											No significant impact										
3	Smart mobility											No significant impact										
4	Smart energy											No significant impact										
5	Wearables											No significant impact										

At the global scale, each technology is defined through four different stages of maturity.

- **R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6**
- **Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9**
- **Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)**
- **Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies**

The impact of the technology on each end-user segment is described as:

- **A critical impact;**
- **A significant impact;**
- **No significant impact;**

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

Country analysis.

Compare to neuromorphic, quantum and even photonic computing, the effort is relatively small and largely disseminated among many groups and technologies. However, the use of non-standard architectures to process uncertain information has experienced a remarkable growth in recent years and one of these groups may come up with an idea which will really make a difference and by itself justify the investment in all other approaches.

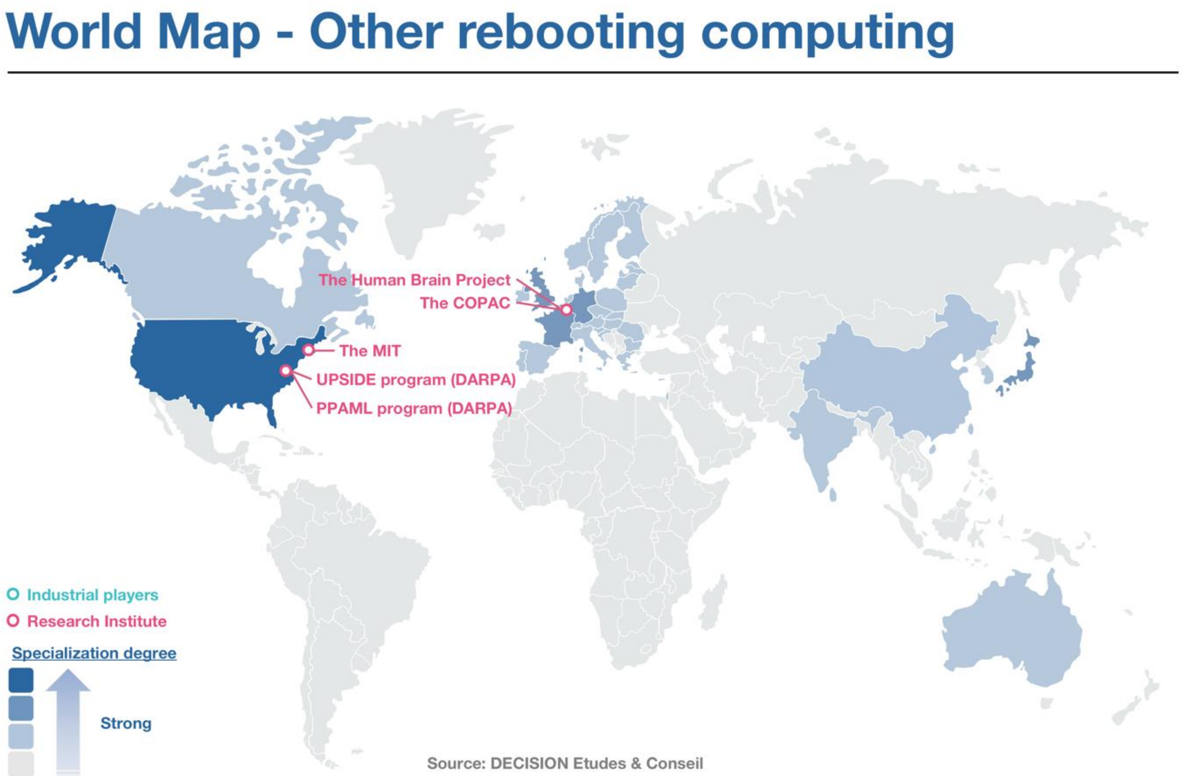
Most of these approaches are taking place in the US and to a less extent in other developed countries (the EU and Japan).

Industrial & research players.

The research is mainly performed by research labs and large industrial players are most of the time mainly involved through technology monitoring. The number of approaches and players involved in other rebooting computing approaches is very large (see the IEEE International Conference on Rebooting Computing) and depends on the specific subfield studied.

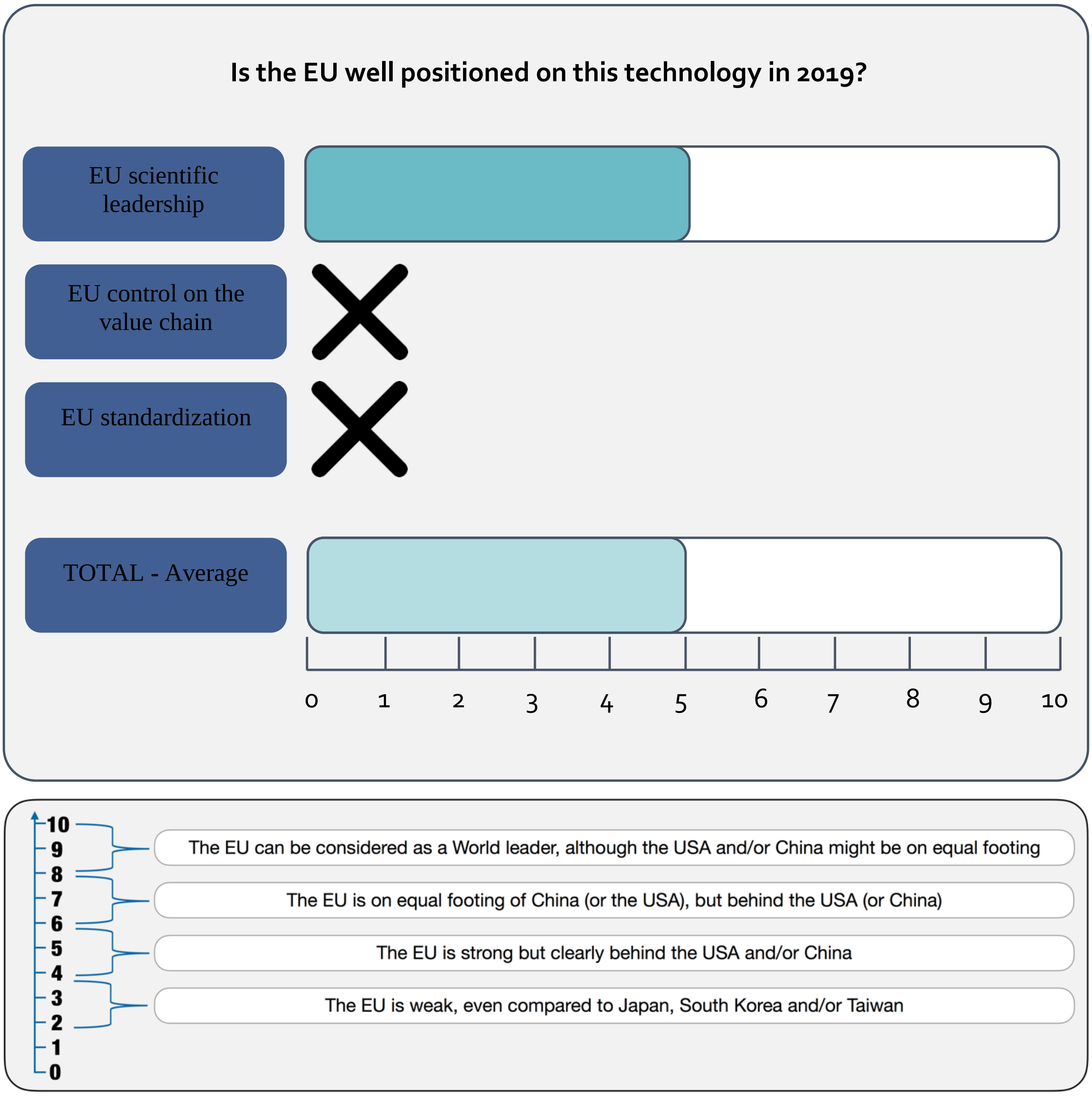
Below are listed some of the most relevant players involved:

- Computing by observable: The European program COPAC (Coherent Optical PArallel Computing);
- Probabilistic programming: Programs of the MIT (the USA), the PPAML program of the DARPA (Probabilistic Programming for Advancing Machine-learning) (the USA), and the company Lyrics which has been acquired by Analog Devices (the USA);
- Crossed projects: The UPSIDE project of the DARPA (Unconventional Processing of Signals for Intelligent Data Exploitation) (the USA), the European projects BAMBI (Bottom-up Approaches to Machines dedicated to Bayesian Inference, ended in 2016), and the Human Brain Project (HBP).



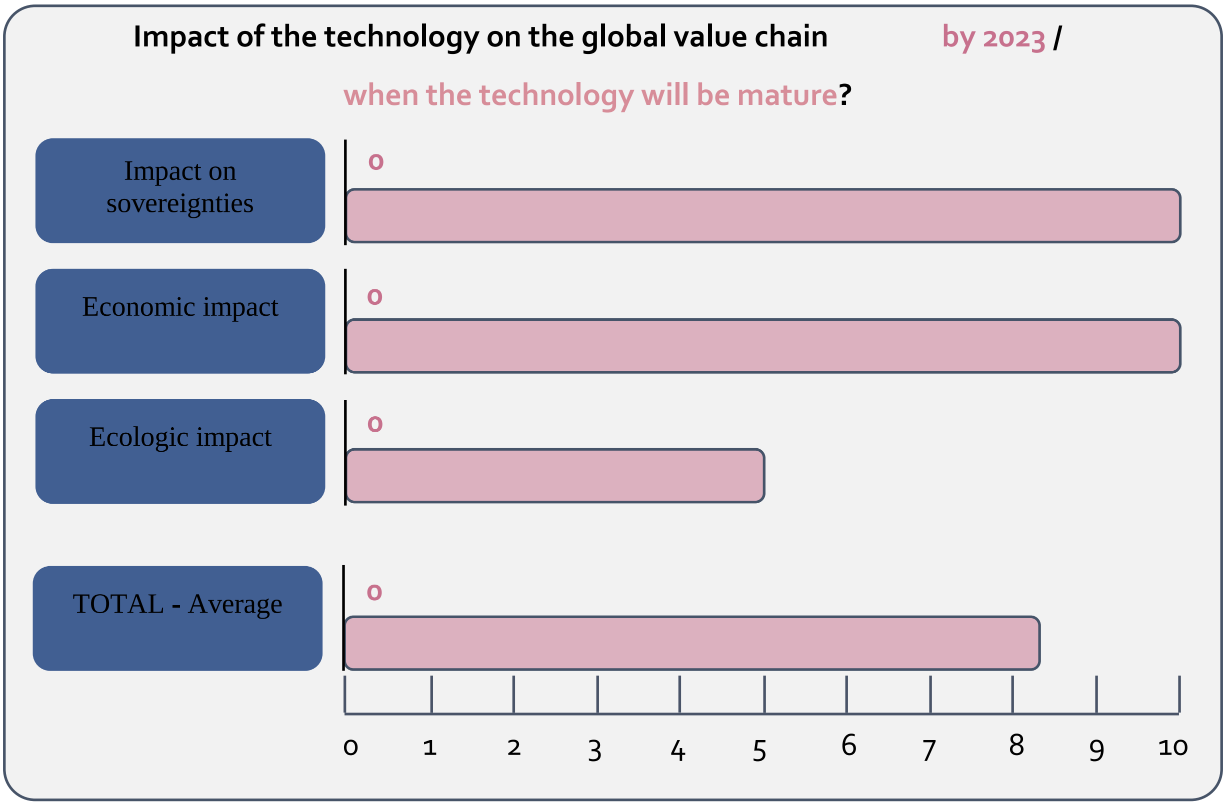
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

Although it depends on the subfields investigated, the USA has in general a clear technological lead on these other approaches in rebooting computing. The EU remains in the race in almost every subfield, in general in second position (well positioned), with Japan, ahead of the rest of the world.

EU control on the value chain

This criterion is irrelevant as this technology is insufficiently mature.

Standard analysis

No standards exist, as this technology is insufficiently mature.

Impact on sovereignties

If these emerging architectures were to be successfully introduced on the markets, they would become the key elements for computing applications requiring high processing capabilities (that is most of emerging computing applications: ADAS, 5G, etc.). A technological security risk could not be excluded if the EU were to use these chips if they were not produced in the EU territory and / or by European players. The rise of protectionism might also lead to a situation where non-European players and / or states might refuse to deliver such products to the EU, placing the EU in a less competitive position towards its competitors. In other words, the impact on sovereignty of quantum computing would be 10/10 in this scenario.

Yet, such a situation is currently highly uncertain and the impact on the EU sovereignty by 2027 is forecasted to be null.

Economic impact

These other approaches in rebooting computing are at the stage of pure R&D, without commercialization currently foreseen. The economic impact of these approaches should therefore remain null until 2023. Yet, by the end of the 2040s, the potential economic impact of some of these approaches might be equivalent to the one of the current More Moore technologies. The situation is similar regarding the ecological impact and the impact on sovereignties of these other approaches.

Ecological impact

The only ecological impact of these emerging architectures might only occur through their increasing energetic yield if they were successfully introduced on the markets.

Yet, in such a situation, a "*rebound effect*" has been observed for any application concerned: the rise of the energetic yield does not lead consumers to maintain their level of consumption while reducing their energy consumption, but rather to raise their level of consumption while maintaining their energy consumption. A typical example is the photo camera. The per-unit energetic cost of a photo in the 1960s was way higher than the current per-unit energetic cost of a photo. Yet, the number of photos taken per person is increasing exponentially since the 1960s.

In other words, the positive ecological impact of these approaches is entirely conditioned to the use made by producers and consumers of these technologies. If efforts are made to maintain the current applications at lower energetic costs, then the impact will be positive. Yet, if these architectures were used to develop ever new and more consuming applications, then the ecological impact will be null.

3. Emerging systems & algorithms

A. Artificial Intelligence: Machine-learning algorithms & AI chips

i. Definition

A. Emerging algorithms for computing applications

Algorithms used to solve complex problems can currently be classified in four main fields:

- **Artificial Intelligence algorithms (machine-learning)**: algorithms based on parameter estimation, usually using gradient backpropagation;
- **Optimization algorithms**: methods to find the best available alternative under given constraints. It includes linear and quadratic optimization with constraints, stochastic optimization, etc. Optimization algorithms are frequently associated with gradient projection methods;
- **Inference algorithms**: algorithms aiming to predict solutions based on evidence (logic inference, Bayesian inference, etc.);
- **Graph Search algorithms**: algorithms visiting (checking and / or updating) each vertex in a graph. Such traversals are classified by the order in which the vertices are visited. Tree traversal is a special case of a graph traversal.

Model-based approaches. Optimization, inference and graph search algorithms can be regrouped under the denomination “Model-based approaches”. The main drawback of model-based approaches is their scalability. For example, in Bayesian Inference the number of stochastic variables is a strong limiting factor. A similar issue occurs for the number of constraints in linear and quadratic programming. The dichotomy between model-based approaches and machine-learning approaches is limited as machine-learning algorithms are often used to solve optimization problems and model-based algorithms are also used in machine-learning algorithms (i.e., parameter estimation).

Many innovative algorithms have been created since decades in optimization, inference and graph search algorithms. There is a great gap between existing algorithms and their exploitation by industrial players in market solutions. Machine-learning is a great example of algorithms that had been developed decades ago without related market solutions until many engineering teams led by industrial players started to work on market solutions using these algorithms.

Finally, the need for data, the ability to explain the result and to debug, the scalability and the energy are axis of improvements for both approaches. Behind these difficulties lies the fundamental notion of complexity (NP-completeness problem), known for years and which is not impeded by any kind of hardware. To overcome these difficulties, stochastic and / or approximate techniques are used to sample the solution space as well gradient descent to refine local solution but as for the learning algorithms the results cannot be certified, and failure may not be explained. Typically, genetic algorithms are capable of inverting any kind of direct models (event very complex ones), but the proof of convergence and completeness are very weak for practical purposes. In the same spirit, gradient-descent methods depend on the starting point and provide no guarantees about the quality of the solution.

In this study, we will focus on the type of algorithms currently having the greatest multidimensional potential: machine-learning algorithms.

B. Machine-learning algorithms

Artificial intelligence (AI) refers to systems that show **cognitive** behaviour: by analyzing their environment they can perform various tasks with some degree of **autonomy** to achieve specific goals.

- An **autonomous** behavior implies an autonomy in the decision-making process, correspond to the capacity to take initiatives in the decision-making process;
- A **cognitive** behavior is a behavior simulating human thought.

Artificial intelligence (AI), also named Software 2.0, is a new way of writing informatics codes. Rather than to write a succession of orders, Software 2.0 consists in assemble modules of artificial intelligence codes in dynamics. The precise operations are learned from data, only the general structure of the program is designed.

Reinforcement learning algorithms, invented in 1913 by the English company DeepMind, are the oldest AI algorithms and are still used for autonomous playing applications in computer games. Yet, these algorithms are currently largely ineffective in the vast majority of the possible applications of AI algorithms as they require permanent interaction with an open environment to operate the learning process, which prevents their use in automotive applications, aeronautics applications, defense applications, etc. Synergies yet exist between reinforcement learning algorithms and machine-learning algorithms as reinforcement learning algorithms are integrated into machine-learning algorithms in emerging fields (Deep Reinforcement Learning (DRL), Q-learning, etc.).

Machine-learning. This chapter focuses on machine-learning algorithms, the most widely used type of AI algorithms, characterized by the use of Artificial Neural Networks (ANN): a computational model based on the structure and functions of biological neural networks where the information that flows through the network affects the structure of the ANN because as neural networks changes- or learn, in a sense - based on that input and output.

Deep learning. Machine-learning includes deep learning, a subset of machine-learning characterized by multi-layer ANN. Finally, the most widely used deep learning algorithms are currently **convolutional neural networks (CNN)** algorithms: a type of network of acyclic artificial neurons (feed-forward), in which the connection pattern between neurons is inspired by animals' visual cortex. The operations consist of a multilayer stack of perceptrons, the purpose of which is to pretreat small amounts of information). The reliability rate of the responses obtained by convolutional neural networks depends on the number of neuron layers they contain, and this number was close to 50-100 layers by the end of 2018.

C. AI chips

AI chips. AI chips are chips specifically designed to run/accelerate artificial intelligence applications, especially artificial neural networks and machine-learning. AI chips can be Cloud-based or Edge-based.

The development of edge AI. A consensus is emerging that the main risk assorted to AI algorithms is power constraints that will be very high and could be a barrier to AI adoption, generating a need for the adoption of a solution which substantially reduce the power draw of high-consuming AI chips and the required bandwidth of communication networks.

A solution is AI at the edge. Edge AI corresponds to edge-based machine-learning chipsets (as opposed to cloud-based AI chipsets, that is to say AI chipsets designed to run cloud-based machine-learning algorithms). Edge AI consist in System-on-a-chip (SoC) accelerators, application-specific integrated circuits (ASICs), Graphic Processing Units (GPUs), Central Processing Units (CPUs), FPGAs, etc.

Regarding edge AI dedicated to IoT applications, it is possible to run inference models on microcontrollers and relatively low-end chips, but most machine-learning and decision functions need to interface with additional (Edge) devices that segregate the data and manage huge data flows with cloud infrastructure for training and model adjustment purposes. Such interface device can be based on dedicated MPU, GPUs, FPGAs, ASICs, SoC or dedicated Neural Networks Units (or any combination of the above) configurations, as well as combinations of GPUs. AI inference also often requires the help of hardware accelerators, designed to help resource-constrained x86-based devices to process large volumes of image or audio data.

AI at the edge is aimed at bringing the following advantages:

- Scalability across a vast number of edge devices, avoiding high-bandwidth towards remote clouds;
- Fast local decision-making processes;
- Lower power consumption at the edge (ultra-low power consumption for endpoint devices);
- Security of the data retained on the device;
- Low cost through inexpensive chips, minimizing data center and transport.

As a counterpart, AI at the edge suffers two possible drawbacks:

- Upgradability, keeping up with firmware updates and new learning capabilities;
- Feedback data will not be available or as frequent as in the Cloud.

ii. Synergies with other emerging technologies

The major interest of emerging algorithms is the low R&D cost required to adapt them into architectures and / or components. Emerging architectures and above all emerging components (biochips, etc.), requires on the contrary large expenses to be combined with architectures and algorithms in order to develop functioning applications. Indeed, an in-depth knowledge of the functioning of the new component / architecture is required from the entire engineering team that would be in charge of developing a functional applicative system from an emerging component and / or architecture.

Below are the main synergies between AI algorithms and other innovation fields (mainly emerging architectures):

Supercomputing. High-performance-computing can accelerate both machine-learning-based algorithm and model-based algorithms. NVIDIA is offering parallel Von Neumann machines (GPU), which are tailored for AI-related problems and will release in the coming months a low-power GPU for that purpose.

Neuromorphic computing. Neuromorphic computing, also named bio-inspired architectures, is closely related to machine-learning algorithms. For example, the SpiNNaker project (Spiking Neural Network Architecture) was initially developed to simulate part of the human brain but may be used to implement optimization algorithms as well as machine-learning algorithm. The TrueNorth is a full-scale project related to bio-inspired computing which includes the design of specialized hardware as well as programming languages. A number of applications have been selected to demonstrate the effectiveness of the approach of TrueNorth which are all related to AI: Speaker recognition, Sequence prediction, Digit recognition, Collision avoidance, Optical flow design, etc.

Quantum Computing. Quantum computing includes quantum architectures and quantum algorithms that can be emulated either on quantum architectures (see IBM Q System One™), or on standard computers. Quantum computing will also both address mode-based and machine-learning algorithms. Indeed, quantum architectures have been initially developed for machine-learning and optimization exploitation.

Other approaches in rebooting computing. Other approaches in rebooting computing also both address model-based and machine-learning algorithms. The searcher Ben Vigoda was the first to initiate, in 2003, the design of non-conventional machine dedicated to Bayesian inference while representing probability distributions on binary variables with analog electrical values. Ben Vigoda concentrated its efforts on a well-known algorithm for exact inference: the message passing algorithm and devised the necessary analog components to perform digitally the message passing in order to obtain the circuit performing the desired inference. The work of Ben Vigoda led to the creation of Lyrics which was bought by Analog Device in 2010. Furthermore, a lot of memristors are nowadays exploited through DNNs. For example, HP has developed an analog solution based on memristor neural networks aimed to be combined with model-based or machine-learning algorithms for artificial intelligence applications with high speed-energy efficiency.

Advanced packaging. Edge AI will be closely intertwined with More than More and Advanced packaging (SIP), as very strong operational constraints on the edge computing devices will require strong bandwidth, extremely low latency and powerful inference capabilities.

iii. Technology roadmap: Maturity levels and expected impacts by application area

A. AI algorithms

Most of the machine-learning algorithms are using back propagation, a learning technique which has been extended since the Perceptron (1960) to a point where it shows remarkable performance. In other words, the principles underlying machine-learning algorithms are known for decades (for instance, the machine-learning algorithms that enable face recognition and self-driving vehicles were invented in the late 1990s). Yet, the effectiveness of these algorithms has been enhanced by specialized hardware initially designed for graphical applications such as video games but now specially developed for that purpose.

The main uses of machine algorithms currently known are:

- **Image analysis**. Recognizing objects in images and locating these objects in real time;
- **Voice analysis**. Voice recognition and voice translation into words;
- **Text analysis**. Classification of texts, archiving, segmentation by keywords;
- **Robotics / Manipulation**;
- **Physics**. High-energy physics, astrophysics;
- **Environmental protection**;
- **Basic chatbots**: play music, information distributor (weather, etc.).

It implies significant market opportunities in the 8 electronic end-user segments out of 10:

- **Mobile phones and PC markets** (production of captions for photos, information distributor, etc.), accounting for €659 B in 2023. Furthermore, the mobile applications market should also be impacted and is expected to reach €260 B in 2023;
- **Audio & Video electronics**. Through autonomous gaming, music chatbots, etc. The video games market is expected to reach nearly €140 B in 2023 (game console sales and video games sales on all media). The chatbot market is expected to reach €0.8 B by 2023;
- **Automotive electronics**. Through autonomous driving (ADAS, accounting for €57 B in 2023), and smart & predictive applications for automotive infotainment (accounting for €156 B in 2023);
- **Defense & Security electronics**. Notably through facial recognition. Defense & Security applications expected to be significantly impacted by AI algorithms developments should account for €20 B in 2023;
- **Industrial & robotics** (autonomous trains, robotics handling, etc.). Industrial electronics applications expected to be significantly impacted by AI algorithms developments should account for €280 B in 2023;
- **Health & Care services** (radiology, dermatology, cancer screening, electroencephalography). Yet, health & care diagnose services should account for €200 B in 2023. The pharmaceutical market should reach €1,080 B by 2023.

The current limitation of AI algorithms known so far are the following:

- **The possibility to deceive algorithms with specially designed data**;
- **The huge amount of data necessary for training algorithms** (a problem that only the GAFAM and the BATX can solve in their specific end-user segments thanks to the cost-free exploitation of the users' data);
- **The high energy consumption of AI algorithms**. Having a base line solution for any solution based on deep learner is therefore certainly very desirable as a simple solution may show similar result for much less hardware. For example, the deep learner algorithms used to recognize digit based on the MNIST Dataset are certainly very efficient but requires much more hardware that alternative solutions which may work almost as well on the MNIST and may be better when switching the database used for testing. As a consequence, many efforts are currently undertaken to develop low-power hardware for CNN (NVIDIA, etc.);

- **The difficulty to certify the performances of algorithms**. This limitation is particularly strong as a large part of AI algorithms' possible application requires very strict levels of certification: autonomous driving (that is ADAS level 4 and 5), but also most of the defense application (missile guidance, robot soldiers, etc.), security application (when a strong identification is required), and health & care embedded applications (smart prosthetics, etc.). As a consequence, AI algorithms cannot be used in such applications and no technical solution currently exist to solve this issue. It is also uncertain that AI algorithms might be used in defense applications for ethical problems it generates;
- **The software using AI algorithms can be corrupted by cyber-attacks**, requiring human monitoring on the systems and therefore preventing real and full artificial control;
- **AI algorithms cannot perform**:
  - Machine with common sense;
  - Intelligent personal assistants / Smart chatbot;
  - Household robots;
  - Agile and dexterous robots;
  - Artificial General Intelligence (AGI).

The next development steps of AI algorithms are:

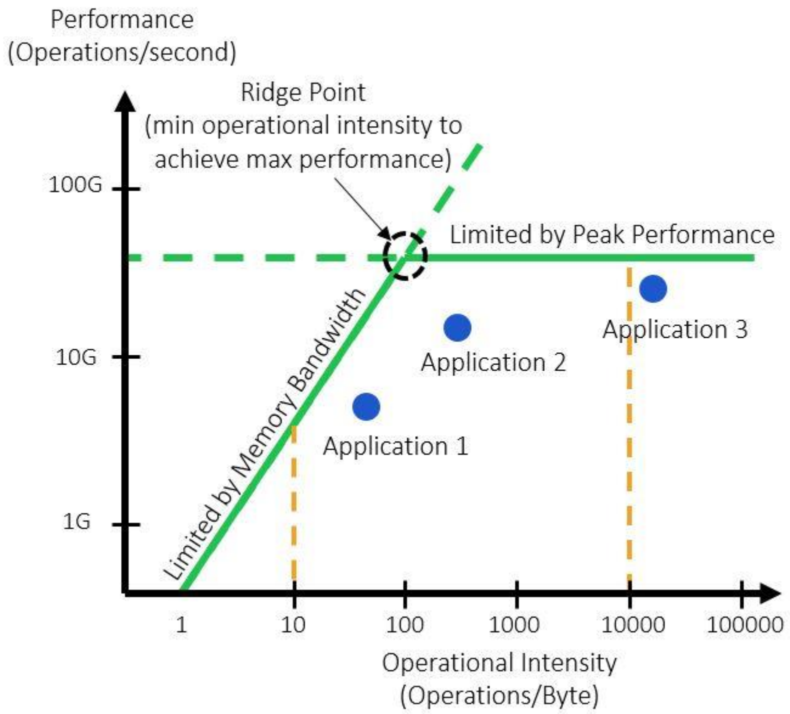
- **The development of unsupervised learning algorithms**[15]. The move towards **self-supervised learning** algorithms, such as adversarial training algorithms where two supervised learning algorithms are used in parallel. The first one tries to define the consistent field of possibilities that are "right" as opposed to the "wrong" field of possibilities. The second one tries to produce outputs that the first algorithms will not succeed to classify as wrong or right;
- **The improvement of Convolutional Neural Network (CNN) algorithms**, through:
  - The rise of the number of layers used;
  - The improvement of the way to tag manually data that serves as input data for machine-learning. The solution that appears to be by far the most effective is the "Transfer learning", corresponding to the use of user data as input data. Yet, this requires the ability to capture and use databases for this purpose: gigantic user data. The proper functioning of these artificial intelligence algorithms is therefore based on the ability to capture and exploit large user databases on a global scale (GAFAM, BATX).

B. Edge AI

In addition to the above considerations on algorithms, Edge AI efficiency is very influenced by the memory architecture of the edge computing node. A well-known analysis tool, the Roofline Model, can be used to show how well applications are able to make use of the full potential of the underlying hardware's memory bandwidth and processing power. This model, illustrated on the picture below, explains how the (Operations per Byte, Operations per second), characteristic of an edge computing node, are limiting the embedded AI algorithms. Two architectural limits are illustrated by the green lines. The first is the sloping line, which shows the limits imposed by memory bandwidth. The second is the horizontal line, which shows limits imposed by the computational performance of the hardware. Together, these lines form a roofline shape, hence the name of the model.

[15] Also named self-supervised learning algorithms.

The Roofline model – edge computing



Source: Steven Woo, Rambus

Applications running on architectures with insufficient memory bandwidth or which perform few operations per byte of data will typically fall at or below the sloping portion of the roofline. Applications with sufficient memory bandwidth or that have high operational intensity will typically fall at or below the horizontal part of the roofline. In the graph plotted above, applications that have operational intensity = 10 are memory-bound, while applications with operational intensity = 10 000 are compute-bound.

This Roof effect has to be taken in account for the various kinds of edge devices to be considered by 2025 and where operational requirements for the various types of edge platforms can be summarized as follows:

Power Class	Processing Class	Chip Internal SRAM	Average
P < 100mW	5 – 50 Gops/s	<40MB	50 - 500Gops/W
100 mW < P < 1W	0,5 – 5 Tops/s	40-100MB	5 Tops/W
1 W < P < 10W	10-20 Tops/s	200MB	2-10 Tops/W

Source: DECISION Etudes & Conseil

The required characteristics of edge for AI will include:

- **Capabilities to manage an embedded AI system including infrastructure and applications**
    - Distributed embedded architecture with many IoT components and edge computers;
    - On the shelf modeling environment and EVVQ tools must be selected (EVVQ = ETFOS VGA Video Quality, a video database pattern), associated in order to be able to design and certify AI solutions for critical video applications;
    - Protection of embedded AI Inference engines.
- **Development of (high level) hardware/embedded software bricks**

  - Ultra-Low Power inference accelerators using new non-volatile memories (NVM) and associated software tool for the learning;
  - Very high-speed connections between processor/coprocessor and memories. Possible use of external high-performance memory chips (HMM3 or GDDR6).

- **Types of MCU needed**
  - IoT computing platform with RISC-V "like" based architecture for the front-end processing and low-end edge range and specific accelerators for the back-end processing (neuromorphic chips);
  - Heterogeneous architecture for the mid-range to high-range edge computing using multicores and many cores, GPU and specific accelerators;
  - Programming tools using standard languages.

- **New or improved software tools**
  - Formal tools for the verification of critical parts;
  - New languages with a high-level of parallelism and explicit taking into account of the time;
  - Optimized code generation tools;
  - Tools to manage simultaneously embedded and AI software.

Technology Roadmap - Maturity of AI algorithms at the global scale and penetration rate of AI applications by segment

<table>
<tr><th colspan="2"></th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><th colspan="2">Technology</th><th colspan="21">Maturity level of the technology</th></tr>
<tr><td colspan="2">Machine learning</td><td colspan="2"></td><td colspan="11">Industrial production</td><td colspan="8">Massive production</td></tr>
<tr><td colspan="2">Self-supervised learning</td><td colspan="4">R&D</td><td colspan="8">Tests & prototyping</td><td colspan="4">Industrial production</td><td colspan="5">Massive production</td></tr>
<tr><th>N°</th><th>Electronic Segment</th><th colspan="21">Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact (through ADAS level 2 & 3, smart infotainment)</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="18">No significant impact</td><td colspan="3">Small impact</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact (through behavioral biometry)</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="2"></td><td colspan="3">Small impact</td><td colspan="7">Medium impact</td><td colspan="9">Critical impact</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="21">No significant impact</td></tr>
<tr><th>N°</th><th>Crossed segments</th><th colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</th></tr>
<tr><td>1</td><td>Data analytics / Big data</td><td colspan="2"></td><td colspan="3">Small impact</td><td colspan="7">Medium impact</td><td colspan="9">Critical impact</td></tr>
<tr><td>2</td><td>Smart home</td><td colspan="5"></td><td colspan="7">Small impact (through personal assistant)</td><td colspan="9">Medium impact (through personal assistant)</td></tr>
<tr><td>3</td><td>Smart mobility</td><td colspan="5">No significant impact</td><td colspan="7">Small impact</td><td colspan="9">Medium impact</td></tr>
<tr><td>4</td><td>Smart energy</td><td colspan="21">No significant impact</td></tr>
<tr><td>5</td><td>Wearables</td><td colspan="21">No significant impact</td></tr>
</table>

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

Impact of Artificial Intelligence (Soft, Hard and associated services) by end-user electronic applications in 2023

	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Medium	Medium	Medium	No	Medium	Critical	Medium	Medium	No	No

Corresponding quantitative impact of Artificial Intelligence (Soft, Hard and associated services) in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
141	281	2 118	4 540	1	1 658	0	140	460	4 540
				Personal assistant	ADAS, automotive infotainment, mobile phones, Professional & consumer PC, Defense & security and & industrial & robotics applications	-	Video games & consoles	Medical diagnoses and mobile applications market	Pharmaceutical market, industrial processes in every manufacturing industry

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of Artificial Intelligence (Soft, Hard and associated services) in 2023

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. Main countries and regions

The leading countries in AI are the ones that control the largest datasets required to trained machine-learning algorithms: the USA and China. Since the mid 2000s, China is progressively outreaching the USA's position according to five different criteria (AI market, AI private research expenses, AI research paper published, AI patent published and AI skilled workforce).

Over the 2021-2027 and under the Horizon Europe program, the EU is planning to invest €20 B per year in artificial intelligence (of which €1.4 B public findings). In comparison, China announced in its "National AI Development Plan" published in 2017 its willingness to invest €49.2 B per year over the 2020-2025 period. Finally, the USA should also invest around €50 B per year in artificial intelligence over the 2020-2025 period (of which €4-5 B public findings through 346 different budget lines).

1. **AI markets**.

The diagram below represents AI markets in 2018 with forecasts for 2023. AI markets are the location where AI soft and associated hard & services are sold. They are B to C markets such as for personal assistants, but most of the time B to B markets, as AI applications are embedded into Cyber-Physical Systems (such as Mobileye's autonomous driving applications).

AI markets are largely dominated by the USA and China (accounting for nearly 60% of the global market both in 2018 and 2023). The European position is progressively being challenged by Other Asia & Pacific (including India, investing a lot in AI), and the Rest of the World (including Israel).

AI market (Soft and associated hard & services)

	Market - 2018		Market - 2023		CAGR 2018-2023
Region	B €	%	B €	%	
China	9	25 %	44	31 %	38 %
North America	11	32 %	38	27 %	28 %
Europe	7	21 %	24	17 %	26 %
Other Asia & Pacific	2	7 %	17	12 %	48 %
Rest of the World	2	5 %	9	6 %	41 %
Japan	4	10 %	9	6 %	20 %
TOTAL	35	100 %	141	100 %	32 %

Content: AI algorithms development, CPS mainly based on AI applications such as personal assistants, ADAS applications, and associated hardware using CPU, GPU, FPGA, ASIC, etc.

Source: DECISION Études & Conseil

2. **AI private research expenses**.

The diagram below represents AI private R&D expenses in 2018 with forecasts for 2023. AI private research expenses are research expenses from private companies dedicated to the development of AI soft and associated hard & services. These expenses include a significant amount of public funding as public programs are often supporting private R&D expenses.

AI private research expenses are also largely dominated by the USA and China (accounting for more than 60% of the global market both in 2018 and 2023). The European position is progressively being challenged by Other Asia & Pacific (including India, investing a lot in AI), and the Rest of the World (including Israel).

As AI markets are expanding, they progressively catch up with AI private R&D expenses. They are supposed to outreach AI private expenses by 2025-2027.

AI private R&D expenses (Soft and associated hard & services) *

	R&D Expense - 2018		R&D Expense - 2023		CAGR 2018-2023
Region	B €	%	B €	%	
North America	32	41 %	65	37 %	15 %
China	18	23 %	47	26 %	22 %
Europe	12	15 %	24	13 %	15 %
Other Asia & Pacific	5	6 %	17	9 %	27 %
Rest of the World	5	6 %	14	8 %	23 %
Japan	7	9 %	12	7 %	11 %
TOTAL	79	100 %	179	100 %	18 %

*Includes public funding of private R&D investments

Source: DECISION Études & Conseil, estimates based on the TOP 30 companies' annual reports and analyses, consistent with inputs from several reports (from Roland Berger, McKinsey, "USA-China-Eu plans for AI: where do we stand?", Digital Transformation Monitor, January 2018)

3. **AI research paper published**.

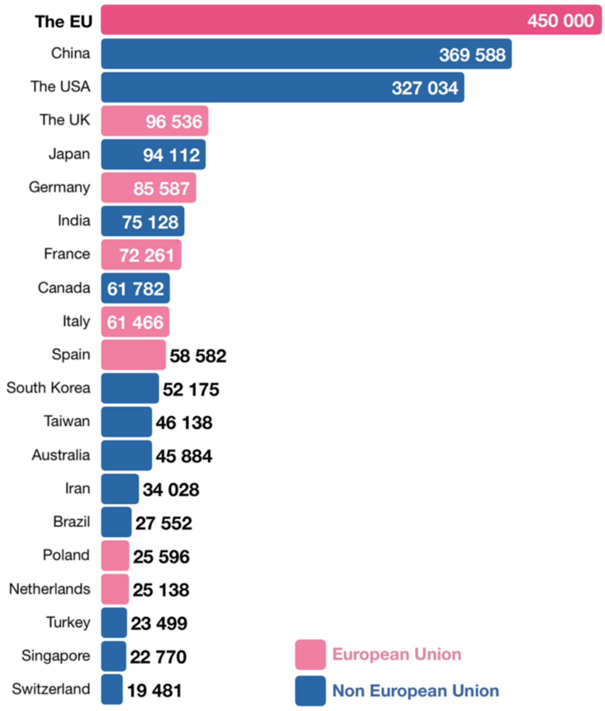
The diagram below ranks the TOP 20 countries in the World according to the sum of the AI-related research papers published over the past twenty years (1997-2017).

The EU ranks first, ahead of China (2nd), and the USA (3rd). Japan, in fourth position, is significantly below its three competitors. Yet, in 2017, China ranks first in terms of AI-related research papers annually published, ahead of the USA (2nd), and the EU (3rd). Indeed, the USA and China have outreached the EU in 2005, and China later outreached the USA in 2006[16].

[16] According to the SCImago Journal Rank (SJR) indicator (another indicator of AI-related research paper published), China is also the first countries in the World in terms of AI-related papers annually published ahead of the USA in 2018, but only overtook the USA's position in 2016.

TOP 20 countries/regions in terms of AI-related research papers published over the 1997-2017period

N°	Country	Number of AI-related research papers published over the period 1997-2017	CAGR 2012-2017 (%)
1	China	369 588	7 %
2	The USA	327 034	6 %
3	The UK	96 536	8 %
4	Japan	94 112	2 %
5	Germany	85 587	4 %
6	India	75 128	16 %
7	France	72 261	5 %
8	Canada	61 782	7 %
9	Italy	61 466	-
10	Spain	58 582	-
11	South Korea	52 175	-
12	Taiwan	46 138	-
13	Australia	45 884	-
14	Iran	34 028	-
15	Brazil	27 552	-
16	Poland	25 596	-
17	Netherlands	25 138	-
18	Turkey	23 499	-
19	Singapore	22 770	-
20	Switzerland	19 481	-



Source: The report "China AI Development 2018", published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University[17], DECISION Études & Conseil

4. **AI research patent published**.

According to the same study, China, the USA and Japan have been the top three countries in terms of AI-related patents published over the 1997-2017 period, accounting for 74% of the total published patents. Since the 2000s, the number of AI-related patents published by the USA and China is growing significantly faster than in the other countries, to the extent that for the year 2017[18], the USA and China largely outreached Japan and ranks respectively first and second. Furthermore, from 2013 to 2017, the number of AI-related patents published grew even faster in China than in the USA, to the extent that the number of Chinese AI-related patents published in 2017 represented 87% of the number of the USA AI-related patents (compared to 68% in 2013).

[17] The dataset for analysis of AI research in this report is mainly based on data retrieved from Clarivate Analytics' Web of Science database using a list of AI keywords provided by experts which includes not only generic AI terms like "Artificial Intelligence" and "Machine Learning" but also specific AI technology categories such as "Natural Language Processing", "Computer Vision", "Facial Recognition", "Image Recognition", "Speech Recognition", "Semantic Search", "Semantic Web", "Text Analytics", "Virtual Assistant", "Visual Search", "Predictive Analytics" and "Intelligent System" and additional author keywords of the highly cited papers identified by the search using the provided list of AI keywords and author keywords of the references of the highly cited papers, with the author keywords used being validated by experts. As this part focuses on AI technology development, the search is limited to the three science-related databases of the Web of Science Core Collection: Science Citation Index Expanded (SCIE); Conference Proceedings Citation Index-Science; and Book Citation Index-Science. As academic conferences are also an important part of AI research activity, the dataset draws on proceeding papers from representative academic conferences on AI. In addition, it includes papers in the "Computer Science, Artificial Intelligence" category of Web of Science. The dataset, with data from the abovementioned three sources combined, consists of a total of 1,875,809 qualifying papers (data retrieved on April 26, 2018, with no time or document type restriction).

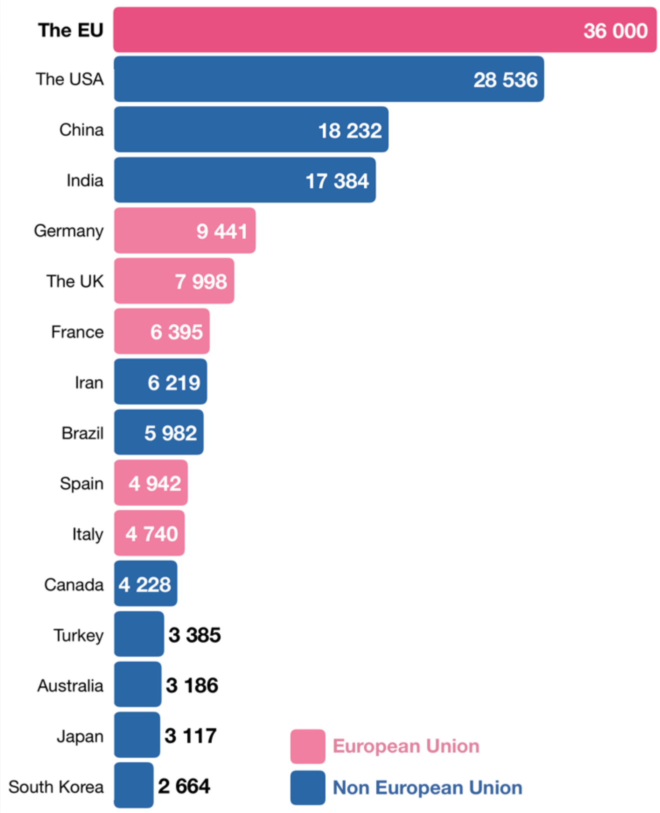
[18] According to the European Patent Office.

5. **AI skilled workforce**.

The report "China AI Development 2018", published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University, provides a mapping of the skilled AI workforce in the World (referred as AI Talent[19]).

Number of AI skilled workforce by country in late 2017

N°	Country	Number of AI skilled workforce	(% total)
1	The USA	28 536	14 %
2	China	18 232	9 %
3	India	17 384	8 %
4	Germany	9 441	5 %
5	The UK	7 998	4 %
6	France	6 395	3 %
7	Iran	6 219	3 %
8	Brazil	5 982	3 %
9	Spain	4 942	2 %
10	Italy	4 740	2 %
11	Canada	4 228	2 %
12	Turkey	3 385	2 %
13	Australia	3 186	2 %
14	Japan	3 117	2 %
15	South Korea	2 664	1 %
	World	204 575	100 %



Source: The report "China AI Development 2018", published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University, DECISION Études & Conseil

The EU remains in first position in 2017 in terms AI skilled workforce, ahead of China and the USA.

B. Main research centers

The table below ranks the TOP 30 research institutes that published the larger numbers of AI-related research papers during the 1997-2017 period.

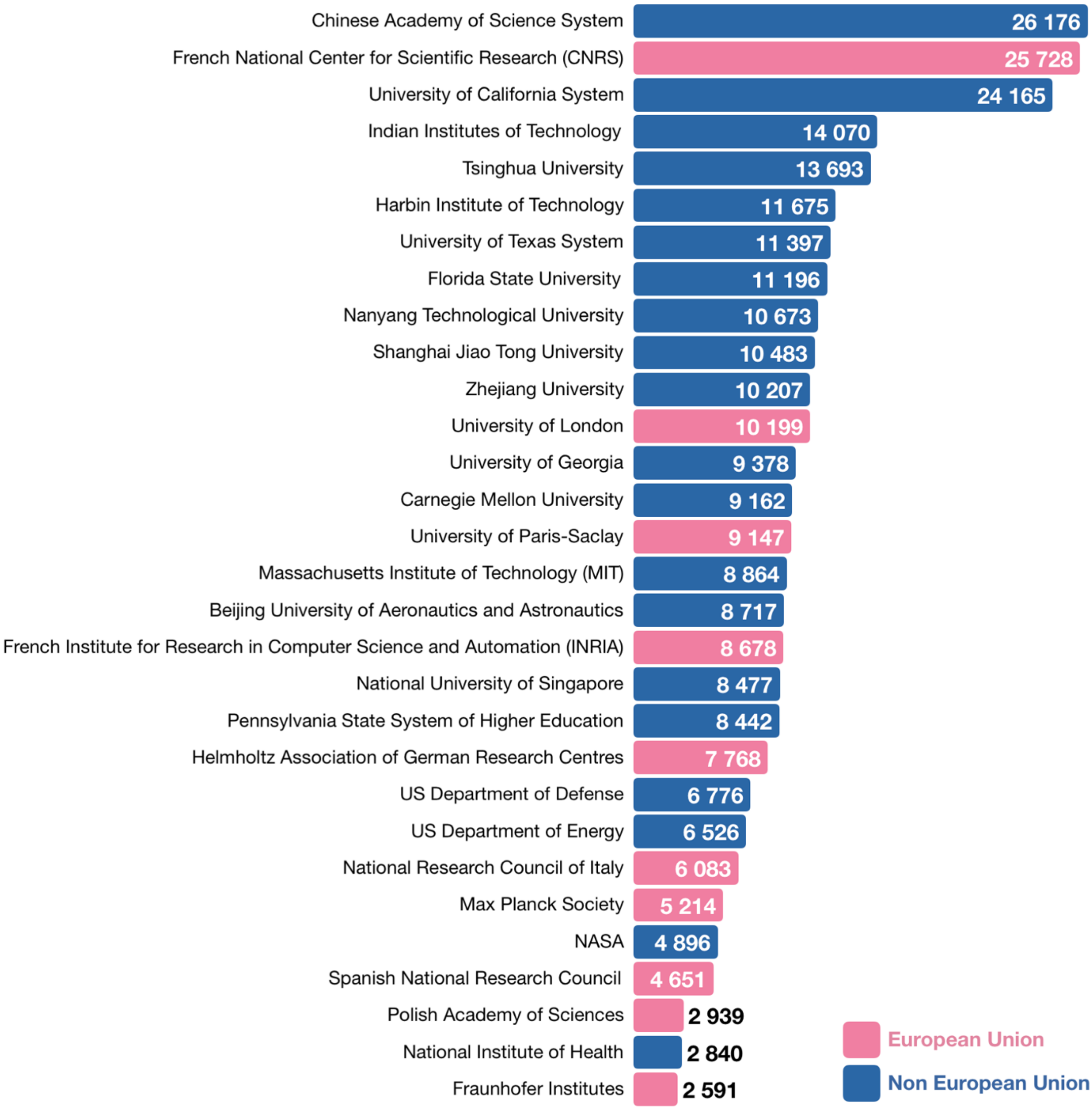
[19] AI talents are researchers possessed of creative research ability and technical expertise in their research area and active in AI research with innovative outcomes. Innovative outcomes refer to issued patents and / or published English papers. "Active" refers to the creation of innovative outcomes in the last ten years.

TOP 30 research players in terms of AI-related research papers published (1997-2017)

N°	Country	Nationality	Number of AI-related research papers published over the period 1997-2017
1	Chinese Academy of Science System	China	26 176
2	French National Center for Scientific Research (CNRS)	France	25 728
3	University of California System	The USA	24 165
4	Indian Institutes of Technology	India	14 070
5	Tsinghua University	China	13 693
6	Harbin Institute of Technology	China	11 675
7	University of Texas System	The USA	11 397
8	Florida State University	The USA	11 196
9	Nanyang Technological University	Singapore	10 673
10	Shanghai Jiao Tong University	China	10 483
11	Zhejiang University	China	10 207
12	University of London	The UK	10 199
13	University of Georgia	The USA	9 378
14	Carnegie Mellon University	The USA	9 162
15	University of Paris-Saclay	France	9 147
16	Massachusetts Institute of Technology (MIT)	The USA	8 864
17	Beijing University of Aeronautics and Astronautics	China	8 717
18	French Institute for Research in Computer Science and Automation (INRIA)	France	8 678
19	National University of Singapore	Singapore	8 477
20	Pennsylvania State System of Higher Education	The USA	8 442
21	Helmholtz Association of German Research Centres	Germany	7 768
22	US Department of Defense	The USA	6 776
23	US Department of Energy	The USA	6 526
24	National Research Council of Italy	Italy	6 083
25	Max Planck Society	Germany	5 214
26	NASA	The USA	4 896
27	Spanish National Research Council	Spain	4 651
28	Polish Academy of Sciences	Poland	2 939
29	National Institute of Health	The USA	2 840
30	Fraunhofer Institutes	Germany	2 591

Source: The report “China AI Development 2018”, published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University, DECISION Études & Conseil

TOP 30 research players in terms of AI-related research papers published (1997-2017)



Source: The report "China AI Development 2018", published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University, DECISION Études & Conseil

C. Main industry players

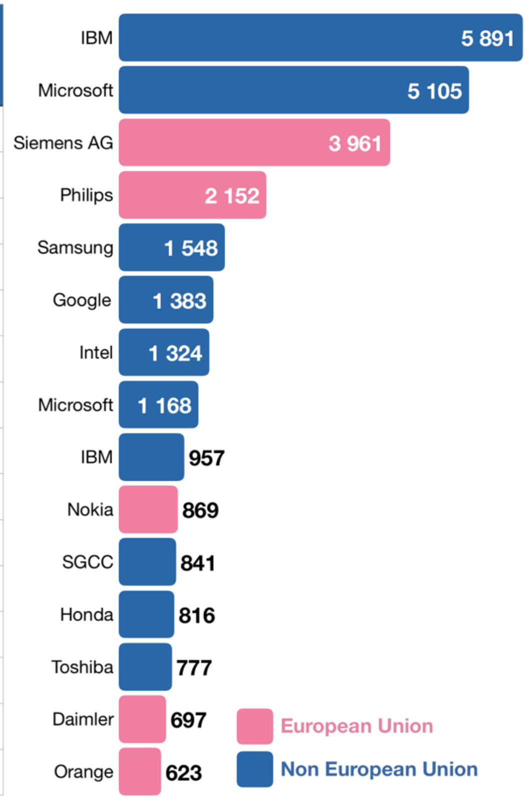
The major players in AI are the players that have access to the largest datasets required to trained machine-learning algorithms. As a consequence, the leaders are:

- **American**. The GAFAMI in the first place (Google, Amazon, Facebook, Apple, Microsoft and IBM), and software companies (Oracle, SAP, Salesforce, etc.), as well as IT integrators to a lesser extent;
- **Chinese**. The BATX (Baidu, Alibaba, Tencent, Xiaomi), and other players having access to large datasets such as iFlytek, an image and voice recognition company having access to public Chinese biometric data (the largest biometric data in volume in the world). China indeed represents a closed internal market of nearly 800 million Internet users in 2018 and an ultra-developed mobile market.

The table below ranks the TOP 15 industrial players that published the larger numbers of AI-related research papers during the 1997-2017 period.

TOP 15 industrial players in terms of AI-related research papers published over the 1997-2017 period

N°	Country	Nationality	Number of AI-related research papers published over the period 1997-2017
1	Microsoft	The USA	5 891
2	IBM	The USA	5 105
3	Siemens AG	Germany	3 961
4	Philips	Netherlands	2 152
5	Samsung	South Korea	1 548
6	Google	The USA	1 383
7	Intel	The USA	1 324
8	General Electric	The USA	1 168
9	NEC Corporation	Japan	957
10	Nokia	Finland	869
11	SGCC	China	841
12	Honda	Japan	816
13	Toshiba	Japan	777
14	Daimler	Germany	697
15	Orange	France	623



Source: The report "China AI Development 2018", published in July 2018 by the China Institute for Science and Technology Policy at Tsinghua University, DECISION Études & Conseil

Finally, the table below shows the TOP 20 companies in 2018 by machine-learning R&D expenses. Amazon, Facebook, Huawei, Alibaba, Apple and Qualcomm are not listed in the TOP 15 industrial players in terms of total AI-related research papers over the 1997-2017 but are among the TOP companies worldwide investing in AI in 2018. These companies recently started to invest a lot in AI R&D.

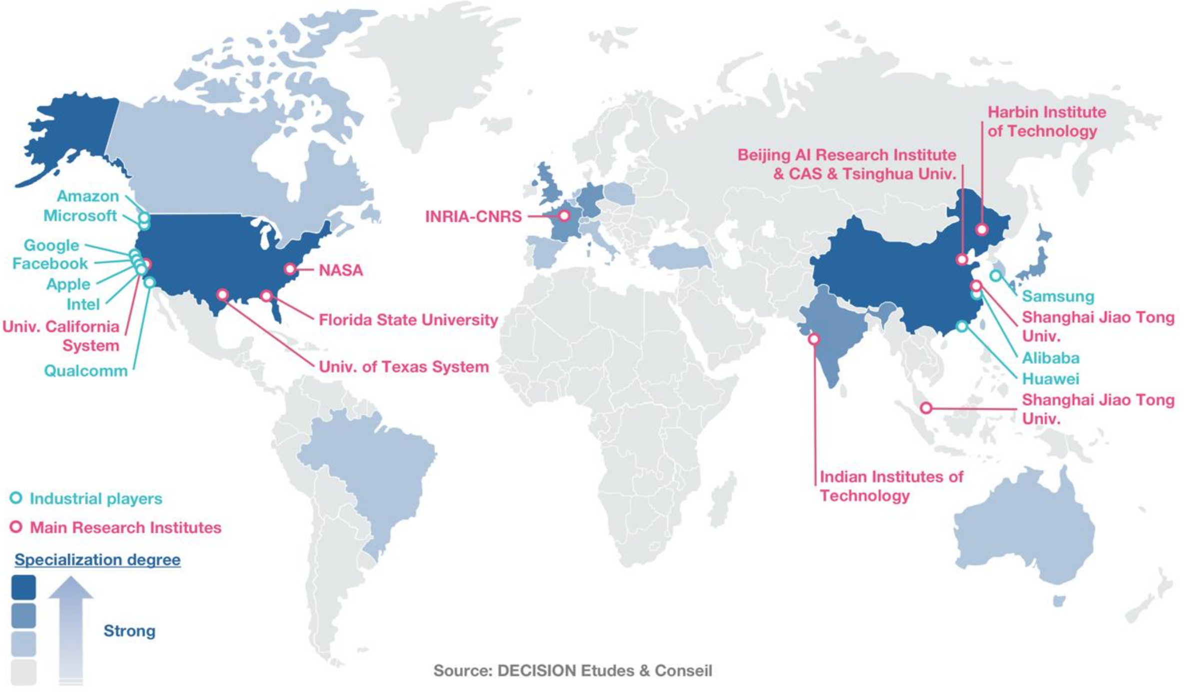
TOP 10 Companies by Machine-learning R&D expenses in 2018 (Soft and associated hard & services) *

N°	Company	Country	R&D expenses (M€)	R&D employees
1	Amazon	The USA	3 840	4 804
2	Samsung	South Korea	3 613	4 241
3	Google	The USA	2 859	2 062
4	Facebook	The USA	2 164	1 088
5	Microsoft	The USA	2 042	2 036
6	Huawei	China	1 895	2 845
7	Alibaba	China	1 286	1 798
8	Apple	The USA	1 186	849
9	Intel	The USA	935	1 191
10	Qualcomm	The USA	852	1 114

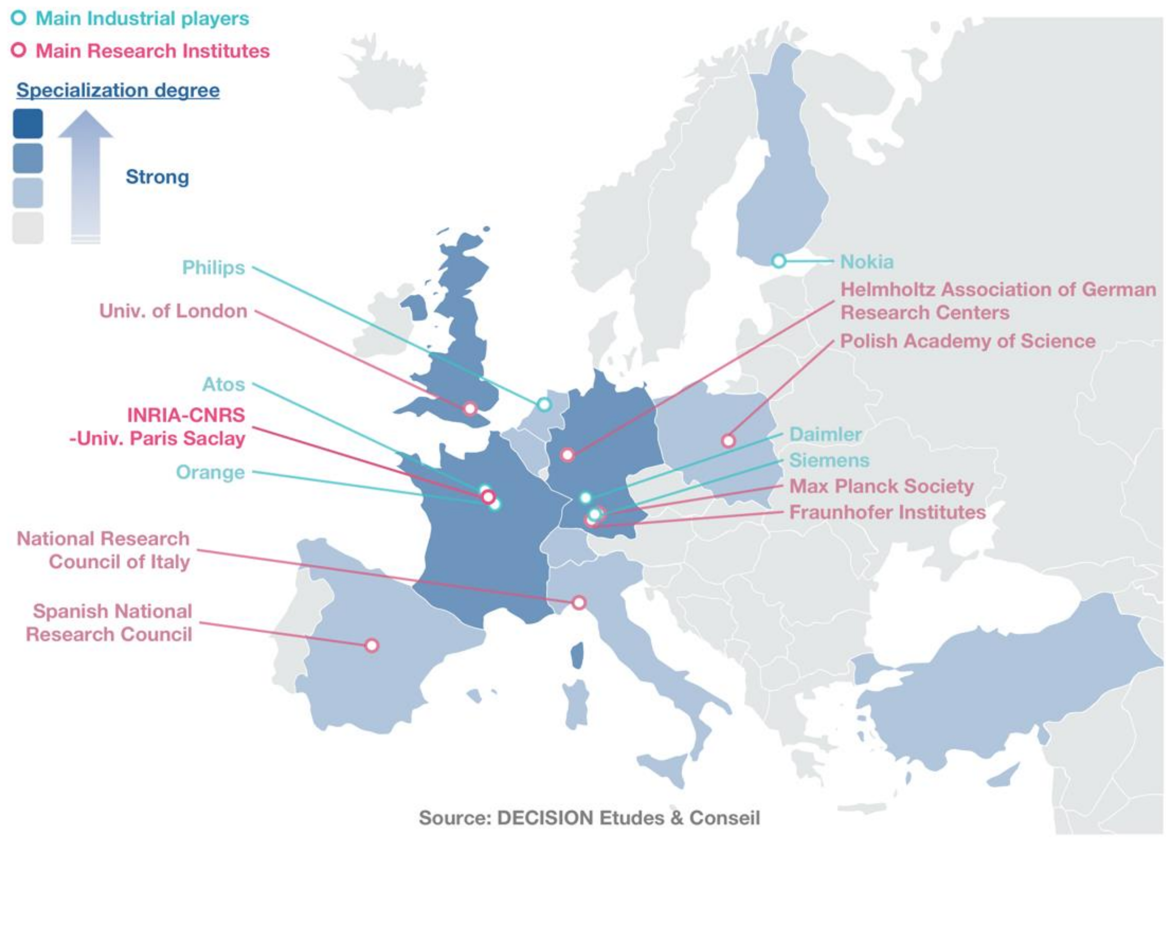
*Includes public funding of private R&D investments

Source: DECISION Études & Conseil, based on companies' analyses

World Map - AI algorithms



Europe Map - AI algorithms



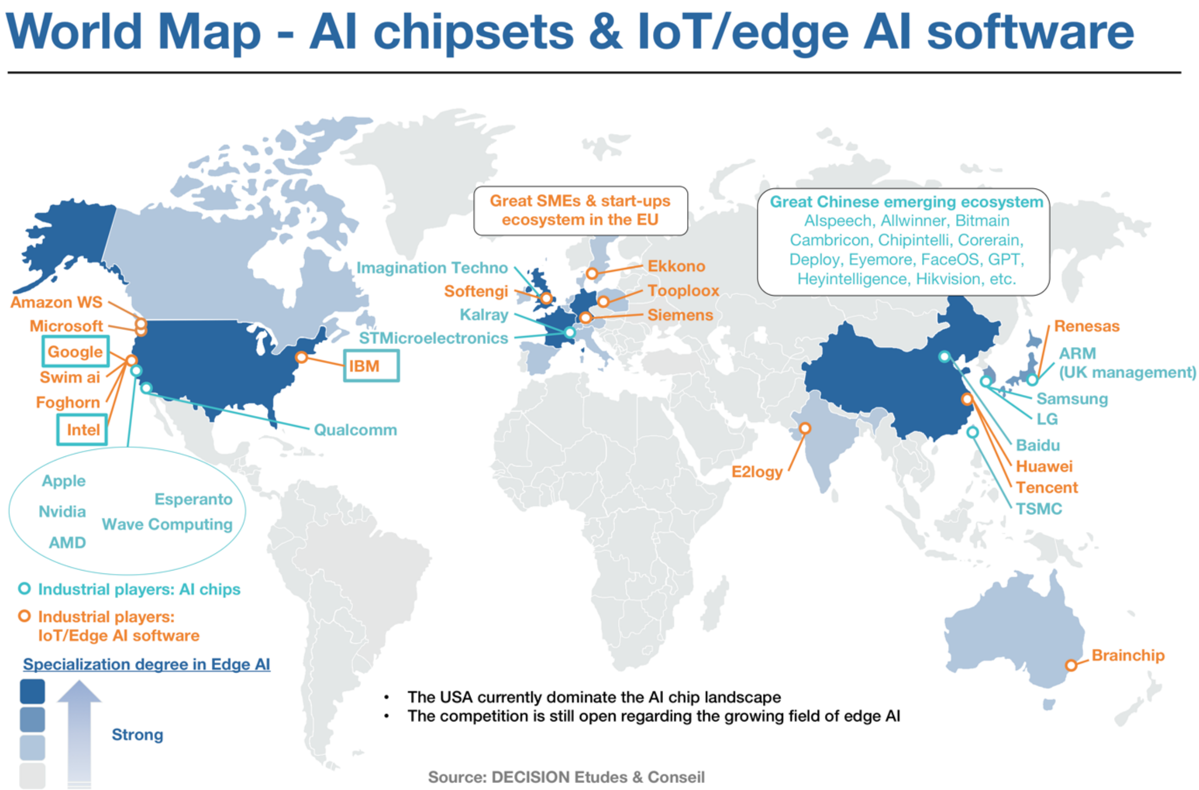
D. Focus on the Embedded (edge) AI market

The edge AI market accounted for €2-4B in 2018 and is expected to reach €20-25B by 2023.

System-on-a-chip (SoC) accelerators such as those found in mobile devices will lead the market in terms of sheer volumes over the 2018-2025, followed by application-specific integrated circuits (ASICs) and graphics processing units (GPUs). In terms of revenue, the ASIC market should exceed SoC accelerators and become the largest sub-market by 2025, followed by GPUs and central processing units (CPUs).

The edge computing market, where AI computation is done on the device, is expected to represent more than three quarters of the total market opportunity, with the balance being in cloud/data center environments. Mobile phones will be a major driver of the edge market, and other prominent edge applications include automotive, smart cameras, robots, and drones. Therefore, although cloud-based AI chipsets currently account for the majority of edge AI revenues, edge-based AI chipsets should largely surpass cloud-based AI chipsets by 2023 and are expected to account for more than 80% of the revenues in 2023.

Furthermore, although Nvidia and Intel currently dominate the market for cloud-based machine-learning applications, the edge market is much more open and represents a huge business opportunity for European manufacturers.



The tables below represent the list of twenty currents leading companies in Edge and Cloud AI chips and chipsets.

Top companies in AI chips	Country	Name of Chip/Family	Targeted markets
Alphabet (Google)	The USA	EDGE-TPU	Mobile devices, IoT
Apple	The USA	A11-A12 (Bionic), A13	Mobile devices
ARM	Japan	Ethos N37, N57, N77	IoT/edge Devices
Intel	The USA	Nervana	Cloud to Edge
NVIDIA	The USA	Xavier, Tesla	Cloud to Edge, ADAS
AMD	The USA	Radeon	Gaming
Baidu	China	Kun-Lun	Cloud to Edge
Qualcomm	The USA	Cloud-to-AI	5G-ADAS
Samsung	South Korea	Exymos	Cloud, Mobile
TSMC	Taiwan	AI Chip for Alibaba	Unknown
IBM	The USA	TrueNorth	Edge
Xilinx	The USA	Everest	Cloud, Edge
LG	South Korea	LG-Neurl Engine	Smart-Home
Imagination Techno	The USA	Power VR	AR/VR on the Edge
Wave Computing	The USA	Triton (MIPS) Core	Edge
Kalray	France	MPPA	Autonomous Car
ST Microelectronics	France/Italy	STM32CubeAIIoT	IoT
Esperanto	The USA	Open Risc V based	IoT to Edge

Source: DECISION Etudes & Conseil

To complete the overview of the competition in the field and the way it could evolve, it is interesting to note that one can today list at least 30 Chinese chip companies developing chips or chipsets for AI: AIspeech, Allwinner, Baidu, Bitmain Cambricon, Chipintelli, Corerain, Deploy, Eyemore, FaceOS, GPT, Heyintelligence, Hikvision, Horizon Robotics, Huawei, iDeepWise, INtengine, Lynxi, Natinal Chip, RNextVPU, NovuMind, Otureo.ai, Rockchip, Thinkforce, Unisound, VeruSilicon, Vmicro, Westwell, Wintinmen.

In the area of IoT and edge AI software the table below shows a list of twenty major companies, at least generating significant revenues in the field.

Top companies in IoT/ edge AI software	Country	Software Package	Targeted markets
Ekkono	Sweden	ML-for IoT	Mobile devices, IoT
Foghorn	The USA	Lightning edge, Mobile	IoT, Edge
Swim	The USA	Data Fabric	IoT/Edge
Renesas	Japan	e-AI	Cloud to Edge
Amazon Web Services	The USA	Greengrass ML	IoT, Edge
Google	The USA	Cloud IoT Edge	IoT, Edge
IBM	The USA	Watson IoT	IoT, Edge
Brainchip	Australia	Studio SW	5G-ADAS
Intel	The USA	AI developer program	AI Tookit
Siemens	Germany	Mindsphere	Industrial IoT and edge
Tencent	China	Machine-learning	Image, Face, Audio,
Microsoft	The USA	Azure IoT hub	Complete AI platform
Huawei	China	Mindspore	Complete AI platform
Tooploox	Poland	ML, Generative Anetw	Custom product opt.
E2Logy	India	Based on AWS	AI services
Softengi	The UK	NLP, DL and ML	Vision, Language, IoT

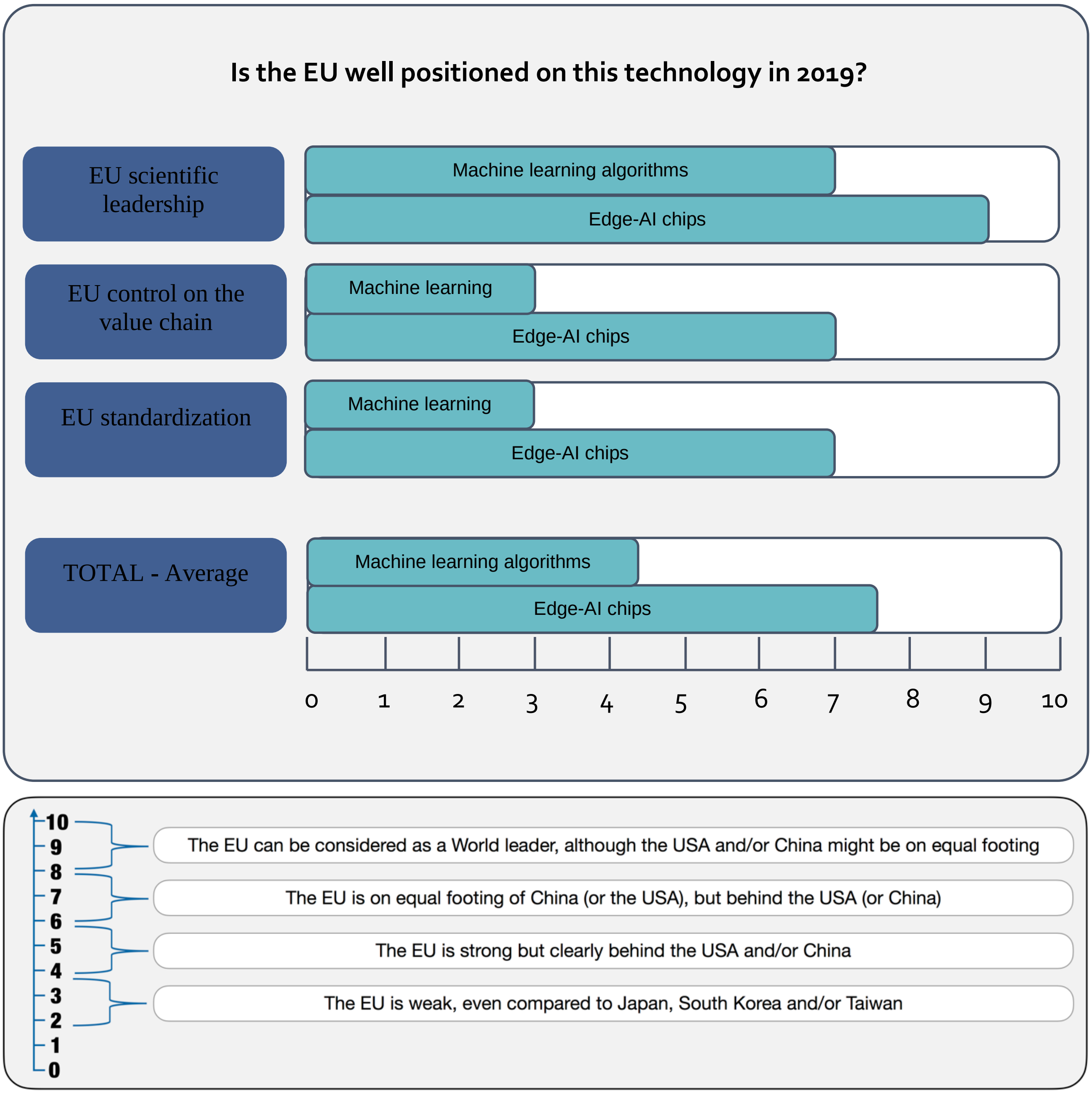
Source: DECISION Etudes & Conseil

All the major American (and Chinese) vendors are trying to "downsize" their AI Cloud tools and platforms dedicated to the IoT and edge domains. This is often far from representing the optimal or most cost-effective solution.

Simultaneously, IA software for edge and IoT is just emerging and many SMEs and start-ups are very active in the field, including in Europe where the UK is the most dynamic country before Germany and France (all three countries accounting for around 50% of European ecosystem.

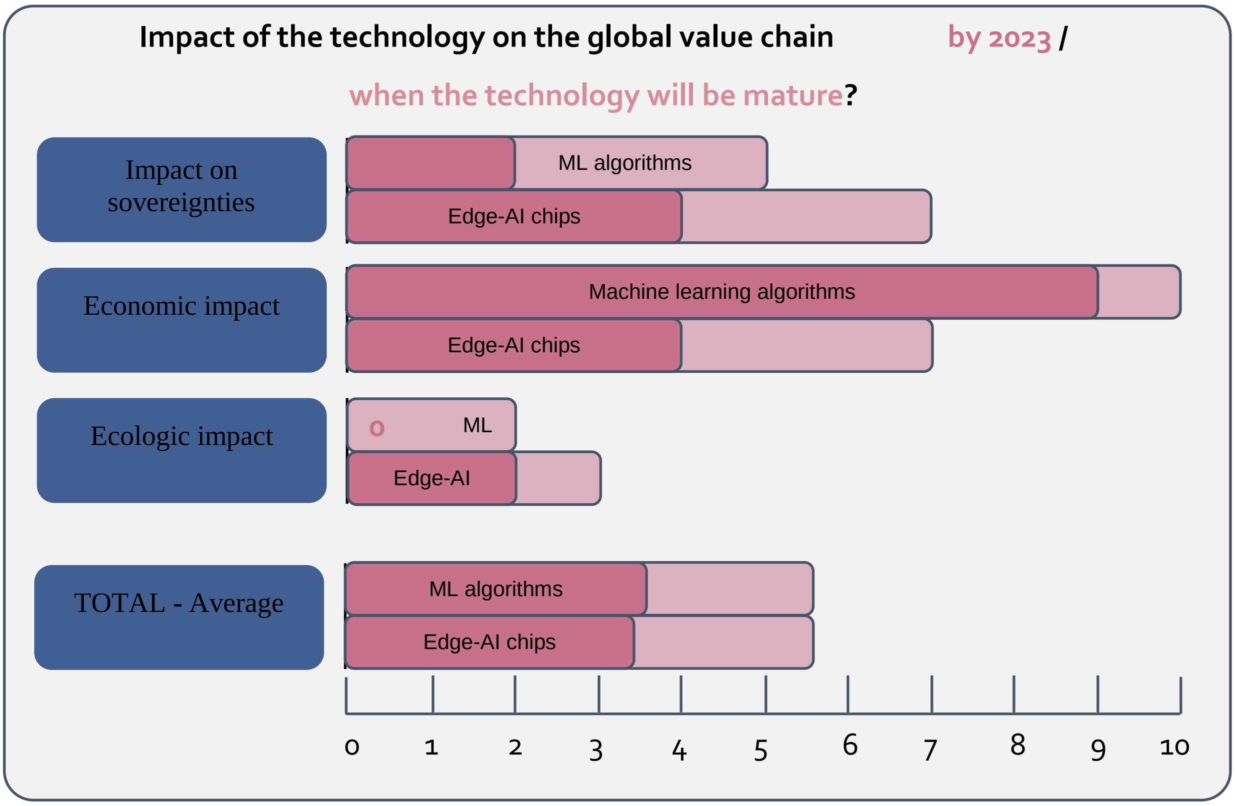
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU (and especially France, Belgium and Germany), excels in DSP (Digital Signal Processors), Mathematics, embedded software, software engineering, machine-learning and deep learning, to the extent that the GAFAMI are installing research centers for years in European cities (Paris, Brussels, etc.), and recruit many European talents, often offering salaries two times higher than European private or public organizations.

Regarding edge AI, there is a strong need to develop education in order to train engineers and scientists in both embedded software, AI algorithms and the design of electronic components (three core skills). It will be a key success factor for the EU to lead the future edge AI applications.

EU control on the value chain

The main R&D players and the main budgets are located in the USA and in China (especially the main industrial players). As a consequence, most of the intellectual property is located outside the EU territory and / or owned by non-European players, although open innovation plays a great role in the innovation process. The major Cloud AI platforms are today operated by American or Chinese leading vendors (GAFAM, BATX).

In the edge domain, and in addition to its high-scientific level in AI algorithms, software and mathematics, the EU has nevertheless some very strong industrial competencies in embedded systems and microcontrollers, which should help promote European domestic AI solutions for emerging high-value IoT applications (Industry 4.0, Connected and Autonomous cars, Defense and Security, Health, Smart-City & systems).

Standard analysis

The main US and Chinese players (Google, IBM and Facebook in the first place), are providing software environments to develop machine-learning algorithms which are becoming industry standards for this architecture. This is amplified by their strategy to put a lot of AI packages in Open Source or Open Access mode.

In Europe, the Edge Computing Consortium Europe (EECC) aims at supporting small, medium-sized and large enterprises in Europe to adopt edge related technologies and in particular with a focus on the chaining between Operational Technologies (OT) in industrial IoT and Information and Communication Technologies (ICT). This initiative could play a key influencing role for the introduction of edge AI.

Impact on sovereignties

Even though a lot of new innovations might occur in the coming years, AI applications in strategic domains such as the defense & security, critical infrastructure protection, health or autonomous cars fields are currently not leading to massive industrial/commercial uses as the certification levels required for such applications are not matched by AI algorithms.

Besides, using AI algorithms for this type of application purpose implies to clarify completely the responsibility chain of the stakeholders involved and to develop the appropriate associated regulatory framework. The non-discriminatory nature of the AI algorithms as well as their explicability will have to be fully transparent and demonstrated. This will require the development of a completely new framework.

In the specific case of Defense, other ethical problems linked to the responsibility of death or injuries (the human that launched the algorithm or the algorithm itself?), will be a potential roadblock for the adoption of such applications and might even often prevent their use.

Besides this extreme use cases, real-time big data analysis for security/defense purposes thanks to AI algorithms appears to be the most significant and practicable application related to sovereignty over the coming years, but also raise the issue of privacy protection and social acceptance.

As a consequence, the global impact on sovereignties should be moderate. There should be a certain level of caution and conscientiousness in introducing AI algorithms in domains pertaining to the EU sovereignty, even if AI algorithms could contribute to improve kingly processes or applications.

Economic impact

AI algorithms will directly generate a global market of €141 B by 2023.

Besides the generated revenues, the main impact of AI algorithms should be indirect as it should lead to great competitive advantages for the players of very significant markets that will succeed to develop the best applications based on AI:

- AI algorithms should have a critical impact (that is leading to critical competitive advantages), in the personal assistant market and in the market for video games & consoles (around €141 B in 2023);
- AI algorithms should have a significant impact in electronic markets accounting for nearly €1,700 B by 2023 (ADAS, automotive infotainment, mobile phones, Professional & consumer PC, Defense & security and & industrial & robotics applications).

There are very good reasons to think that AI at the edge will have a more important impact as AI in the Cloud. As more IoT devices are deployed, the need for AI-enabled solutions supported by edge computing grows exponentially. It will no longer be feasible to rely on the cloud to process and analyze data to drive real-time decision-making. The capabilities of edge computing to handle AI algorithms and machine-learning locally without the inherent latency of cloud computing will provide insights to drive more efficiently operations and increase productivity.

Ecological impact

None of the current foreseeable IA applications have an interest in terms on fight against climate change and / or fight against the 5th massive extinction. On the contrary, AI applications currently implies greater energy consumption to perform. This is a major challenge for the edge AI and the expected development of IoT to develop edge nodes with Low to Ultra-Low Power consumption.

B. High-performance computing

i. Definition

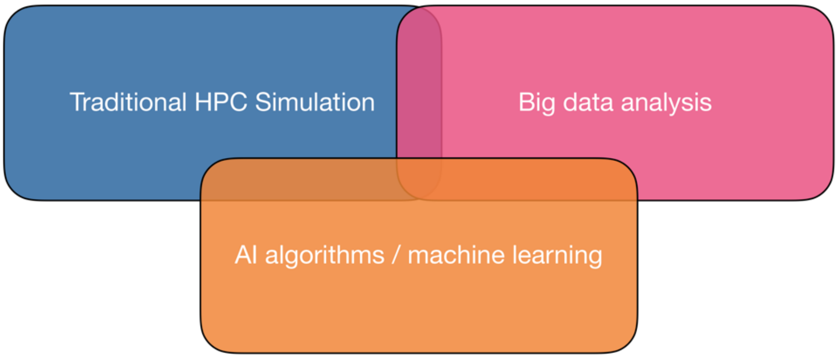
In its **common definition**, High-Performance Computing (HPC), refers to computing systems having extremely high computational capabilities through thousands of processors working in parallel. Today these systems are able to perform more than 10^{15} operations per second (petascale) and are expected in a few years to reach 10^{18} operations per second (exascale).

In its **restrictive definition**, HPC is synonymous with “technical computing using supercomputers” to model and simulate complex scientific phenomena (HPC simulation). Classic HPC modeling and simulation seeks to represent the dynamics of a system based on a mathematical model for that system, which is usually derived from scientific or engineering laws. HPC focuses on interaction between parts of a system and the system as a whole. For example, weather modeling will take initial conditions (such as historic temperatures, estimates of energy input from the sun, and so on), as an input. Then, using a commonly accepted model about the causal interactions between these variables (captured in equations and code), it will produce forecasts of the weather in, e.g., five days.

Yet, in a **broader definition**, HPC nowadays also refers to the convergence of traditional HPC (simulation) with processing and storage of big data and processing of artificial intelligence (AI) applications in the same data center, along with ways of orchestrating computing resources for the different workloads. HPC might also concerns the interfaces of this structure with external devices (distributed and edge devices).

In this report, we consider the restrictive definition of HPC: HPC simulation. Key interactions between HPC, big data analysis and AI algorithms are discussed in the next paragraph.

The future pillars of HPC applications



Source: HIPEAC Vision 2019, DECISION Études & Conseil

ii. Synergies with other emerging technologies

AI algorithms. The convergence of HPC simulations and AI algorithms using large datasets accelerate the emergence of the applications already mentioned in the AI algorithms chapter of this study. AI algorithms can also replace HPC simulation in certain cases, where exact models are not available. Conversely, AI can also be accelerated by HPC technology thanks to the pre-processing of large datasets, data cleansing, massive and fast training of deep neural networks or more than real-time inference phase.

Big data analysis. High-Performance Computing and AI algorithms can be combined to perform High Performance Data Analytics (HPDA)[20] (considered as an emerging crossed application). HPDA is useful for extremely fast analysis results (e.g., real-time high-frequency analysis), extreme problem complexity requiring high capability analytics (e.g., those found in large-scale scientific research and industrial settings), and when patterns or insights are of an extremely valuable nature (e.g., economic, scientific or social).

Edge computing. The different types of deployment methods of HPC are cloud-based and on-premise based methods. Cloud deployment is currently most popular in the industry, as cloud-computing technologies are popularly adopted by the players in different industries. Cloud technology market for HPC should grow due to its high adoption rate, while the usage on-premise deployment method should decline slowly.

Emerging components & architectures. More Moore technologies, beyond CMOS technologies, innovative memories but also emerging architectures such as neuromorphic computing, quantum computing and other rebooting computing architectures are technologies that might greatly improve the power of high-performance computing.

Open Platform. The ETP4HPC, in its last Strategy Research Agenda (2017), was calling for the development of open platforms in HPC: “If we want a new distributed infrastructure to support science and engineering research in the era of Big Data [and HPC], an infrastructure with the kind of openness, scalability, and flexible resource sharing that has characterised the legacy Internet paradigm, then we will have to define a new, common and open distributed services platform (DSP), one that offers programmable access to shared processing, storage and communication resources, and that can serve as a universal foundation for the component interoperability that novel services and applications will require”.

[20] See the report “The Technology Stacks if High-Performance Computing and Big data computing: What they can learn from each other” from the ETH4HPC and the BDV, released in 2019.

iii. Technology roadmap: Maturity levels and expected impacts by application area

HPC technology is being rapidly adopted by the academic institutions and various industries to build reliable and robust products that would enable to maintain a competitive edge in the business. The HPC market is therefore growing strongly and steadily, and it should continue its growth in future with an expected 18% CAGR over the 2018-2023 period.

HPC involves hardware, software, system management and professional associated services (consulting, integration, training, outsourcing, etc.). Hardware components are the most essential parts in any HPC system. Hardware includes memory capacity (storage), energy management, servers and network devices.

High-Performance Computing markets 2018-2023 (€ B)

Company	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
Supercomputers*	5	6	7	9	12	16	28 %
Other HPC	8	9	10	11	12	13	11 %
TOTAL HPC	12	14	17	20	24	28	18 %

*Supercomputers (HPC systems sold for $500 000 or more)

Source: DECISION Études & Conseil, Hyperion Research

The first Petascale computer (10^{15} operations per second), is the “Roadrunner” commercialized by IBM in May 2008. The next step in high-performance computing is Exascale performance: machines able to perform 10^{18} operations per second, a technology which is expected to be reached by top global players by 2020-2022.

World timescale of High-Performance Computing

Supercomputer power *	Year of the first supercomputer produced	First producer	Nationality of the first producer
10^{15} operations per second	2005	IBM	The USA
10^{16} operations per second	2010	IBM	The USA
10^{17} operations per second	2015	Cray	The USA
10^{18} operations per second	Expected 2020-2022	-	Expected China, the USA or Japan

* Maximal performance achieved

Source: The TOP 500 project on HPC, DECISION Etudes & Conseil

The table below provides a state-of-play in terms of supercomputers produced by power in 2019.

Supercomputer world state-of-play in June 2019

	Petascale	Pre-exascale		Exascale
	10^{15}	10^{16}	10^{17}	10^{18}
Number of companies able to produce	> 34	15	5	0
Number of supercomputers produced	> 500	471	267	0

Source: The TOP 500 project on HPC, DECISION Etudes & Conseil

The Chinese supercomputer Sunway, considered as the second most powerful supercomputer in mid-2018, was built around custom processors, while the US supercomputer Summit, considered as the most powerful, was built around a processor which is very efficient for data processing and management and a lot of GPUs as accelerators. It is therefore foreseen that the future HPC machine will not only have simulation loads, but also more loads based on high-performance data analytics (HPDA), and also that applications will use more and more artificial intelligence-based solutions.

The major challenges for these HPC systems are power, cooling system management and storage & data management.

Applications.

Previously, HPC was used only by the navigation and aerospace industries. However, diversification of the IT industry, growing adoption of cloud computing, continuous developments in artificial intelligence, and the rising need for business analytics are prompting various end-use industries to adopt HPC.

Therefore, HPC's applications currently include:

- Health & Care: Computational biology (protein behaviors modeling, drug design, etc.), genetics (DNA sequencing), early detection and quicker diagnose of diseases, deciphering the human brain… Yet, health & care diagnose services should account for €200 B in 2023. The pharmaceutical market is estimated to reach €1,080 B by 2023;

- Security & Cybersecurity: HPC helps to detect strange systems' behavior, insider threats and electronic fraud and cyber-attack patterns, leading to a shortening of the response times. Defense & Security applications expected to be significantly impacted by HPC developments should account for €20 B in 2023;

- Automotive, Industrial & Robotics: Reducing development time, minimizing costs, optimizing decision processes and producing higher quality goods and services. Transportation industries (automotive, trains, boats and aeronautics), defense & security industries and robotics industries should account for €3,460 B in 2023;

- Research & Development tools: HPC provide scientists with deeper insights into previously unexplored areas and systems of the highest complexity, driving the innovation and discovery of almost all scientific disciplines, from earth sciences (climate modeling, weather forecasts, preventing and managing large-scale natural disasters) to high-energy physics, mathematical modeling, astrophysics and space exploration, among others. Using HPC, climate scientists can predict the size and paths of storms and floods more accurately, meaning that people can be alerted and evacuated faster, saving lives. The climate monitoring market account for €11 B in 2023.

- Smart energy: HPC might be used to monitor smart grids data;

- Smart mobility: HPC might be used to monitor traffic data under the hypothesis of the development of a connected network of autonomous vehicles (corresponding to autonomy level 4).

Technology Roadmap - Maturity of HPC at the global scale and by application area

<table>
<tr><th colspan="2"></th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td colspan="2">Technology</td><td colspan="21">Maturity level of the technology</td></tr>
<tr><td colspan="2">Petascale (10^{15} operations per second)</td><td colspan="21">Industrial production</td></tr>
<tr><td colspan="2">10^{16} operations per second</td><td colspan="21">Industrial production</td></tr>
<tr><td colspan="2">10^{17} operations per second</td><td colspan="5">Tests & prototyping</td><td colspan="16">Industrial production</td></tr>
<tr><td colspan="2">Exascale (10^{18} operations per second)</td><td colspan="5">R&D</td><td colspan="6">Tests & prototyping</td><td colspan="10">Industrial production</td></tr>
<tr><td colspan="2">Post-exascale (>10^{18} operations per second)</td><td colspan="11">R&D</td><td colspan="5">Tests & prototyping</td><td colspan="5">Industrial production</td></tr>
<tr><td>N°</td><td>Electronic Segment</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="21">No significant impact (but medium impact in related health & care services)</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="21">Small impact Small Impact (strong impact but only in cybersecurity applications)</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="21">Medium impact</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>N°</td><td>Crossed segments</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Data analytics / Big data</td><td colspan="21">Critical impact</td></tr>
<tr><td>2</td><td>Smart home</td><td colspan="21">No significant impact</td></tr>
<tr><td>3</td><td>Smart mobility</td><td colspan="21">Small impact</td></tr>
<tr><td>4</td><td>Smart energy</td><td colspan="21">Small impact</td></tr>
<tr><td>5</td><td>Wearables</td><td colspan="21">No significant impact</td></tr>
</table>

At the global scale, each technology is defined through four different stages of maturity.

- **R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6**
- **Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9**
- **Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)**
- **Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies**

The impact of the technology on each end-user segment is described as:

- **A critical impact;**
- **A significant impact;**
- **No significant impact;**

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain by 2023.

Source: DECISION Etudes & Conseil

Impact of HPC by end-user electronic applications in 2023

	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	No	No	No	No	No	Medium	No	Small	Critical	No	No

Corresponding quantitative impact of HPC in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
28	68	220	4 540	57	20	0	11	200	4 540
				Professional Computer	Security & Cybersecurity	-	Climate monitoring	Medical diagnoses	Pharmaceutical market, industrial processes in every manufacturing industry

*** Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency**

Estimated economic impact of HPC in 2023

Source: DECISION Etudes & Conseil

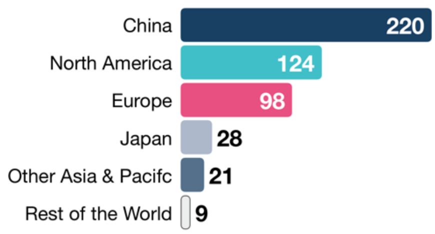
iv. Main players in the World and in the EU

A. Main countries & regions

North America is the largest market for HPC technology due to the technological advancements and early adoption of technology in the region followed by China (2nd), the EU (3rd), and Japan (4th). Yet, the USA is being catch-up by China, to the extent that in November 2017, China outreached the USA for the first time in terms of the number of supercomputers in the TOP 500 worldwide ranking made by the TOP 500 project.

Number of supercomputers in the TOP 500 list by region (June 2019)

N°	Region	Number of supercomputers	CAGR 2009-2019
1	China	220	26 %
2	North America	124	-8 %
3	Europe	98	-3 %
4	Japan	28	6 %
5	Other Asia & Pacific	21	8 %
6	Rest of the World	9	12 %



Source: The TOP 500 project in HPC, DECISION Etudes & Conseil

The candidates to build the first exascale computer are American (HP, Dell, IBM and Cray), Chinese (Sugon / Dawning, Lenovo and Inspur), and the Japanese Fujitsu:

- China's first exascale supercomputer should enter service by 2020 according to the head of the school of computing at the National University of Defense Technology (NUDT);
- On 18 March 2019, the United States Department of Energy and Intel announced the first exascale supercomputer would be operational at Argonne National Laboratory by the end of 2021. The computer, named "Aurora" is to be delivered by Intel and Cray;
- Japan is also in the exascale computing race. The Riken Advanced Institute for Computational Science (AICS), and Fujitsu announced that they have finished the design of the Post-K exascale platform, paving the way for production of the hardware, followed by shipping and installation. Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) is aiming to make the system available to its users "around 2021 or 2022";
- Although the EU is leader in the use of HPC applications, it owns no supercomputer in the global top 10. Furthermore, the EU industry provides about 5% of HPC resources worldwide, while it consumes one third of it. In other words, the EU suffers from a discrepancy between its great competitive position in terms of scientific leadership and its reserved HPC industry and capacities (as it is the case for most of the emerging technologies). This state-of-play leads to the risk of having the data produced by EU research and industry processed elsewhere for lack of corresponding capabilities in Europe. The goal of the EU is to maintain its position as 3rd player at the global scale (behind the USA and China), through the EuroHPC Joint Undertaking, and:
    - 2020-2021: acquire at least 2 pre-exascale supercomputers in the global top 5 and several petascale supercomputers in the global top 50;
    - 2022-2023: acquire at least 2 exascale supercomputers in the global top 5 (and at least 1 based on European technology);
    - 2025+: acquire post-exascale and hybrid (classical and quantum) supercomputers.

  To reach this goal, the EuroHPC has an annual budget of €198 M in 2019 dedicated to Extreme Scale Technologies and Applications, Widening HPC skills and the European Processor Initiative. €450 B should also be invested on an annual basis over the 2021-2027 period through the Digital Europe Program.

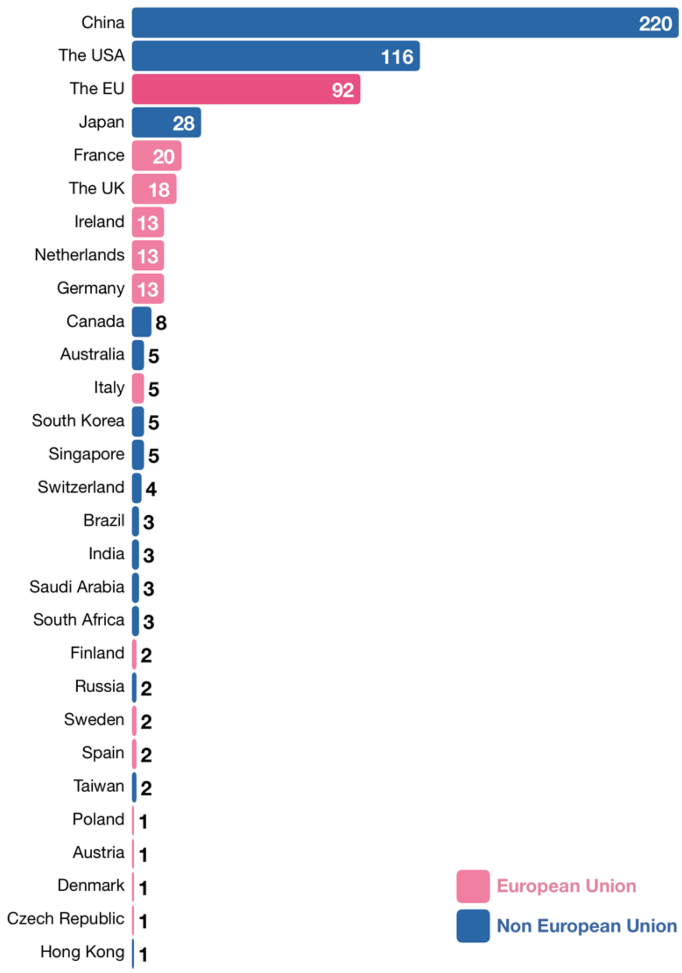
Switzerland and South Korea are also advanced countries in terms of HPC. These countries own at least one supercomputer ranking respectively 6th and 8th in the TOP 500 world ranking of supercomputers.

Nine other countries are also significantly advanced in terms of HPC: Canada, Australia, Russia, India, Taiwan, Saudi Arabia, Brazil, Singapore and South Africa.

Based on the work of Hyperion research, the US total investments on the exascale race approximate €1.7 B annually. China's investments are estimated to be similar to the US. The EU's investments account for around €1.3 B annually and Japan's investments are estimated to worth €200 M.

Number of supercomputers in the TOP 500 list by country (June 2019)

N°	Country	Number of supercomputer	CAGR 2019-2009
1	China	220	26 %
2	The USA	116	-9 %
	The EU	92	-3 %
3	Japan	28	6 %
4	France	20	-1 %
5	The UK	18	-8 %
6	Ireland	13	29 %
7	Netherlands	13	16 %
8	Germany	13	-8 %
9	Canada	8	0 %
10	Australia	5	17 %
11	Italy	5	-2 %
12	South Korea	5	-
13	Singapore	5	17 %
14	Switzerland	4	0 %
15	Brazil	3	-
16	India	3	-7 %
17	Saudi Arabia	3	0 %
18	South Africa	3	-
19	Finland	2	7 %
20	Russia	2	-7 %
21	Sweden	2	-15 %
22	Spain	2	-7 %
23	Taiwan	2	7 %
24	Poland	1	-13 %
25	Austria	1	-15 %
26	Denmark	1	-
27	Czech Republic	1	-
28	Hong Kong	1	0 %



Source: The TOP 500 project in HPC, DECISION Etudes & Conseil

B. Main research centers

The main R&D players in HPC are listed in the map below. All the R&D centers listed in this map were running supercomputers among the TOP 120 ranking (made by the TOP500 organisation, in TFlop/s), in June 2019. Among the European players, the ETP4HPC initiative is coordinating the research based on the French labs CEA and INRIA and the German Fraunhofer Institutes. The European leading industrial player is Atos/bull, followed by Megware.

C. Main industry players

The table below shows the 12 main players of the HPC market. Five of them are American, four of them are Chinese and two of them are Japanese. The market for supercomputer is more and more becoming a concentrated market as HP bought Silicon Graphics in 2016 and Cray in late 2018. In China, Sugon's activities are virtually shut down, victim of an American embargo that deprives the firm of the vital components of its supercomputers. Japanese Fujitsu and NEC tend to stick to their local market, so that in the end, there will be only a handful of global manufacturers, including the American HP, Dell and IBM, the Chinese Lenovo, Inspur and Huawei and the French Atos.

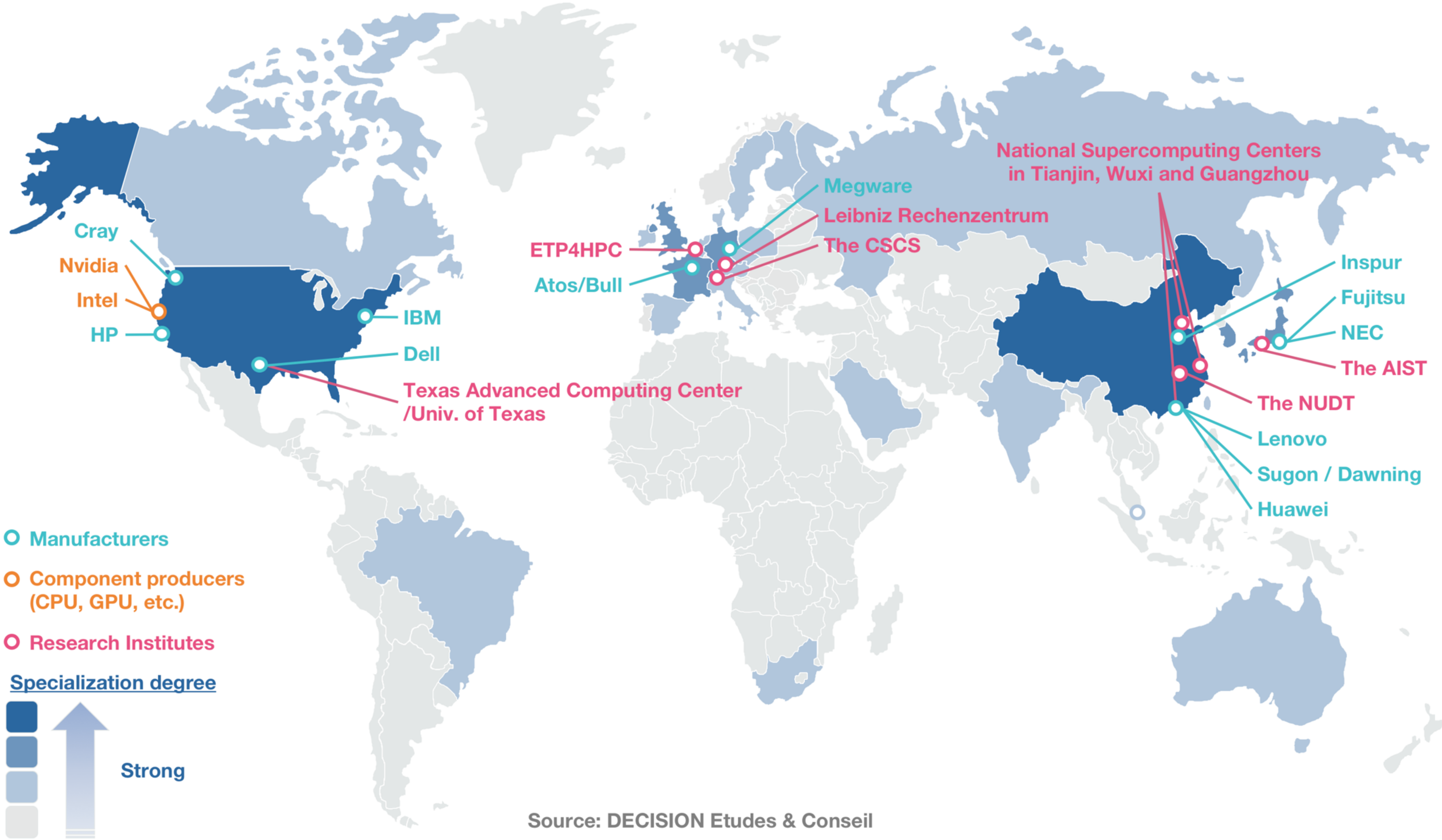
Atos is reinvesting on HPC and supercomputing since 2013n so that according to the company, its market shares for supercomputers move from 2-3% in 2013 to 7-8% in 2019 worldwide. Its main factory is located in Angers (France), with 20 employees producing a dozen supercomputers and a few thousand servers per year for a turnover of €500 M. The five most powerful supercomputers produced by Atos are located in the military branch and in the TGCC Center of the CEA (Bruyères-le-Châtel, southern Paris), in the Forschungszentrum Jülich (Jülich, Germany), in the German Climate Computing Center (DKRZ, Hamburg), and in the British Atomic Weapon Establishment (Aldermaston, West London).

High-Performance Computing main players

N°	Company	Nationality	Number of supercomputers in the TOP500 in June 2019 (in % of total)	HPC sales 2018 (€ Million)
1	**HP**	The USA	8 %	3 972
2	**Dell**	The USA	3 %	2 381
3	**Sugon / Dawning**	China	13 %	1 117
4	**IBM**	The USA	2 %	809
5	**Lenovo**	China	35 %	798
6	**Inspur**	China	14 %	657
7	**Cray**	The USA	8 %	261
8	**Fujitsu**	Japan	3 %	224
9	**Penguin Computing**	The USA	2 %	203
10	**NEC**	Japan	1 %	201
11	**Atos**	France	4 %	150
12	**Huawei**	China	1 %	150
	Others		6 %	1 278
	TOTAL		100 %	12 200

Source: The TOP 500 project in HPC, DECISION Etudes & Conseil, Hyperion Research

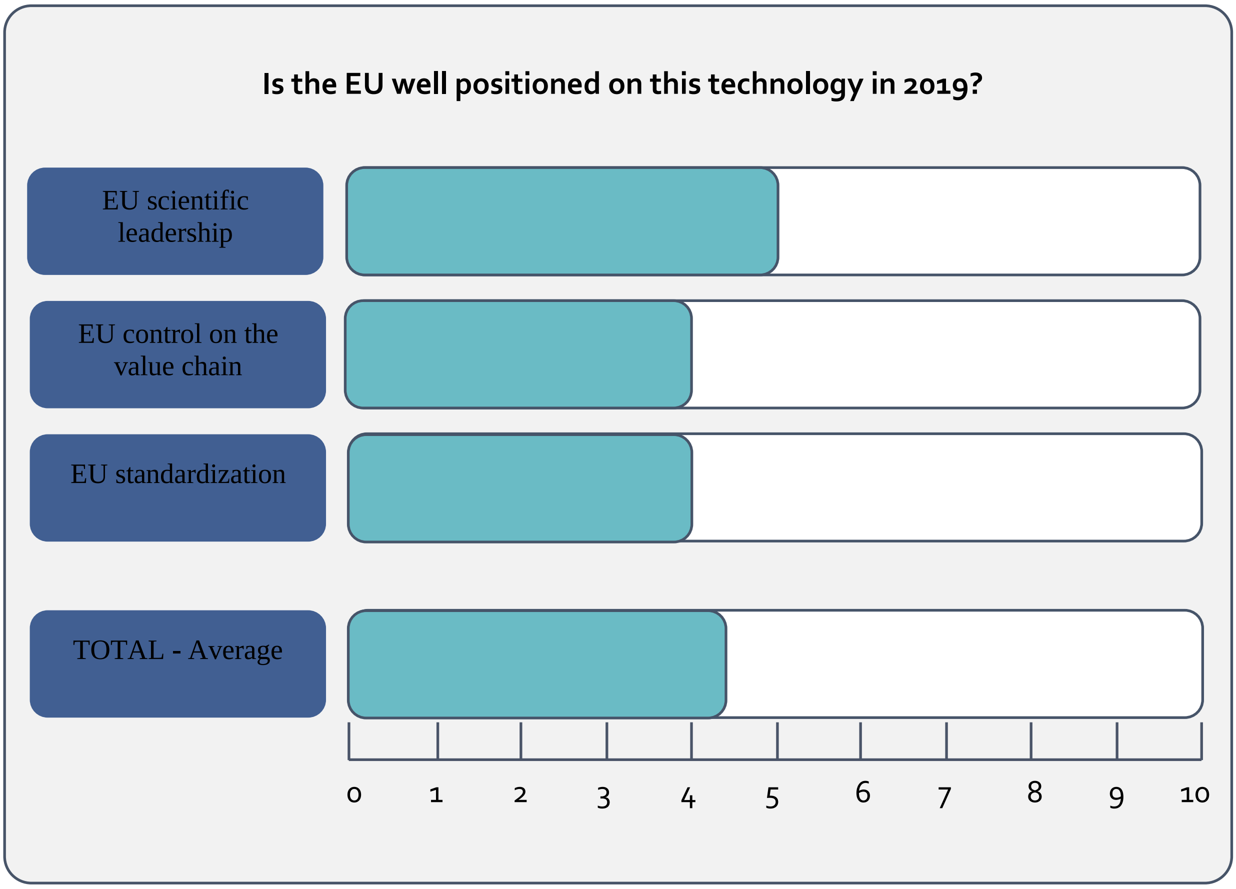
World Map - High Performance Computing

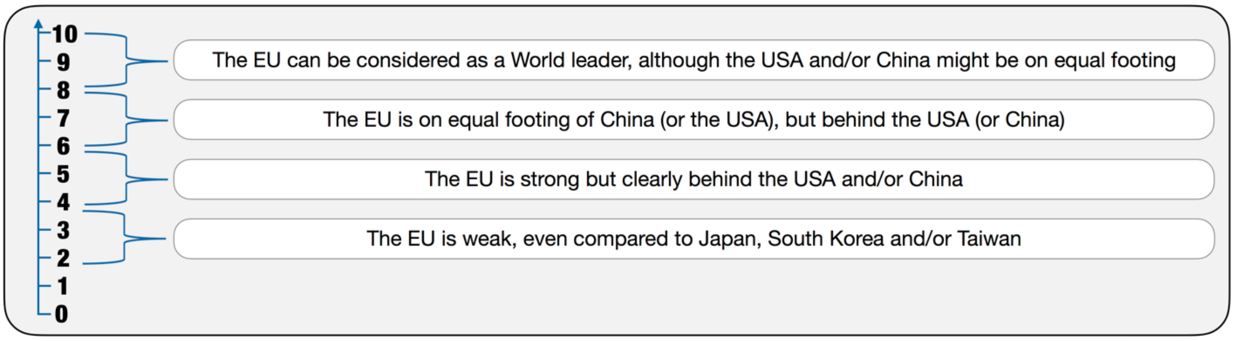


Source: DECISION Etudes & Conseil

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

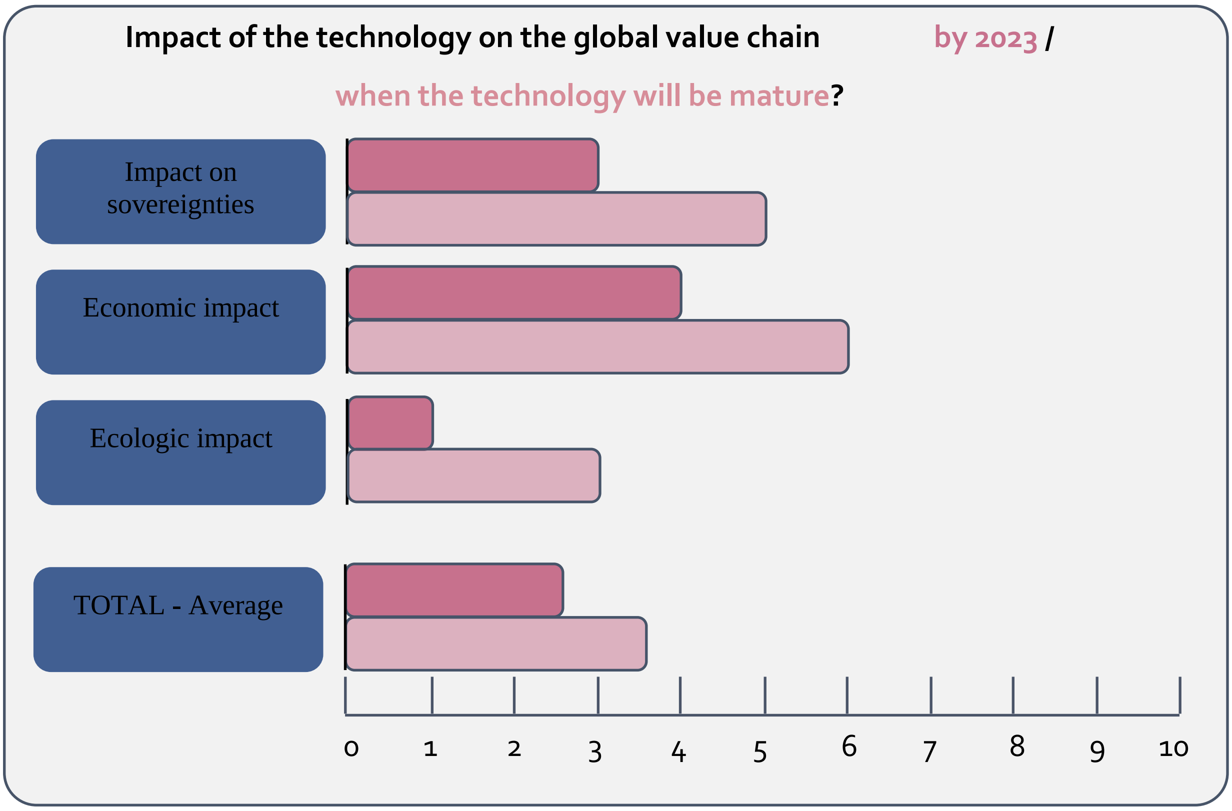
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.
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EU scientific leadership

Although the EU should not win the Exascale race and build the first Exascale computer, the EU remains very well positioned in terms of HPC scientific leadership along with the USA, China and Japan.

EU control on the value chain

In terms of control on the HPC value chain, the EU is facing two main issues as the European Processor Initiative (EPI), will be a "fabless" project:

- The chip production for the EPI might be done by Infineon or STMicroelectronics. Yet, the production process will occur in Asia if it uses technologies under 28 nm. A similar issue occurs for the memory used.

- Moreover, the USA is currently the dominant provider of computing solutions with CPUs (Intel) and GPUs (NVIDIA), which are used to build high-performance computing and servers. Yet, components that are only produced in the USA can be banned from export under a number of US regulations, such as the International Traffic in Arms Regulations (ITAR), which controls the export and import of defense-related articles and services. In 2015, for instance, the US Department of Commerce prevented Intel and NVIDIA (but also AMD and IBM for their processors and HP for its optoelectronic devices), from shipping the processors required for the upgrade of the Chinese Tianhe-2 supercomputer.

Open-source hardware processors like RISC-V are also attracting a lot of interest as there is a growing movement away from well-established US computing platforms, such as those of Intel, Google, Apple and Microsoft, either to avoid bans on accessing core components, or because of fears that hardware and software might have spyware deeply implanted.

In other words, the EU suffers from a lack of control on the upstream portion of the HPC value chain. This lack of control might lead to sovereignty issues as discussed below.

Standard analysis

HPC relies on a large number of sub-technologies and research fields being more or less developed and each involving several standards. The EU's global position in terms of HPC standardization remains relatively low, reflecting the position of its main industrial players compared to the American and Asian players.

In terms of communication between computing nodes within the program code, HPC generally relies on the MPI (Message Passing Interface) industry standard that has been presented for the first time at the 1993 ACM/IEEE conference on Supercomputing and has been conceived by European and American researchers. Alternative models like for instance PGAS (partitioned global address space) programming models only account for a very small part of HPC use. In 2004, Intel released the PCI express standards which has been largely adopted, although a number of (partly competing) international standardization activities are underway which target storage and accelerator interfaces both within a node and between nodes (CCIX[21], Gen-Z, OpenCAPI[22], etc.). At this point in time, it is not clear which of these will succeed in being adopted for the majority of relevant platforms, whether different standards will be brought forward, and where the balance between the specific benefits brought by standardization (interoperability and stability) and the promises of very tight proprietary (on-package or SoC) integration will end up being. For the OS and driver software this means that potentially a mix of standard or proprietary interfaces will need to be supported. The ETP4HPC is working on new standard interfaces available for integrating CPUs and accelerators on nodes and to accommodate innovative unified memory and storage architectures on networks that should be set up by 2021.

In terms of programming environment, no standard is generally established and the ETP4HPC called for long-term formal or de facto standardization of the programming models and Application Programming Interfaces (APIs), in its last Strategic Research Agenda (2017), since interoperability between program models and runtime systems has a broad impact.

In terms of privacy & data security, specific requirements for HPC arise from the need to protect sensitive data (for instance medical data). Research into strengthening the security of the key communication layers (such as MPI and PGAS implementations), to bring them up to the same standard as common data center communication solutions and into isolating system partitions from each other to avoid leakage of data or meta-information is required and underway.

[21] The CCIX founding members are IBM (US), Qualcomm (US), AMD (US), Mellanox (US), Xilinx (US), Huawei (China) and ARM (UK).

[22] OpenCAPI's strategic members are AMD (US), Google (US), IBM (US), Mellanox (US), Nvidia (US), Western Digital (US), and Xilinx (US).

New standards are also needed for dense linear algebra standards and new standards for shared memory parallel processing.

The ETP4HPC plans to design and promote new standards or guidelines for the industry and recommends supporting commonly used tools (compilers, MPI, OpenMP, numerical libraries, etc.), as much as possible while novel technologies should provide standard interfaces where possible.

Impact on sovereignties

The two main applications of HPC involving the EU sovereignty are cybersecurity (developing strong encryption technologies, helping security authorities to access encrypted communications or perform large-scale suspicious pattern detection), and an improved capability to simulate the impacts of disasters such as nuclear reactions. HPC might also affect sovereignties as a key consumer technology with significant economic outcomes (for instance if foreign powers were to limit the access of the EU to this technology in a context of economic war). In other words, the mastering of HPC might be useful but not crucial for the EU sovereignty.

Economic impact

Despite an impressive growth rate, the potential HPC market is expected to be €28 B in 2023 and to have a medium/critical impact on markets accounting for €288 B by 2023. In other words, the potential economic impact of HPC is significant but not exceptional compared to other emerging technologies studied in this report.

Ecological impact

No specific HPC application is currently designed for ecological purpose (except eventually a better climate forecasting). Furthermore, High-Performance Computing is very energy consuming.

The only foreseen ecological impact of HPC would be to replace current applications with better energy efficiency.

C. Smart sensors

i. Definition

1. Smart sensors

Smart sensors are devices that take input from the physical environment and use built-in processing and local storage resources to perform predefined actions upon detection of specific input and then process data before passing it on to an actuator (i.e., a device which convert electrical signal to physical properties), or to another connected device.

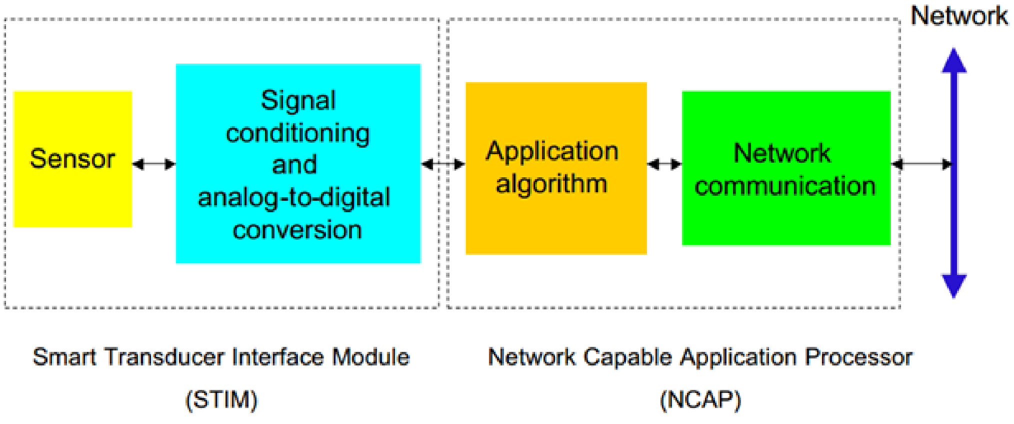
The typical architecture of a smart sensor consists in the combination of a sensing unit (Sensor, Analog to Digital Converter), a processing unit (microcontroller with memory), a transceiver unit with short-range communication capabilities and a power unit. Some applications have extra-components such as geo-localization (e.g., GPS, Magnetic), power harvesting and so on. Smart sensors are generally built using a combination of advanced semiconductor, nanotechnology and System-in-Package technologies (SiP).

Major types of sensors include:

- Temperature sensors;
- Pressure sensors;
- Humidity sensors;
- Flow sensors;
- Accelerometers;
- Magnetometers;
- Gyroscopes;
- Inertial sensors;
- Occupancy sensors (Image processing occupancy sensors (IPOS), and Intelligent occupancy sensors (IOS).
- Image sensors;
- Touch sensors;
- Proximity sensors;
- Acoustic sensors;
- Motion sensors;
- Co2 sensors;
- Others (Light sensors, Radar, Lidars, etc.);

The following picture shows the basic concept of a connected smart sensor:

Connected smart sensor architecture



Source: Mukama Florentine, "Welcome to the understanding of Smart Sensors and Actuators"

Smart sensors are aimed to be simple, miniaturized devices that convert physical analog signals into digital signals and perform some local processing on them before sending them on the network. While this functionality is an essential starting point, sensors used in IoT configurations need eight additional properties:

1. Low cost and robustness, so that they can be economically deployed in large configurations with minimum or no maintenance costs;
2. Miniaturization to “disappear” unobtrusively into any environment;
3. Very low power consumption (including low power software), so they can survive for years without a battery change, or manage lifetime with energy harvesting;
4. Security & privacy by design software as well as self-identification and self-validation capabilities;
5. Over-the-air firmware upgradability;
6. Wireless connectivity, as a wired connection is seldom available;
7. Self-updating capabilities: Self-diagnostic, self-healing and self-calibrating (or accepting calibration commands via wireless link);
8. Data pre-processing, to reduce load on edge Nodes (collecting and segregating data from various sensors) and cloud resources.

2. <u>The key underlying technology: MEMS</u>

Smart sensors used in IoT, are more and more based on MEMS technology. MEMS is an umbrella term for a wide range of micro-fabrication designs, methods and mechanisms that involves realizing moving mechanical parts at microscopic scale. MEMS aimed at miniaturizing traditional bulky mechanical systems while improving performances in a similar way integrated circuit and semiconductor technologies have disrupted electrical and electronics systems.

MEMS are used in a wide range of sensors, actuators, generators, energy sources, biochemical and biomedical systems and oscillators. Some examples of MEMS applications include:

- Sensors such as MEMS accelerometers, MEMS gyroscopes, MEMS pressure sensors, MEMS tilt sensors and other types of MEMS resonant sensors;
- Actuators such as MEMS switches, micro-pumps, micro-levers and micro-grippers;
- Generators and energy sources such as MEMS vibration energy harvesters, MEMS fuel cells and MEMS radioisotope power generators;
- Biochemical and biomedical systems such as MEMS biosensors, lab-on-chips, and MEMS air microfluidic and particulate sensors;
- MEMS oscillators for accurate time keeping and frequency control applications.

At an even smaller nanometer scale, the fabrication technology moves into nanoelectromechanical system (NEMS).

Furthermore, where MEMS is integrated with other technologies, various combinatory embodiments can take form, such as:

- BioMEMS where biochemical and biomedical systems are realized on micro-fabricated devices (e.g., Lab-in-chip devices);
- Micro-opto-electro-mechanical system (MOEMS) or OptoMEMS where optical systems such as micro-mirrors or lenses are integrated to manipulate or sense light at the microscopic scale;
- Radio frequency microelectromechanical system (RFMEMS) typically involves close integration with semiconductor microelectronics to provide RF transduction and switch capabilities.

3. Wireless Sensor Networks (WSN)

Sensors usually belong to a hierarchical and capillary communication network. Individual smart sensors are connected by a wired or most of the time a wireless protocol to a concentrating node (e.g., and edge node in an IoT configuration). Edge nodes can receive sensing data of a plurality of sensors and manage in/out fluxes to and from the cloud. Each concentrating node in a sensor network is typically equipped with radio transceivers and antenna(s) which are used to communicate (e.g., to cellular protocols) with either other neighbor nodes or the remote cloud.

WSN can be defined as: “a network of endpoint and concentrating devices, sensing and processing information gathered from a monitored field (an area or a volume) through wireless links. The data are forwarded, possibly via multiple hops, to a sink (e.g., an edge node or a fog node) that can use it locally or send it to the cloud. The nodes can be stationary or moving. They can be aware of their location or not. They can be homogeneous or heterogeneous (in terms of packaging, communication protocols, power characteristics and so on)”[23].

Sensor networks are often heterogeneous, the distributed network of very numerous small sensing devices being often of a capillary nature with a variety of connectivity protocols used. The wireless protocols that are the most commonly used in WSN are:

- Wi-Fi;
- Zigbee;
- UWB;
- Z-Wave;
- NFC;
- RFID;
- EnOcean;
- Thread;
- 6LoWPAN;
- Wireless-Hart (WHART);
- Process Field Bus (PROFIBUS);
- DECT-ULE;
- Cellular (3G, 4G soon 5R);
- Bluetooth: Bluetooth Smart, Wi-Fi/Bluetooth Smart, Bluetooth Smart/ANT+, Bluetooth 5;

Some dedicated smart sensor networks may use wired protocols. For example, CAN, LIN or Flexray are buses used in the automotive segments to connect sensors or micro-actuators. Other examples are KNX for smart home, Ethernet, Modbus for programmable automata, LonWorks or Digital Addressable Lighting Interface (DALI) in building automation.

4. The main emerging sub-technology: Smart dusts

Advances in hardware technology and engineering design have led to dramatic reductions in size, power consumption and cost for digital circuitry, wireless communications and Micro Electro Mechanical Systems (MEMS).

Smart dust refers to a collection of tiny wireless computers (also named “motes”) embarking in a very small footprint package microelectromechanical sensors (MEMS). Typical volume is a grain of sand or a few cubic millimeters. These sensors are able to detect conditions such as light, vibration, temperature and noise, and autonomously communicate this information back to a receiver. As their name suggests, individual smart dust motes measure only a few millimeters in size. They are therefore a miniature combination of electronics, processing and nanotechnology.

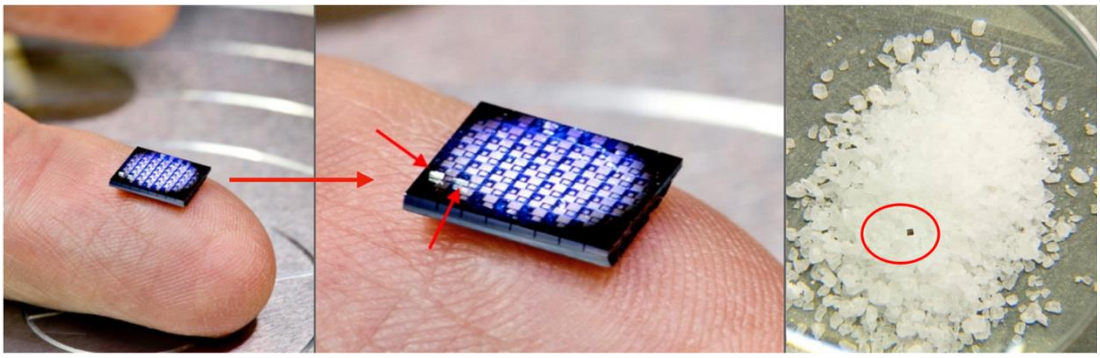
The concept of smart dust was conceived in the 1990s by a US military defense (DARPA) research project with the support of the RAND corporation as a detection strategy on the battlefield. It was imagined that smart dust motes could provide real-time information on their environment in a battle situation. Due to their minuscule size, they would be almost impossible for an enemy to detect, either scattered on the ground or traveling freely through the air with the wind.

[23] See “An overview of Wireless Sensor Networks toward Internet of Things”, IEEE, Mustafa Kocakulak and Ismail Butun, Department of Mechatronics Engineering, Bursa Technical University, Turkey

The foreseen civilian applications are various: Health & Care (implanted sensors), environmental monitoring, building monitoring (smart home), industry 4.0 in addition to Defense & Security.

The picture bellows shows IBM smart-dust computer: it is small (about 1 mm x 1 mm), but it has the power of a complete computer. With a few hundred thousand transistors, some bytes of RAM, a solar cell and a communications module, it has about the power of a chip from the early 1990s. The left-hand side picture shows an assembly of several tens of such computers (motes). The two arrows point out two individual motes. The right-hand side picture shows the size of one single mote, comparable to a grain of salt (inside the red circle). According to IBM, such chips could be produced at a cost of 10 cents in the coming years.

The IBM smart-dust computer



Source: IBM

ii. Synergies with other technologies

Smart sensors are driven by many emerging technologies studied in this report.

- **Beyond CMOS.** Smart sensors are more based on a combination of CMOS devices, MEMS and other nanocomponents;
- **Integrated photonics.** More and more micro and nano-optical components will be integrated into smart sensors (lenses, filters, polarizers, etc.);
- **Advanced packaging.** Miniaturization, performance and cost are key design criteria for smart sensors. As most of these sensors will integrate heterogeneous components, this will require innovative packaging (heterogeneous SIPs, 3D, Polymers, Flexible, etc.);
- **Cryptography.** It is very important to boost security or firmware updates over-the-air during the lifetime of smart sensors. This requires specific lightweight cryptographic protocols;
- **Artificial Intelligence.** It is expected that future advances in technology will enable to have some smart sensors able to embark forms of local Artificial Intelligence.

iii. Technology roadmap: Maturity levels and expected impacts by application area

A. Markets

Smart sensors are already mature to a large extent. Yet, the penetration rate in the end-user application domains is expected to boom within the next decade.

- The smart sensors market represented €20-25B worldwide in 2018 and should reach €40-45B in 2023, at a ~15% CAGR;
- The smart dust market represented less than €300M in 2018 but should exceed €1B by 2023, at a ~30% CAGR.
- Finally, the Global MEMS Sensors production represented €2.7B in 2018 and is expected to reach a value of €3.6B in 2023, growing at a projected CAGR of 6.1% during the forecast period (figures based on Yole Development estimates). According to SEMI, the global capacity for the production of MEMS and sensors will increase by 25% between 2018 and 2023 to reach the equivalent of 4.7 million 200 mm diameter silicon wafers per month in 2023.

B. Economic impact

Although the maturity of smart sensors depends on the technologies used, smart sensors (and related WSN network) is definitely an **enabling and critical technology for all application domains** and will therefore have a significant impact on every electronic end-user industry. Yet, the main markets for smart sensors will be:

1. IoT & smart systems (smart home, smart city, smart grids, industry 4.0, etc.);
2. Automotive (ADAS);
3. Smartphones.

Last but not least, **smart sensors will play an ever-increasing role in all emerging IoT domains** related to all business applications: Consumer, Home Automation, Smart City, Wearable Electronics, Commercial, Retail, Aerospace and Defense, Drones/unmanned aerial vehicle (UAV), Logistic & supply chain, Entertainment, Financial institutes, Corporate offices, Industrial, Energy, Transportation, Health Care, Smart-Agriculture, etc.

Automotive (ADAS) is another key and strategic domain of application for smart sensors, especially in the race towards autonomous cars: for example, ADAS applications use various sensors to collect physical data about the vehicle and its surroundings. After collecting data, an ADAS will then use object detection, recognition and tracking processing techniques to evaluate threats. Another example is LDWS (Lane Departure Warning Systems), which alerts the driver when an unintentional lane change is detected. The number of sensors per car is projected to reach 200 in the next few years. These numbers translate to more than 20 billion sensors sold annually in the automotive industry by 2020. For instance, LDWS uses CMOS camera sensors, night vision uses an infrared sensor, adaptive cruise control typically uses radar, ultrasound sensors are required in park assist applications, etc.

A modern **smartphone** can handle over 15 different types of smart sensors, as shown below:

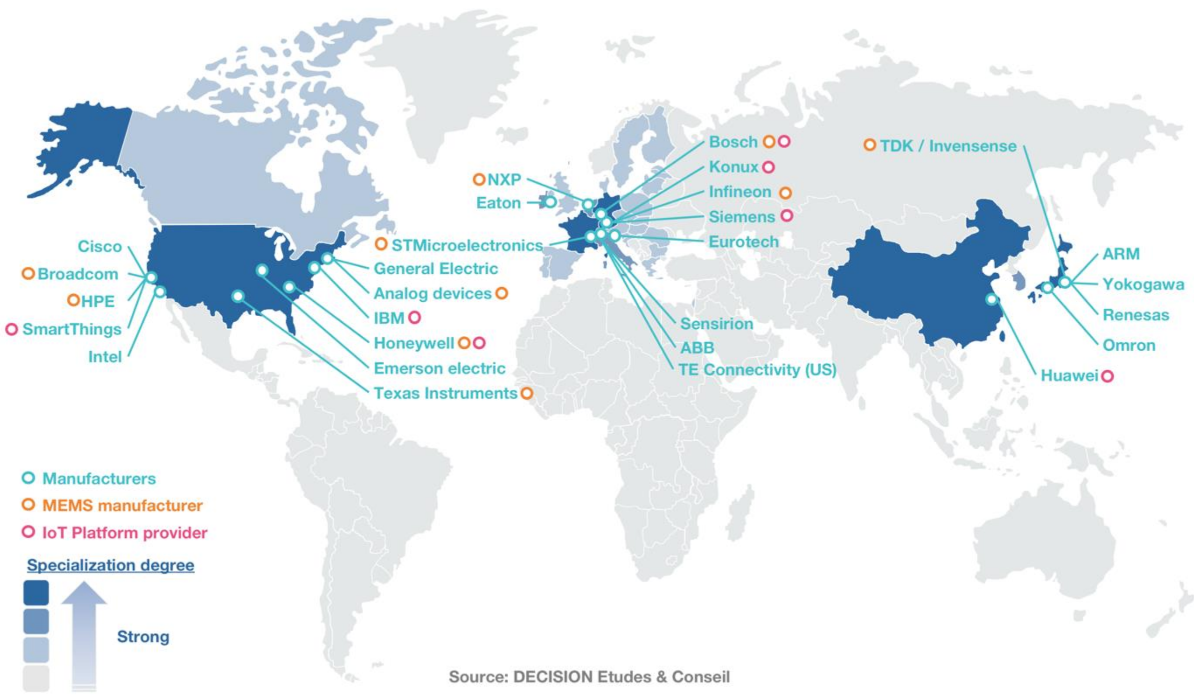
Built-in sensors in a typical present-day smartphone

Source: Smartphone Sensors for Health Monitoring and Diagnosis, Sumit Majumder and Jamal Deen, 2019.

iv. Main players in the World and in the EU

A. World competitive landscape

The World map below present the main competitors worldwide and the players also involved in MEMS manufacturing (upstream the value chain), and IoT platforms (downstream the value chain).



The EU has strong companies in the areas of smart sensors, MEMS and tiny (low-footprint) embedded systems and benefits from some very strong integrators in all major verticals (Automotive, Energy, Defense, Transportation, Telecoms, Utilities and Environment). Therefore, the EU can be considered -as a whole- on equal footing with the USA, China and Japan.

The European situation is more contrasted in the area of data analytics and fusion of sensing data, which will be critical for developing service businesses (associated with large revenue opportunities). As the EU miss leading actors in the field of large IoT platforms, this may create challenging positions in a long-term perspective. In particular, this might be critical for some large-scale applications such as Smart-Cities, Smart-Mobility where large American software vendors could capture the biggest part of the value from their IoT platforms.

The EU is almost not present in the area of smart dust. Among the main companies investing in smart dust development, one can find:

- In the USA: IBM, BetaBatt, Civicsmart, Crossbow technology, Valarm, etc.
- Hitachi (Japan), Cleverciti (Germany), etc.

B. Main R&D centers in the EU

The table below presents some of the main R&D center in the EU:

Country	Main R&D centers
Belgium	IMEC
France	CEA, CNRS
Germany	Fraunhofer Institutes
Italy	Centro Research Fiat
Spain	CNIM
Switzerland	CSEM
Austria	AIT
Ireland	Tyndall
Finland	VTT

Source: DECISION Etudes & Conseil

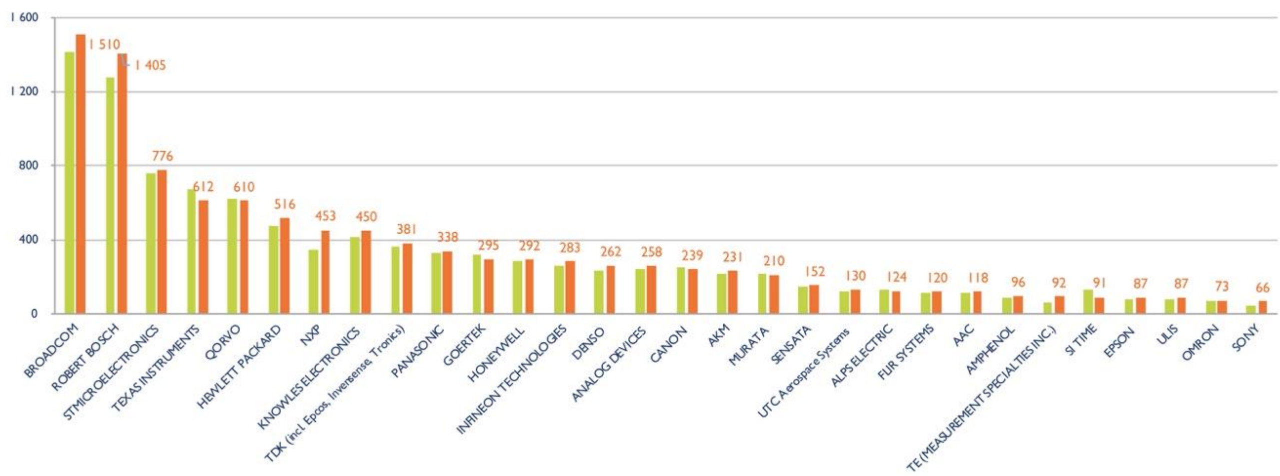
C. Upstream the value chain – Focus on the MEMS

The following bar charts from Yole Development show the Top 30 MEMS manufacturers and the 18 Top MEMS foundries in 2018.

According to SEMI, geographically, in 2018 and in terms of wafer production capacity equivalent, the largest share returned to Japan, followed by Taiwan, the Americas and EMEA. China, which was in sixth place in 2018, is expected to advance to third place in 2023. Japan and Taiwan will retain first and second place respectively in 2023.

2018 Top MEMS manufacturers – In US$ million

(Source: Status of the MEMS Industry report, Yole Développement, 2019)



2018 Top MEMS foundries * – In US$ million

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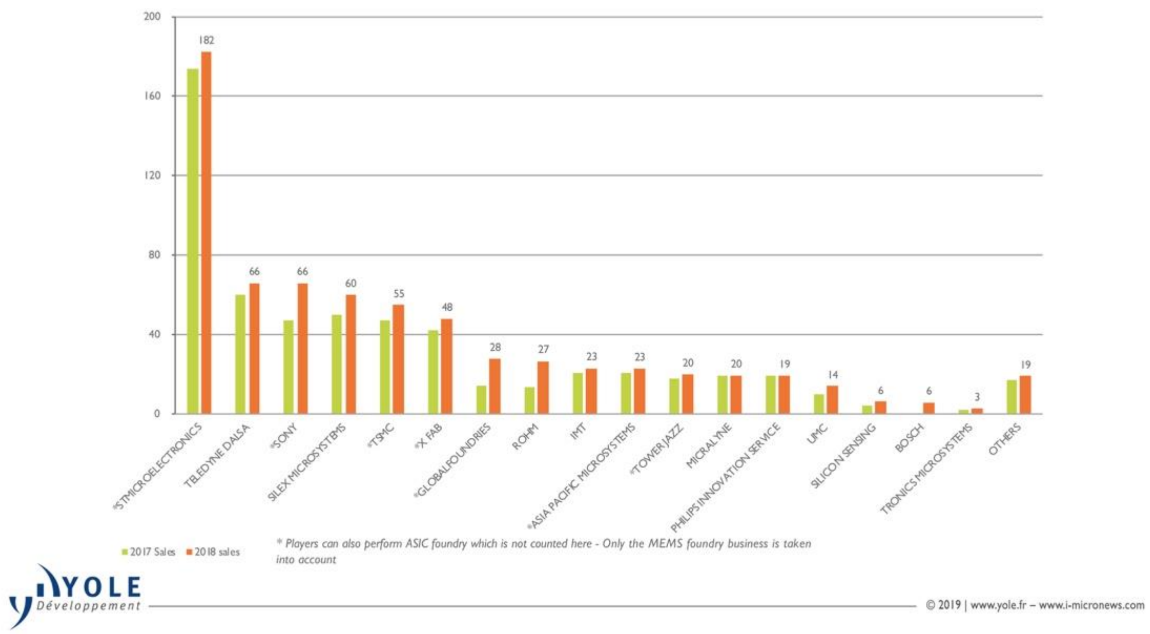


Impact of smart sensors by end-user electronic applications in 2023

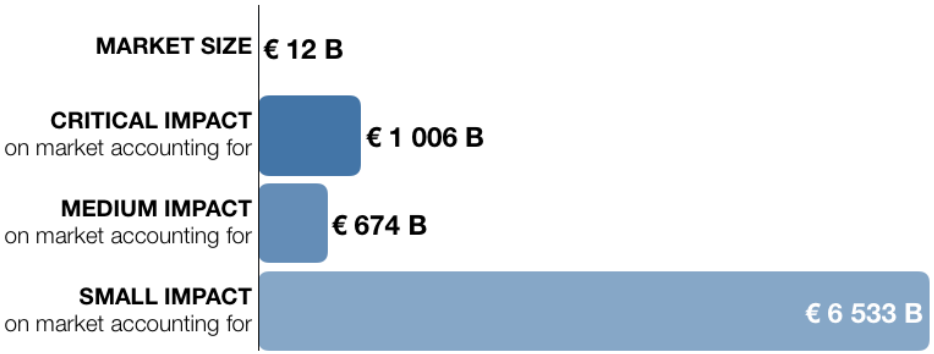
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Critical	Critical	Small	Medium	Small	Medium	Small	Medium	Small	Medium	Medium

Corresponding quantitative impact of smart sensors in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
12	1 006	674	6 533	1 006	674	846	0	0	5 687
				Automotive electronics, Industrial & Robotics electronics	Mobile phones, Defense & Security, Health & Care, Home Appliances, Aerospace electronics	Consumer PCs, Telecommunication infrastructures, Audio/Video, Professional PCs	-	-	Industrial equipments industry, automotive industry and Aerospace/ Defense/Security industries

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of smart sensors in 2023



Source: DECISION Etudes & Conseil

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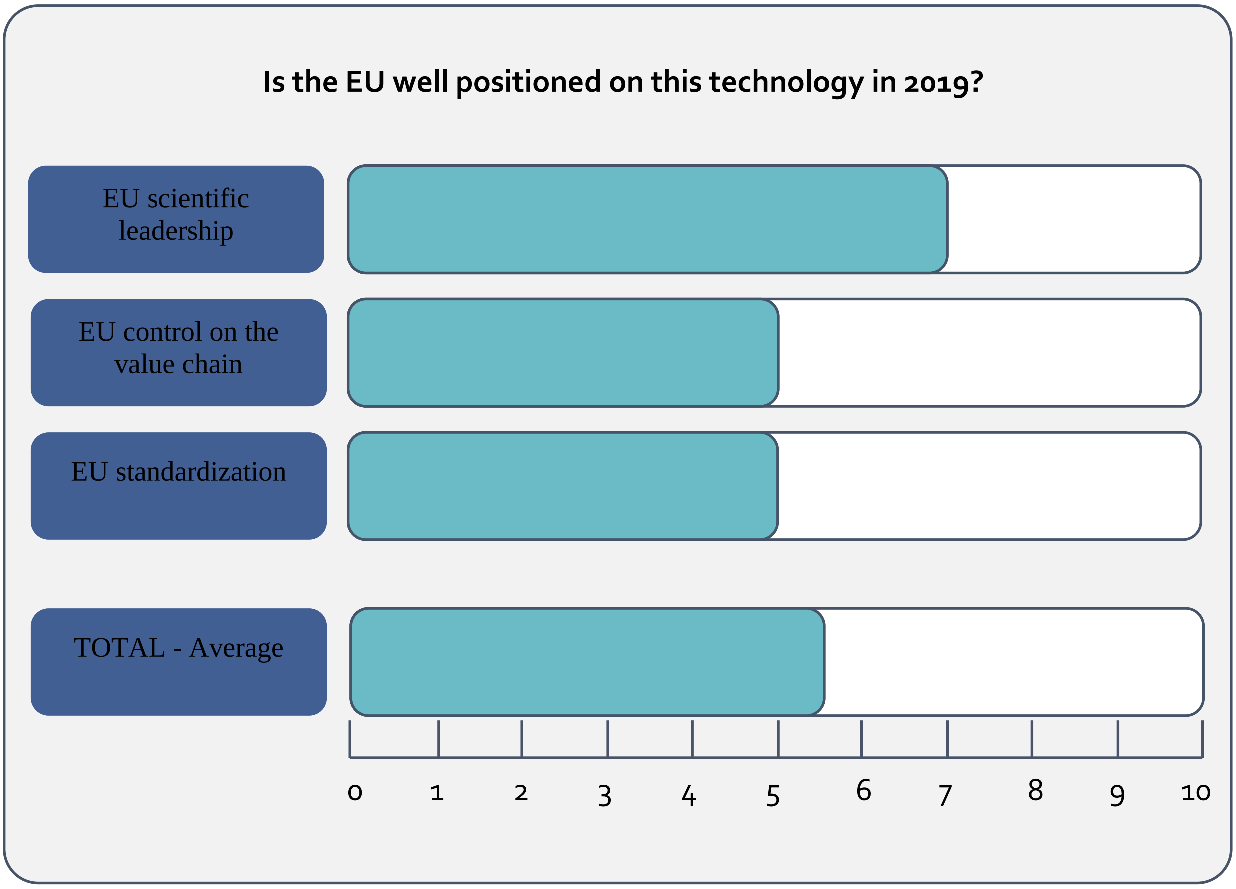
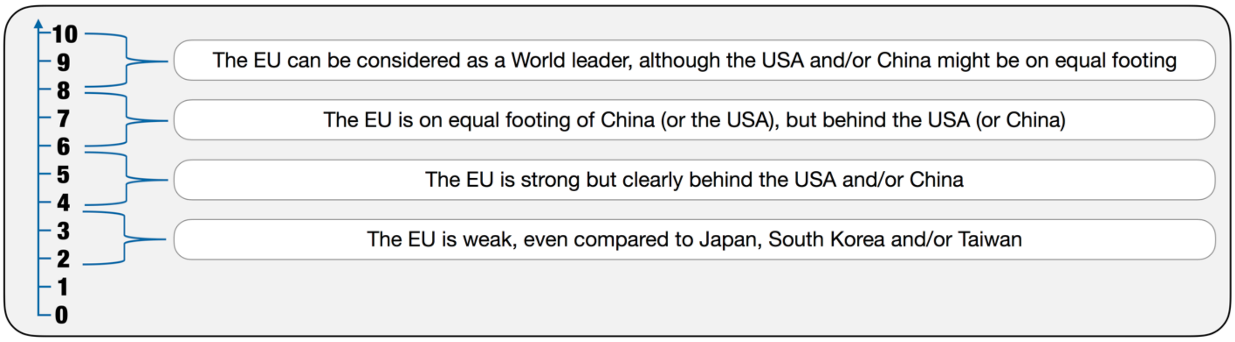
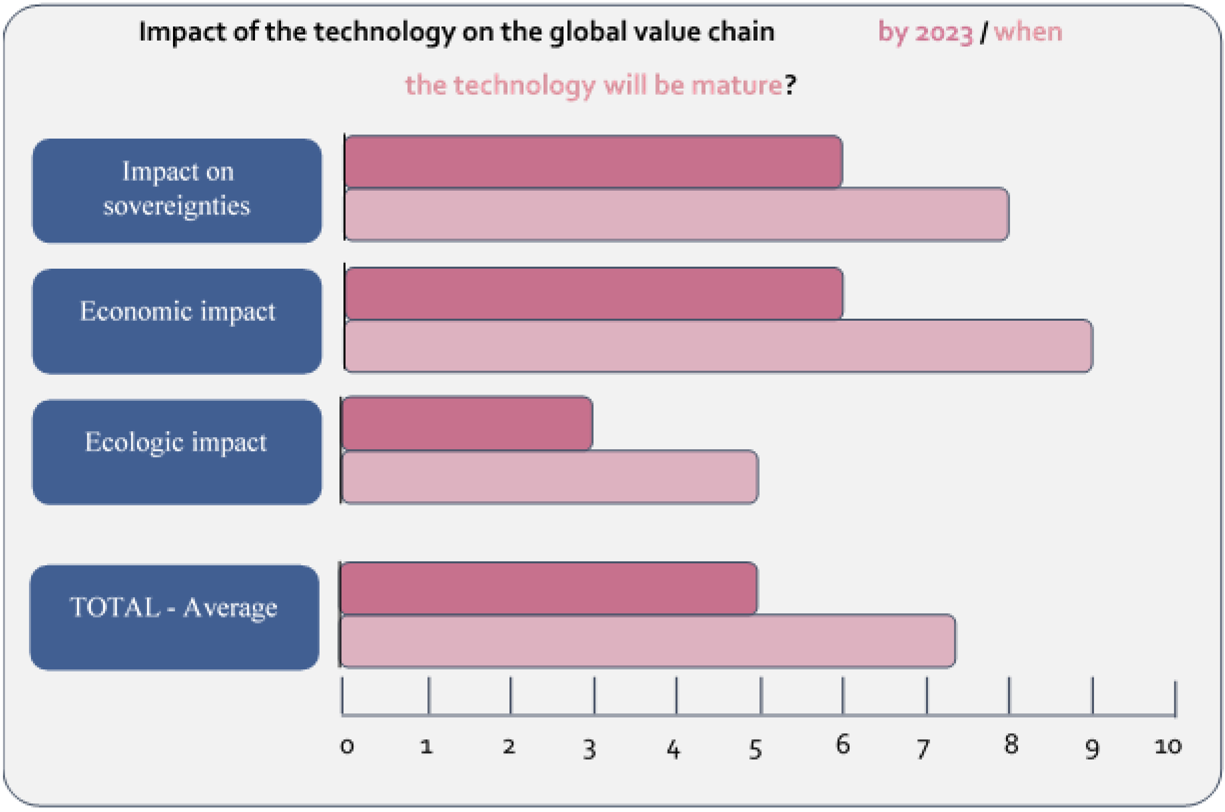




Source: DECISION Etudes & Conseil

B. Critical level for the EU



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- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU is on the leading edge of industrial and scientific R&D in sensing and MEMS technologies, with some worldwide renowned excellence clusters in the areas of Grenoble, Leuven/DSP Valley and Dresden, gathering together dynamic research centers, SMEs and large groups. The research results find immediate applications in the Automotive, Industrial Automation, Defense, Security and Health fields, where the EU has strong industrial leaders.

The European situation is, however, more contrasted in the area of data analytics and fusion of sensing data. As the EU presents a shortage of leading actors in the field of large IoT platforms, this may create challenging positions in a long-term perspective.

Finally, the EU is almost not present in the area of smart dusts.

On the skills level, another challenge is the relative shortage of human resources in the related research areas as compared with its main competitors.

EU control on the value chain

The EU has strong companies in the areas of smart sensors, MEMS and tiny (low-footprint) embedded systems. The EU also has some very strong integrators in all major verticals (Automotive, Energy, Defense, Transportation, Telecoms, Utilities and Environment).

The weakest point in the chain is in the data collection and aggregation and in IoT platform enablement, which will be critical for developing service businesses, which is expected to represent large revenue opportunities. This might be critical for some large-scale applications such as Smart-Cities, Smart-Mobility where large American software vendors could capture the biggest part of the value from their IoT platforms.

Finally, the EU is lagging in the emerging smart dust field.

Standard analysis

Standard is a complex issue in Smart sensors.

- First, wireless communication protocols proliferate and there is no “one size fits all” solution for heterogeneous networks of sensors, such as one could imagine in large applications (although IEEE 802.15.4 is gaining popularity in home automation, smart cities, industrial automation);
- On the smart sensor side, European actors should closely follow the evolution of the various related IEEE standards related to the field (e.g., IEEE 802.22/2019, IEEE 2700 series on smart cities and so on);
- The lack of security standards for IoT/Smart Sensor platforms is more problematic. This is as a major bottleneck for the growth of the IoT sensors market because enterprise, government and individual data security and privacy are highly important for the development of analytics solutions for several vertical-specific applications.

Impact on national sovereignties

Smart sensors and Wireless Sensor Networks (WSN) are enablers for almost all domains involving the EU sovereignty (e.g., Border or maritime surveillance, Critical Infrastructure monitoring, Defense and security, Transportation systems, Utilities, etc.). This emphasizes, along with the need for domestic secure and privacy preserving IoT architectures, the importance of mastering the domestic development and manufacturing of the related technologies.

Economic impact

In addition to their own expected generated revenues in the next 5-10 years (expected €40-45B market by 2023), smart sensors and Wireless Sensor Networks (WSN) clearly represent one of the most promising technologies studied in this report in terms of economic impact. Smart sensor and WSN will leverage a lot of IoT businesses with several multiplying effects in the Infrastructure (e.g., 5G, Cloud), service (e.g., Sensing as a Service new business models), and integration (e.g., smart-cities, critical infrastructure) domains.

The value chain on the top of sensors and WSN system is however complex, involving multiple manufacturers, integrators, operators, and vertical customers. To take the maximum benefit of the technologies, European actors should build wide-ranging alliances or ecosystems. These questions are of crucial importance for the target commercial applications in all future Business to Business (B2B) and Business to Government (B2G) models.

The business potential of smart dust is subject to some serious challenges linked to privacy and security as well as to their deployment and social acceptability. Large projects are, however, engaged in the World: For example, HP's goal is to deploy over a trillion smart dust sensors across the planet to generate a Central Nervous System of the Earth and is working with Royal Dutch Shell to install a million monitors to aid in oil exploration.

Ecological impact

Smart sensors will likely be deployed by billions of units by 2025-2030 and undoubtedly contribute to an increase of energy consumption even if they will be Ultra-Low or Low power devices and if some of them will be provided with energy harvesting capabilities. Nevertheless, numerous eco-friendly applications are foreseen for smart sensors and smart dusts in the coming decade:

- Forest monitoring: To fight illegal deforestation;
- Fauna & flora monitoring: To protect endangered species;
- Ocean monitoring: To preserve Ocean's quality;
- Air quality monitoring: For instance, Methane and Co2 detection;
- Smart-farming and minimization of chemical substances used;
- Waste management through waste monitoring;
- Etc.

Conclusion

Smart sensors will be key for the development of future IoT applications along with Wireless Sensor Networks (WSN) and IoT Cloud platforms. Mastering these technologies should enable the EU to develop the complete IoT ecosystem around its key industries (automotive, utilities, defense and security, health…). This will suppose an intensive R&D support in nanotechnologies, MEMS and sensing data analytics, IoT security and privacy architectures.

The European research on security and privacy issues in smarts-sensors, Wireless-Sensing Networks (WSN) and IoT platforms should be developed as cybersecurity will represent a major challenge for the future.

The EU should also start investigating the smart dust domain, which could represent the new wave of energy-conscious computing.

4. Cybersecurity and trust

A. Secure elements

This domain is especially important for the EU as all basic related technologies have been born in Europe, enabling the development of a large and profitable business for domestic champions, as well as creating a lot of highly qualified jobs in Europe.

i. Definition

Definition

E-secure components refer to micro or nano-electronics components showing a combination of secure embedded Software (SW) and / or Hardware (HW) and aimed at being integrated in communicating devices in order to manage in a secure way all the interactions between these devices and the outside world by storing dedicated applications and confidential data in a ciphered way.

The main usual functions of an e-secure element are to manage secure identification, authentication of users (or objects), to compute trusted signatures, to enable remote provisioning of data of embedded SW and to manage life cycle of confidential data. E-secure components generally include a local processor with strong cryptographic capabilities, a local RAM and ROM, and secure embedded non-volatile storage capabilities (e.g., EEPROM, Flash, etc.).

E-secure components can be either packaged in a dedicated removable module, such as a plastic card, a paper booklet (passport), sold on the motherboard of an electronic device, embedded in a complex SiP (System in Package) or directly embedded as a dedicated IP block in a SoC (System on a Chip).

The security of e-secure elements must in many cases be certified by an independent body such as national agencies (e.g., ANSSI in France, BSI in Germany, NIST is the US), according to internationally recognized standards (e.g., Common Criteria, Global Platform, FIPS).

Historical development

- **Payment cards**

Historically the development of the e-secure component technology has started in the 1980s, pushed by the financial sector and the progressive deployment of the chip-based payment cards. The corresponding form factor has been a microelectronic chip embedded in a plastic card according to a set of specifications fully standardized by the ISO/IEC organizations (known as “ISO/IEC 7816 international standard related to electronic identification cards with contacts”, set up in 1987).

On the application side, the EMV (Europay, MasterCard, Visa), is the worldwide standard for payment cards introduced in 1995 that provides global interoperability between all cards and the acceptance networks (payment terminals). The EMV standard is also applicable to mobile payment solutions such as mobile EMV with NFC (Near-Field-Communication). Yet, the EMV Payment is based on the chip & PIN technology i.e., the use of a secure element (Certified Silicon chip), and a PIN code used by the cardholder to secure his/her payment transactions.

A very specific feature of this chip card technology is that every e-secure component contains a set of unique diversified cryptographic data generated during the so-called “personalisation” phase (i.e., after the manufacturing of the microelectronic component containing the application code and its embedding in the plastic substrate).

Alternatives to PIN technology for payment (e.g., based on biometric features), are, however, now experimented in most geographic areas in the world.

Nowadays, all the identity documents used by governments and packaged in plastic (e-identity, Schengen permits immigration cards based on the IAS standard), or through paper booklets (e-passports standardized by the ICAO organisation), are also using secure elements based on the ISO 7816 standards and using biometric algorithms. They have been introduced in the late 1990s.

- **SIM cards/UICC**

By the end of the 1980s, GSM networks started to develop, and network operators needed a reliable method of identifying users and checking the authenticity of endpoint devices. This need spurred the development of the Subscriber Identity Module (SIM), based on the same physical standards as the payment card (ISO/IEC 7816). The network identification and authentication algorithms implemented in the SIM follow the standards developed by the ETSI and 3GPP organizations.

Over the years, with the evolution of GSM towards GPRS, 3G, 4G and soon 5G networks, the level of programmability, connectivity and remote provisioning of SIM cards has dramatically evolved. The UICC (Universal Integrated Circuit Card), is the generic term used for designing all components of this evolution. On the physical side, and thanks to the progress of microelectronics but also under the pressure of mobile handset manufacturers, SIMs have shrunk from the original 1FF (*form factor*) to 2FF (Mini SIM), 3FF (Micro SIM), and finally 4FF (Nano SIM).

Although SIM cards (especially with new programming platform such as embedded Java and OTA connectivity), can manage a dynamic portfolio of embedded applications, they are mostly used for storing operator profiles that enable authentication on cellular networks.

Traditional SIM cards have the operator-defined profile programmed during the manufacturing process and are therefore tied to one given operator.

- **IoT and new form factors: e-UICC, I-UICC**

IoT devices bring the promise of many new possibilities, but only if they can be connected and deployed in a scalable manner and identified securely. This is especially true for all critical applications linked e.g., to smart-cities, health care, industry 4.0, connected cars, smart-grids and so on. The recent examples of successful and large-scale Distributed Denial of Service attacks (DDoS), performed with IoT botnets such as “Mirai” show, however, that very low IoT device security can generate enormous financial and operational damages. E-secure components represent a strategic technology for achieving this objective, with the key design point to integrate an e-secure element inside every critical IoT device.

With the explosion of IoT devices, traditional SIM cards show, however, several issues including:

- Size. Even Nano SIMs, along with their socket, can occupy too much space in very small devices;
- Fragility. User-replaceable SIM cards are easy to damage;
- Physical security. If a pluggable SIM can be accessed, it can be easily stolen or destroyed in order to deny service or to connect to the outside;
- Management and cost. Because traditional SIM cards are replaceable, there are additional costs linked to the related inventory, shipping or installation processes.

Embedded UICCs (e-UICCs), are an evolution of the SIM card designed to address the limitations mentioned before. E-UICCs incorporate many new functionalities needed for the world of M2M (Machine to Machine) or IoT devices. The key driver for this evolution is remote provisioning, corresponding to the ability to change remotely the SIM profile on a deployed SIM card without having to change physically the SIM card. The GSMA is actively working on the corresponding use-cases and technology characteristics. Contrarily to the replaceable SIMs, e-UICCs are soldered into the device and enable storage and remote management of multiple network operator profiles.

A variant of the e-UICC, which could lead to other types of optimizations while retaining SIM security, is the concept of integrated UICC (i-UICC). In this case one moves the UICC from a separate chip into a secure enclave alongside the application processor and the cellular radio chip on a purpose-built system on a chip

(SoC). Delivering these three building blocks in one embeddable component greatly reduced the circuit board footprint, component sourcing, and IoT device manufacturing costs. ARM (now owned by the Japanese Softbank), and Qualcomm, for example, are working on this concept. There are however some issues on standardisation and assurance concerns on this emerging technology.

- **Soft secure elements / Soft SIMs & Trusted Execution Environment (TEE)**

A soft SIM is an e-secure element made of a collection of software applications and data that performs all the functionality of a SIM card but does not reside in any kind of secure data storage neither use a dedicated secure processor. Instead, it is stored in the memory and processor(s) of the communications device itself. This type of e-secure element offers the following advantages:

- It saves space within the device and does not require any physical integration;
- It is “costless” for the device manufacturer and simplifies value chain;
- It is fully scalable.

However, there are many concerns related to this technology:

- Soft SIM is a concept that has not been standardised;
- There is no clear security certification due to the software-only architecture;
- Soft SIMs are more susceptible to security breaches given their architecture design. They cannot ensure that critical data loads are secured;
- There are uncertainties as to whether Soft SIMs would be a viable authentication mechanism.

A Trusted Execution Environment (TEE) is the main type of soft secure element currently explored. It is a secure area of the main processor in a smartphone or connected device which ensures that sensitive data is processed and protected in an isolated, trusted environment. This e-secure element technology offers the following advantages:

- It is cost-effective and removes some supply chain and logistical complexities;
- TEE are relatively easy to integrate, deploy and update;
- TEE SW can be certified at very high levels (up to the level EAL7).

There are, however, some potential drawbacks:

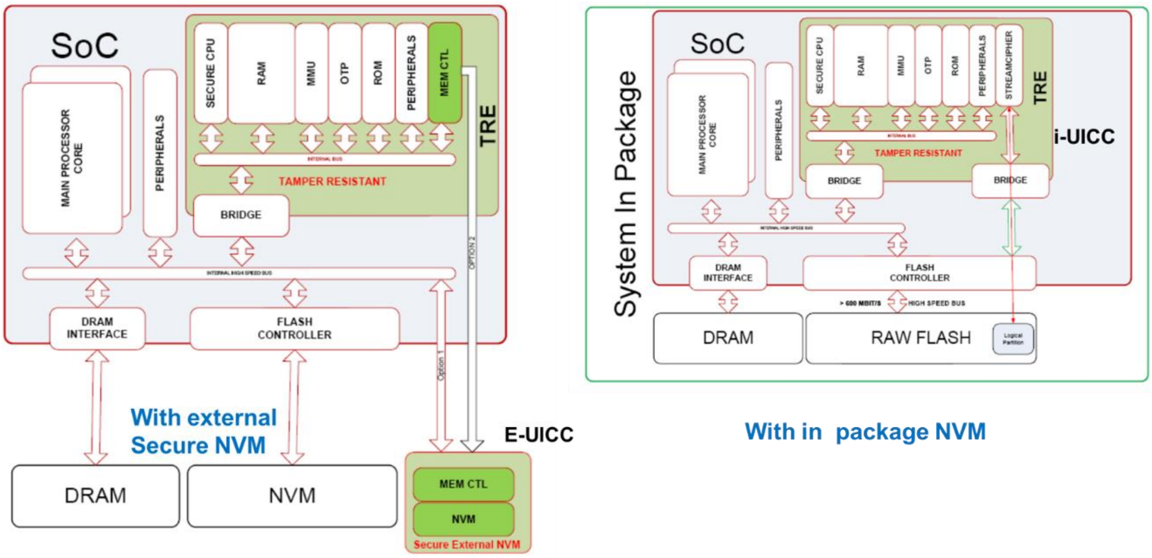
- There is no standardized UICC application running within the TEE;
- TEEs use shared memory with other “non-trusted” SW;

There are insurance concerns as TEE represents a new model for the industry (it is not clear how to assess the global security even with a high-security TEE).

ii. Synergies with other emerging technologies

More-Moore. The i-UICC concept is currently actively worked out by companies like Qualcomm or ARM who target the integration of the UICC directly in the main SoC they develop for fixed or mobile devices. Technologies below 10 nm are targeted leading to complex insurance and standardization. The picture below explains the possible implementation choices.

Different implementation choices of UICC on SoC



Source: Gemalto, presentation at the NEREID workshop, 2017

Advanced packaging and innovative memories. Current HW-based e-secure elements are nano-electronic chips integrating a CPU, RAM and ROM memory, special communication channels and a NVM (Non Volatile Memory). Over time, the NVM has evolved from EPROM to EEPROM and now Flash technology. In the future, driven by the IoT constraints, the embedded NVM could evolve towards alternative NVM technologies (e.g., PCRAM, CBRAM, MRAM, etc.). Such new choices of NVM could lead to alternative packaging.

Edge AI. Most biometric recognition algorithms are enhanced through the use of AI. A major future trend is to have recognition algorithms (behavioral biometrics, etc.), with a small footprint, low-power consumption and AI capabilities directly integrated in the e-secure element.

Identity and Authentication. E-secure elements are by definition aimed at ensuring security of electronic transactions. Secure identification and authentication are enforced thought the use of e-secure elements. Most identification and authentication algorithms are hence fully or partly implemented in e-secure elements. The current trend is to implement biometric algorithms (fingerprint, face recognition, etc.), directly in e-secure element. This process is named “Match on Card”, in opposition to the “match on server” approach, where biometric recognition is done on a remote server (with the e-secure element storing and transmitting in an enciphered way the biometric data to the remote server in charge of the authentication.

Cryptography & Quantum cryptography. All e-secure elements embed cryptographic algorithms based on world encryption standards (e.g., AES for secret key algorithms, RSA or Elliptic Curves for Public Key, SHA hash functions). The next generation could embark lightweight cryptographic algorithms for IoT support, or post-quantum algorithms for replacement of existing secret key or public key algorithms.

5G. As commercial e-UICC services are not expected to be massively deployed until the early 2020s, it is very likely that only a minority of e-UICC enabled devices will operate under currently available mobile networks (2G/3G/4G). The progressive deployment of 5G will be a disruptive factor a change, and new concepts such as NFV (Network Function Virtualisation), or slicing will accelerate the development of massive IoT configurations, provided the cybersecurity is guaranteed.

iii. Technology roadmap: Maturity levels and expected impacts by application area

A. Secure elements markets

The market of secure elements, mainly based on Payment/Card and UICC will continue to represent massive quantities with 11 B units expected in 2023, corresponding to a market of €18 B and an average growth rate of 1.4% per year over the 2018-2023.

Currently, the related hardware accounts for more than 75% of the market value. The remaining 25% market value is related to management system software, databases, consulting, support, and maintenance services.

Secure elements market (B€)

	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
Market (B€)	17	17	17	18	18	18	1,4 %
Average Selling Price (€)	1,6	1,6	1,6	1,6	1,6	1,6	-0,5 %
Market (Unit)	10	10	11	11	11	11	1,9 %

Source: DECISION Études & Conseil, based on Eurosmart estimates

The market of secure elements is distributed in five classical segments:

1. Telecommunication (SIM cards), accounts for 55% of the total market in 2018;

2. Finance. Payment and banking cards account for 31% of the total market in 2018. Contactless transactions are the driving force in the financial service market (nearly 50% of the secure elements sold in the finance segment in 2018 were dedicated to contactless transactions, against 24% in 2016). This will end locking the maximum amount to be paid when using contactless technology at the point of sale;

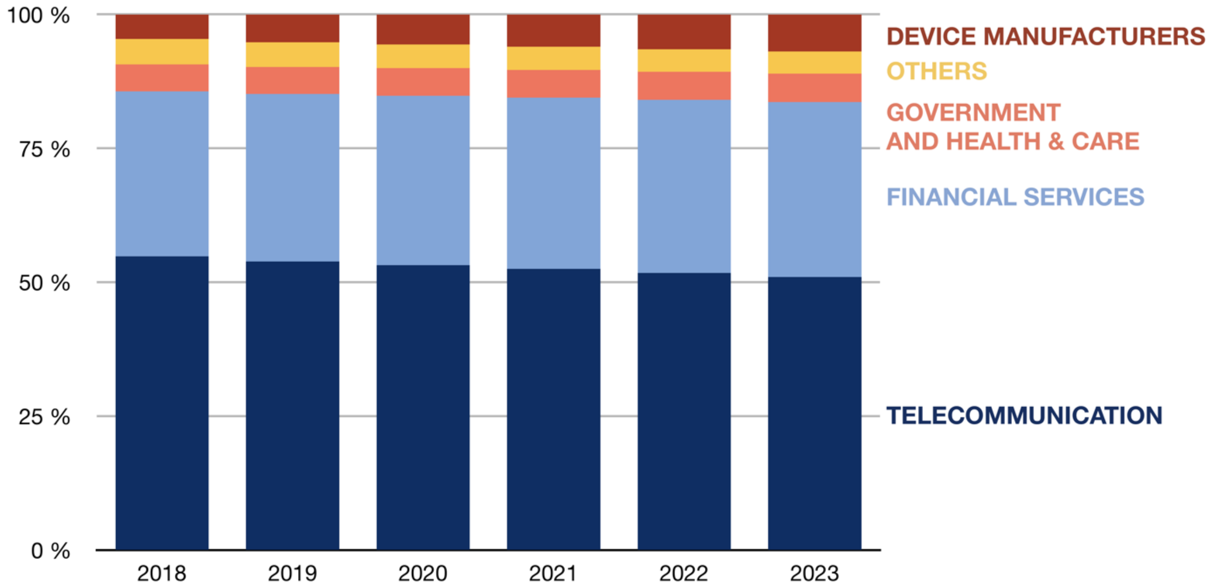
3. Government and Health & Care (eIDs and e-passports), accounting for 5% of the total market in 2018;

4. Others: Cards issued by operators, for transport, toll or car park services; cards for pay TV; physical and logical access cards;

5. Device manufacturers. The fifth segment “device manufacturers segment” accounts for 5% of the market in 2018. This market currently represents the e-UICC market for telecommunications, tablets, navigation devices and other connected devices. It is the most recent market.

Secure elements market - by segment (% in units)

	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
Telecommunication	55 %	54 %	53 %	52 %	52 %	51 %	-1,4 %
Financial Services	31 %	31 %	32 %	32 %	32 %	33 %	1,1 %
Government and Health & Care	5 %	5 %	5 %	5 %	5 %	5 %	1,3 %
Others	5 %	5 %	4 %	4 %	4 %	4 %	-2,3 %
Device manufacturers	5 %	5 %	6 %	6 %	6 %	7 %	8,6 %
TOTAL	100 %	100 %	100 %	100 %	100 %	100 %	-



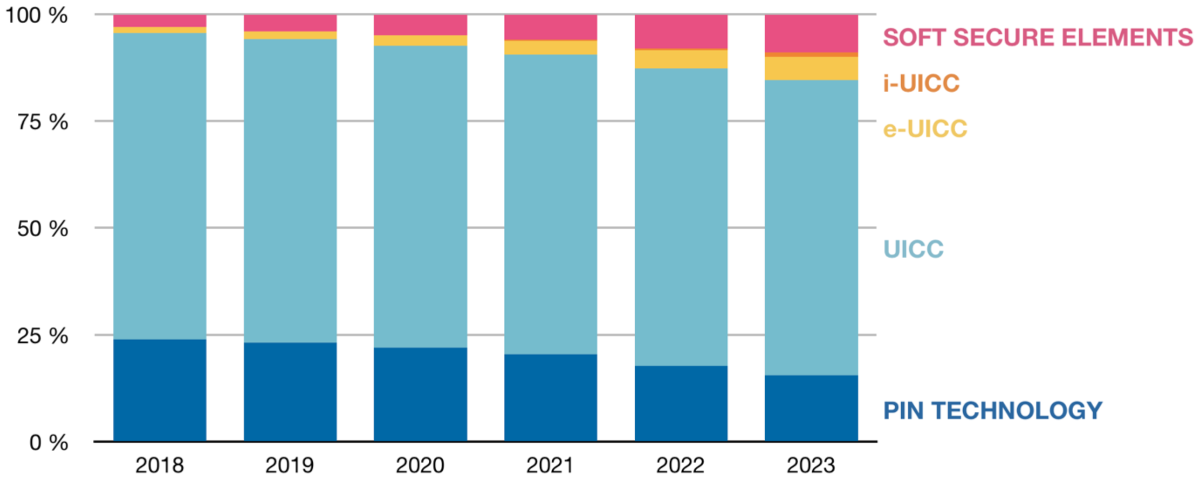
Source: DECISION Études & Conseil, based on Eurosmart estimates

A growth led by the IoT markets. The fast-expected growth of IoT in the next decade leads the current UICC/eUICC market leaders to develop open IoT platforms based on their UICC/e-UICC technology so that operators can use them for developing new Value-added Services. As all major American or Asian operators develop this platform concept, players from the EU are still remaining a bit behind.

The two main drivers of growth are the development of IoT networks (on the demand side), and the development of e-UICC (on the supply side).

Secure elements market - by technology (% Market value)

	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
PIN technology	24 %	23 %	22 %	20 %	18 %	16 %	-8,3 %
UICC	72 %	71 %	71 %	70 %	70 %	69 %	-0,7 %
e-UICC	1 %	2 %	2 %	3 %	4 %	5 %	31,1 %
i-UICC	0 %	0 %	0 %	0 %	1 %	1 %	-
Soft secure elements	3 %	4 %	5 %	6 %	8 %	9 %	24,6 %
TOTAL	100 %	100 %	100 %	100 %	100 %	100 %	-



Source: DECISION Études & Conseil

B. UICC

UICC like form factor (with related plastic or paper packaging-for e-passports), remain the mainstream option for the first 4 main segments in 2018 (telecommunication, finance, government and health & care and others). While UICC will remain stable or slowly declining in the telecommunication sector (mostly a renewal market even with the 5G introduction), there are still some growth expectations for the Payment and Government and Health & Care sectors.

A sustained innovation in UICC will be needed in the following areas:

- New memory architecture;
- Incorporation of biometry and alternatives to classical PIN technology;
- Impact of edge/embedded AI;
- Enforced HW/SW security protection against physical attacks;
- New cost-efficient, ecological packaging;
- Remote management of data, profiles and applications;
- Provisioning of new services.

C. E-UICC

The overall e-UICC market was valued at €150 Million in 2017 and should reach €815.3 Million by 2023, at a CAGR of 31.0% between 2018 and 2023. In terms of volume, the overall e-UICC market will show a growth from 287.7 million units in 2016 to a global shipment of 1,700 million units by 2023, at a CAGR of 32.4% between 2018 and 2023.

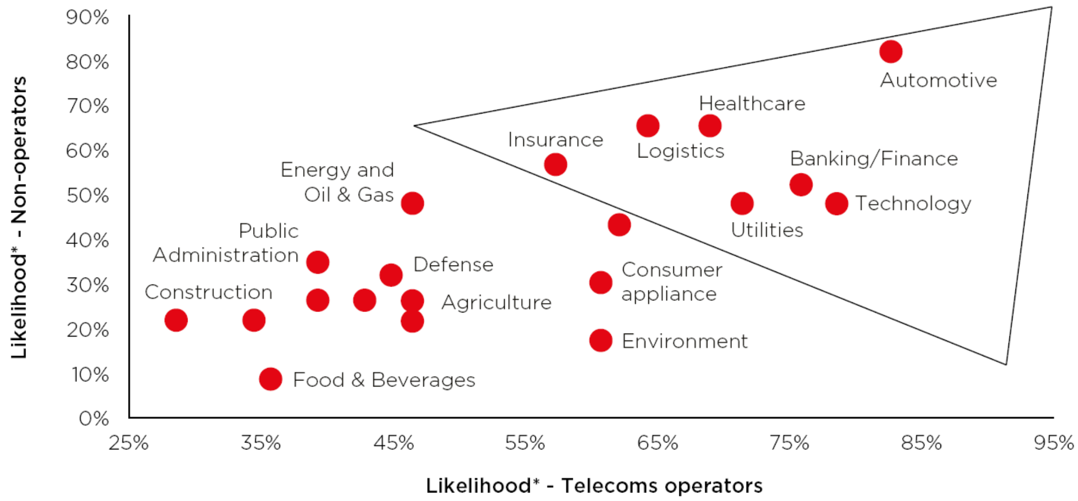
The majority of IoT devices – typically in indoor environments – will likely be connected by wireless technologies, such as Wi-Fi, Bluetooth, UWB which operate on unlicensed spectrum and are designed for short-range connectivity. They are considered as less critical in view of e-UICC adoption.

This is not the case for the other IoT devices that require wide-area network coverage, mobile connectivity, lower latency and strong reliability. This is especially true for the telecommunications, automotive, health & care, industrial and critical infrastructure domains. The telecommunication sector will also progressively make intensive use of e-UICC, targeting the development of new value-added services in many business verticals. Several telecommunication players (e.g., Apple), are currently strongly pushing for the introduction of e-UICC.

These IoT will likely be primarily connected by cellular networks using licensed spectrum. This means that cellular connectivity will be provided by either traditional cellular networks (2G/3G/4G/5G), or the emerging low-power, wide area networks (e.g., GSM-IoT, LTE-M and NB-IoT –Narrowband IoT), e-UICC playing a great role in these IoT developments.

The following picture indicates the likelihood to develop services in the targeted e-UICC domain.

Type of applications likely to be addressed through the use of e-UICC by mobile operators and non-mobile operators



Source: GSMA Intelligence

Next technology development steps.

Key research areas for e-UICC will mostly concern:

- Remote provisioning technology as a key priority;
- New memory architecture;
- New authentication methods for IoT;
- Impact of edge/embedded AI;
- Enforced HW/SW security;
- Standardized government policies in key sectors such as utilities, smart cities, automotive, healthcare;
- Module cost reduction;
- Low-cost standardized solutions for specific requirements (e.g., low data, long battery life);

- Increased API standardisation;
- Greater insurance of end-to-end security;
- Scalable architecture for e-UICC based IOT;
- Low energy, resilient, IoT architecture.

D. I-UICC

The massive deployment of i-UCC should not happen before 2024 that is once insurance and standardization problems will have been solved. The telecommunication sector should be strongly interested in the progressive introduction of i-UICC.

E. Soft secure elements

Pure SW solutions also represent a strong threat, mostly from the GAFAM and BATX which can leverage on their strong marketing and installed base to bypass the European differentiators, especially security.

F. Main impacts of secure elements on end-user applications

Secure elements have a strong impact on the following markets (accounting for €114 B in 2023):

- The payment card market, which represents €70 B in 2018 and should represent €81 B in 2023;
- The government ID markets, which represents €5.5 B in 2018 and should represent €6.1 B in 2023;
- The access control market (including the protection of critical infrastructures), which represent €27 B in 2018 and should represent €39 B in 2023.

Furthermore, as e-UICC will significantly impact the IoT networks requiring wide-area network coverage, mobile connectivity, lower latency and strong reliability, secure elements will have a small impact on the following markets (accounting for €13,000 B in 2023):

- Through industrial IoT networks / manufacturing 4.0 & industrial robotics, secure elements should play a role in the robotic industries, accounting for €280 B by 2023;
- Through automotive IoT networks / connected cars, secure elements should play a role in the automotive industry, accounting for €1,911 B by 2023;
- Through e-health & connected hospitals applications, secure elements should play a role in the health & care market, accounting for €7,254 B by 2023;
- The telecommunication market, accounting for €3,500 B by 2023.

Technology Roadmap - Maturity of secure elements at the global scale and by application area

Technology	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	Maturity level of the technology																				
UICC	Massive production																				
e-UICC	R&D	Tests & prototyping				Industrial production								Massive production							
i-UICC	R&D						Tests & prototyping					Industrial production					Massive production				
TEE	R&D						Tests & prototyping					Industrial production					Massive production				

N°	Electronic Segment	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production
1	Automotive applications	Medium impact (e-UICC)
2	Industrial & robotics applications	Medium impact (e-UICC)
3	Health & Care applications	Medium impact (e-UICC)
4	Aerospace applications	Small impact (e-UICC)
5	Defense & Security applications	Medium impact (e-UICC)
6	Phones applications	Medium impact (UICC, e-UICC, i-UICC)
7	Telecommunications infrastructures applications	No significant impact
8	PC & data processing applications	Medium impact (e-UICC)
		Small impact (TEE, Soft-SIM)
9	Audio & Video applications	No significant impact
10	Home appliances applications	No significant impact

N°	Crossed segments	Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production
1	Data analytics / Big data	No significant impact
2	Smart home	No significant impact
3	Smart mobility	Medium impact (e-UICC)
4	Smart energy	Medium impact (e-UICC)
5	Wearables	Medium impact (e-UICC)
6	Finance applications	Small impact (All: UICC, e-UICC, i-UICC, TEE, Soft-SIM)
7	Government applications	Medium impact (All: UICC, e-UICC, i-UICC, TEE, Soft-SIM)

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain by 2023.

Source: DECISION Etudes & Conseil

Impact of secure elements by end-user electronic applications in 2023

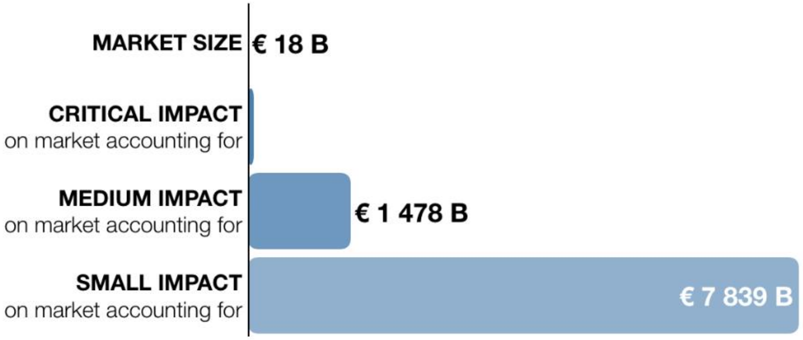
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Medium	Small	Medium	No	Medium	No	Medium	Small	No	Small

Corresponding quantitative impact of secure elements in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
18	102	1 478	7 839	102	1 478	478	0	0	7 361
				-	Mobile phones, Industrial & Robotic electronics, Automotive electronics, Defense & Security electronics, Health & Care electronics	Consumer & professional PC, Aerospace electronics	-	-	Finance sector

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of secure elements in 2023



Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. Main countries & regions

The EU has a strong leadership in the domain of e-secure HW/SW components and masters all constituents of the value chain. This is probably because the technology was born in France and Germany about 35 years ago and the market also started to develop in Europe. Idemia was formed through the progressive purchase of the French companies Oberthur Technologies and Safran-Morpho by the American fund Advent International. As a consequence, although the majority of the employees and the management are still French, Idemia can be considered as American. China has two important players (Shanghai Huahong, Shanghai Fudan Microelectronics), but also RedTea (that established the Shenzhen Association of Electronic Identity Technology Application (SAET) in 2017).

B. Main industry players in the World

Thales/Gemalto (France), Idemia (The USA), and Giesecke & Devrient (Germany), are the leading worldwide suppliers of classical UICC devices in the main market segments (telecommunications, payment, government and access cards & transport cards). The three European microelectronics companies (STMicroelectronics, Infineon, NXP Semiconductors), have also a leading position in the delivery of secure UICC, e-UICC chips together with Samsung, Shanghai Huahong and Shanghai Fudan Microelectronics. As far as IoT develops, newcomers are, of course, entering the competition.

TOP 20 main industry players in the World – Secure elements

Name of the organization	Nationality of capital ownership	Position in the electronic value chain
Bosch	Germany	M2M for cars (Bosch IoT suite)
Deutsch Telecom	Germany	M2M platform for secure IoT
Apple	The USA	e-USIM
Samsung	South Korea	e-UICC, TEE
Sierra Wireless	The USA	M2M modules
Singtel	Singapore	M2M solutions
Cisco Systems	The USA	e-USIM for network solutions
NTT Docomo	Japan	UICC, e-UICC
Telefonica	Spain	Networking M2M platform
Orange	France	e-UICC
Ericsson	Sweden	M2M device connexion/management
Thales/Gemalto	France	UICC, e-UICC, i-UICC, TEE
Idemia	France	UICC, e-UICC
Giesecke & Devrient	Germany	UICC, e-UICC, TEE
Infineon	Germany	UICC-e-UICC, TPMS
NXP Semiconductor	The Netherlands	UICC, e-UICC
STMicroelectronics	France	UICC, e-UICC
Qualcomm	The USA	UICC, e-UICC
Beijing HuaDa ZhiBao Electronic System (BHZ)	China	UICC, e-UICC
Sierra Wireless	Canada	UICC, e-UICC

Source: DECISION Etudes & Conseil

C. Main players in the EU

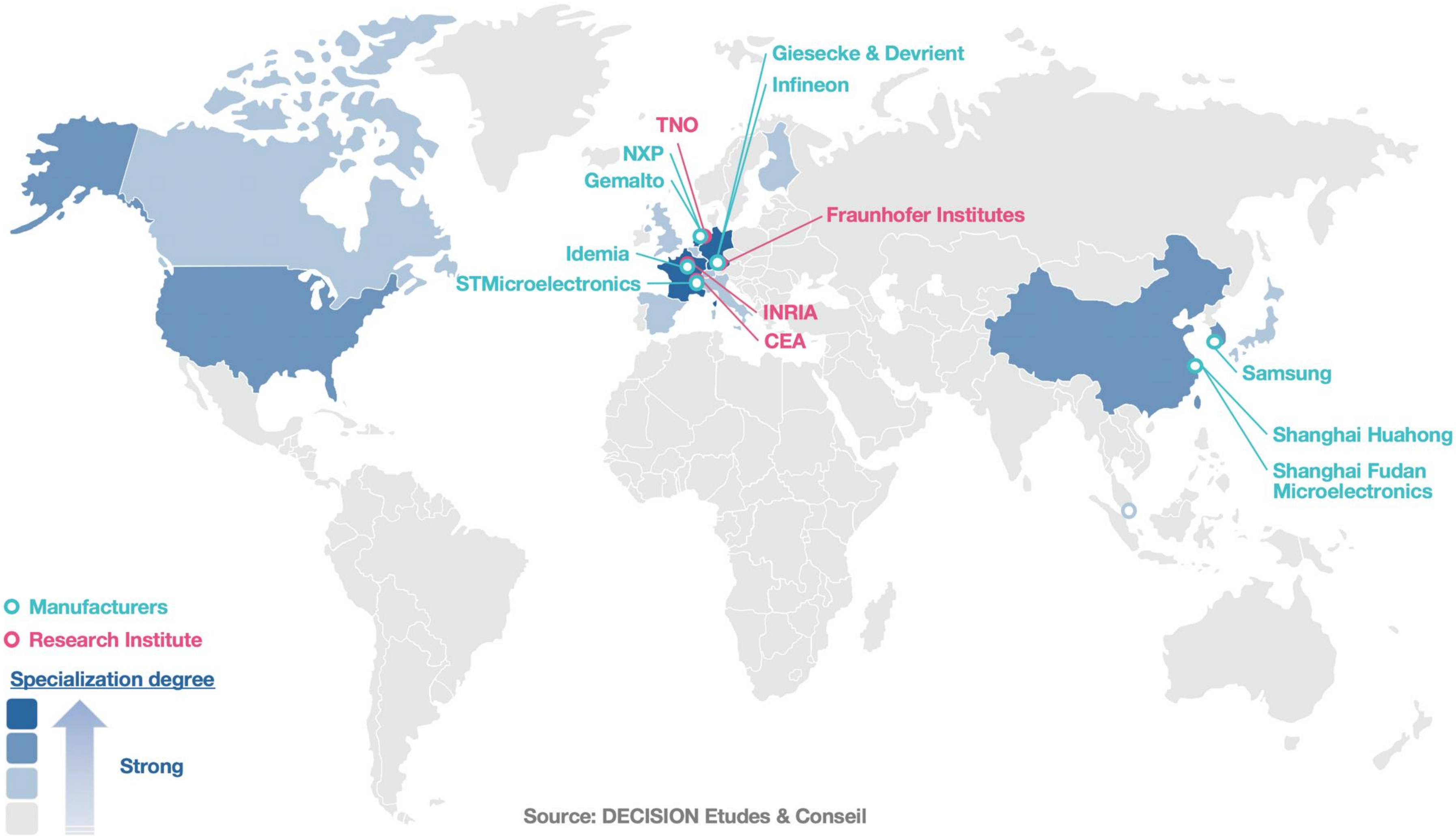
The table below present the main EU industrial players (in terms of capital ownership).

TOP 20 main players in the EU – Secure elements

Nationality of capital ownership	Name of the organization	Type of player	Position in the electronic value chain
France	Thales/Gemalto	Industry player	Components, boards, electronics systems, services
France	Idemia	Industry player	Components, boards, electronics systems, services
France	STMicroelectronics	Industry player	Materials, Components,
France	INT	Research player	HW/SW security, components
France	INRIA	Research player	HW/SW security
France	CEA List/Leti	Research player	HW/SW security
France	Orange	Industry player	Components, services
France	Inside Secure	Industry player	HW/SW security
Germany	Giesecke & Devrient	Industry player	Components, boards, electronics systems, services
Germany	Infineon	Industry player	Materials, Components
Germany	FhG	Research player	JW/SW security
Germany	Bosch	Industry player	Components, materials, services
Germany	Deutsche Telecom	Industry player	Services
The Netherlands	NXP semiconductors	Industry player	Materials, Components
The Netherlands	TNO	Research player	HW/SW security
Finland	Nokia	Industry player	Services
Sweden	Ericsson	Industry player	Services
Spain	Telefonica	Industry player	Services
The UK	EE UK	Industry player	Services

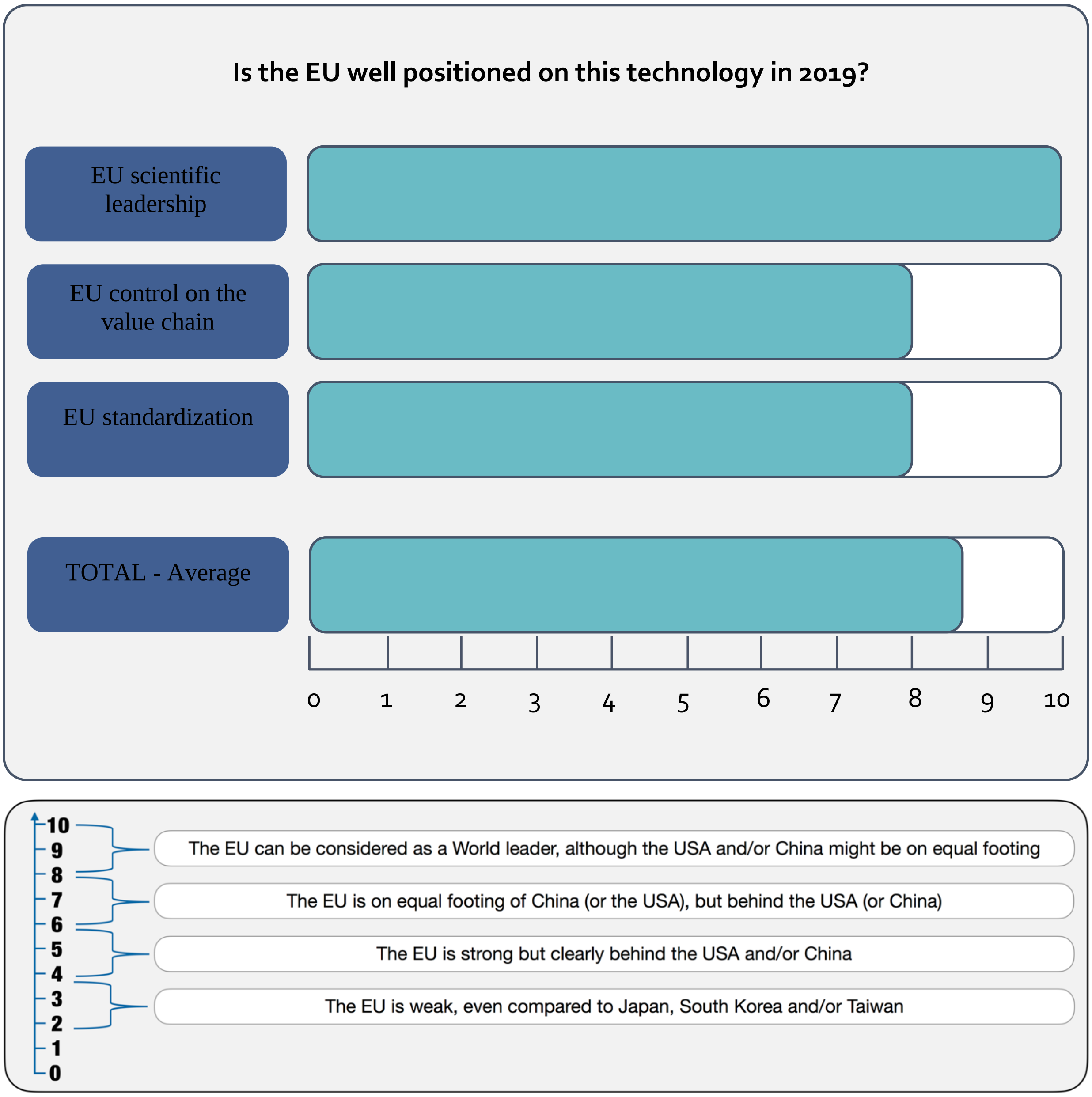
Source: DECISION Etudes & Conseil

World Map - Secure elements



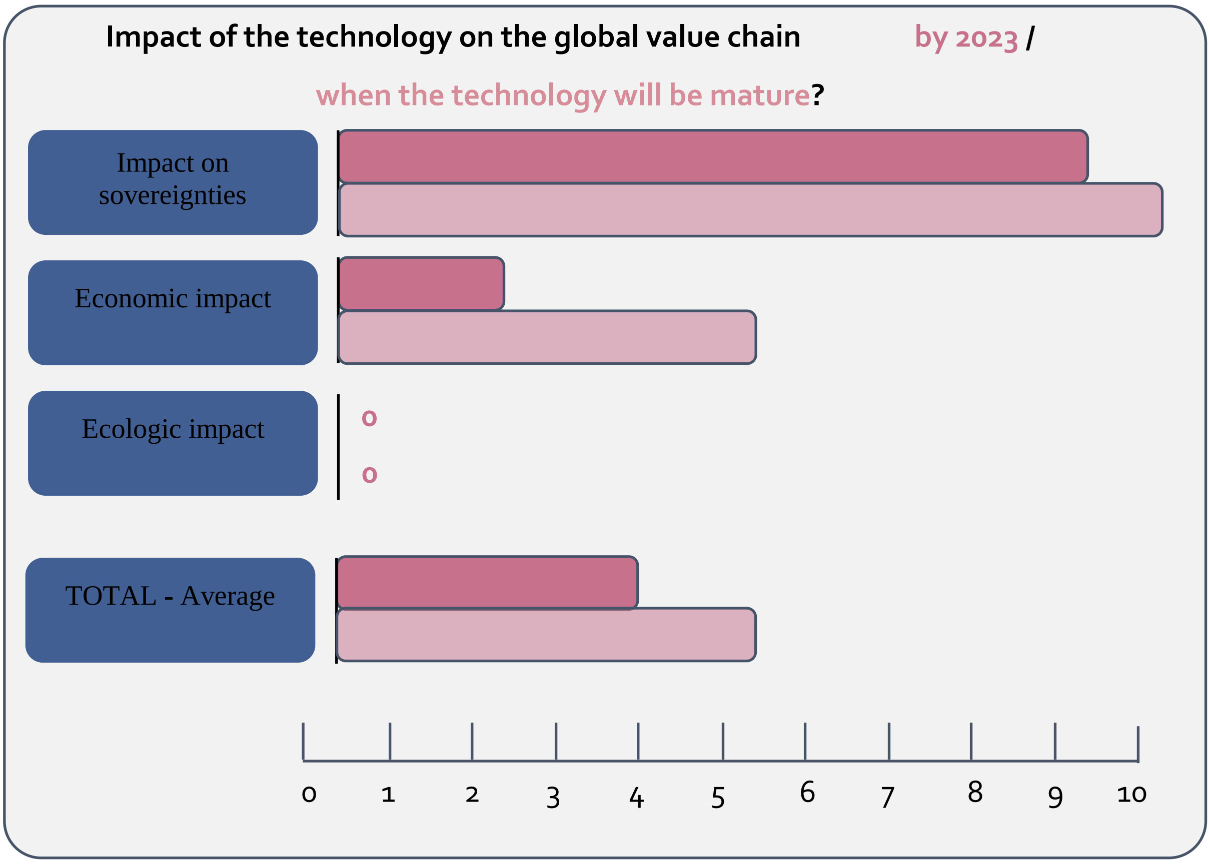
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Critical level for the EU



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.
- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023** **/** **when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023** **/** **when the technology will be mature**.
- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

The EU has created the domain and has currently a strong scientific, industrial and business leadership in the e-secure element domain (at least those involving a secure chip).

EU control on the value chain

The EU has currently a very good control of the key parts of the e-secure element value chain: research, HW and SW technology, manufacturing and integration. There is a strong workforce in the EU in the field, both at the academic and industry levels.

Yet, there is potential threat on the middle-run due to the lack of More Moore competency in Europe, so that i-UICC might be a successful approach only available to US or Asian manufacturers.

Standard analysis

The EU has led the way in developing standards related to e-secure elements, playing for a long time a key role in all UICC standardization committees (ISO/IEC, ETSI, 3GPP, Global Platform, ICAO). The European Industry has also created a lot of domestic standards in digital identity (the eIDAS for example).

Europe has also played a key role in the establishment of the international ISO/IEC 15408 standard, also named the “Common Criteria” or CC, aimed at providing unbiased and recognized ways to evaluate the security of IT systems and SW.

Common Criteria distinguish 7 evaluation levels (EAL1 to EAL7) each level with a given strength (low, medium, strong). Products evaluated in one country according to the CC methodology in one country are not supposed to be re-evaluated in another-one providing suitable mutual cooperation and recognition agreement exist between the two countries (this is, however, valid for the most common EAL1 to EAL4 medium levels, hardly disputed between Europe, the USA and the rest of the world for the levels EAL4 strong (EAL4+) and upper where Europe has strong differentiators).

SOG-IS is an agreement for cooperation and mutual recognition between the main national security agencies in Europe such as BSI (Germany), ANSSI (France), NLNCSA (Netherlands), CCN (Spain), allowing mutual recognition of certified products in the area of IT systems and incorporating the CC area. E-secure element (e.g., smart-cards, passports) certification by the SOG-IS procedure is done according in a suitable version for smart cards of the Common Criteria methodology. The resistance of the card to the attacks and the conformity of the development and manufacturing processes are taken into account in the SOG-IS certifications. Following the adoption of the Cybersecurity Act on June 7, 2019, the certification of e-secure elements such as smart-cards falls from now on into the "high" category of the levels introduced by the Cybersecurity Act. SOG-IS will so logically evolve towards a European framework, the “European Cybersecurity Certification Group” whose one of the first missions will be, in collaboration with the ENISA agency, the establishment of a new “Common Criteria Scheme” for smart cards and other e-secure elements.

This evolution is necessary because the massive introduction of devices like e-SIM, M2M and possibly iSIM in the next years change the battle field with new actors and rises new risks for operators (disintermediation, higher churn, increased competition and risk of loss of business), so that achieving a European consensus in standardization bodies is becoming a necessity, while becoming harder and requesting more flexibility and agility in product certification. The pressure from US and Asian actors in standardization bodies is also becoming stronger for lowering the “security barrier” (and pushing their products) so that coordinated actions at European level is mandatory.

Impact on sovereignties

E-secure elements represent a key element of European sovereignty for the following reasons:

- Secure elements are a key constituent of all critical secure e-transactions (payments, health, etc.) over fixed or mobile platforms;
- Secure elements are the key enabling technology of all e-documents used by governments for managing identities (e-ID cards, e-passports, immigration cards, driving licenses);
- Secure elements will remain the key technology used by mobile operators to protect their assets, protect the user privacy, as well as develop and deploy new value-added services;
- Secure elements will be essential for managing the future cybersecurity of critical IoT applications (connected cars, smart-cities, smart-grids, critical infrastructures, manufacturing 4.0);

- The EU has accumulated an unrivaled scientific and industrial knowledge in the field, which represents a precious asset for all European operators, giving them a competitive advantage in terms of security in comparison with the US and Asian companies.

Economic impact

Secure elements are already having a small but significant economic impact, in particular as an enabling technology. This trend should strengthen in line with the development of IoT networks and with the development of e-secure element applications in telecommunication, automotive, health & care, industrial and critical infrastructure domains.

Ecological impact

On the ecological side, all European manufacturers have made tremendous efforts during the last 15 years to reduce the energy and ecological impact of the materials used for the manufacturing of e-secure elements. Yet, secure elements are not linked to ecological issues and cannot help fighting climate change.

Conclusion

The EU has currently a world-leading position in the field of e-secure components, both on the scientific, industrial and business aspects.

Yet, new form factors are expected to develop in an extremely fast manner in the next 10 years, creating dramatic changes in the ecosystem, especially in the M2M and IoT areas. The EU historic leadership position is therefore likely to be challenged and this situation could lead to the loss of control of some parts of the value chain for the EU.

Furthermore, as e-secure elements enable scalable, resilient, flexible and secure IoT architectures, e-secure elements should represent a strategic enabling technology to catch the new business opportunities offered by connected cars, manufacturing 4.0, smart cities, health and connected hospitals, data protection of critical infrastructure (defense & security), and new telecommunication applications.

As technologies evolve and due to a fierce competition in the field, the EU must continue to invest in the technology to maintain its leadership. The support of this technology should go along two major objectives:

- Protect the current business where the EU has acquired a world-leading position (telecommunication, payment, government and access cards & transport cards), and is fully in control of its value chain, ensuring its sovereignty;
- Create the required conditions for the development of new sustainable business in the area of M2M and IoT.

The related investment should target both the technology and the creation of open platforms enabling the creating of new value-added service businesses by European operators, SMEs and start-ups.

B. Cryptography

i. Definition

Cryptography is the science of constructing cryptographic systems. It must not be confused with cryptanalysis, the area of breaking cryptographic systems. Cryptography and cryptanalysis are the two branches of the cryptology. Cryptography is a field of computer science and mathematics that focuses on techniques for secure communication between two parties, while a third party is present and intents to intercept the communication secrecy.

Cryptography basic procedures include encryption, decryption, signatures, generating of pseudo-random numbers, timestamping and so on. The four ground principles of cryptography are confidentiality, data integrity, authentication and non-repudiation. At a higher level, a cryptosystem is a structure or scheme consisting of a set of algorithms that converts plaintext to ciphertext to encode or decode messages securely. The term “cryptosystem” refers to a computer system that employs cryptography.

Fundamentally, there are two types of cryptosystems based on the manner in which encryption-and decryption is performed in the system: Symmetric Key (SK) cryptosystems and Asymmetric or Public Key (PK) cryptosystems. The main difference between these cryptosystems is the relationship between the encryption and the decryption key.

Symmetric Key (SK) Cryptosystems

The encryption process where same keys are used for encrypting and decrypting the information is known as Symmetric Key Encryption. The study of symmetric cryptosystems is referred to as symmetric cryptography.

Public Key (PK) / Asymmetric Cryptosystems

Every user in this system needs to have a pair of dissimilar keys, a private key and a public key. These keys are mathematically related − when one key is used for encryption, the other can decrypt the ciphertext back to the original plaintext. When *User1* needs to send data to *User2,* he obtains the public key of User*2* from repository, encrypts the data, and transmits. *User2* uses his private key to extract the plaintext.

It requires to put the public key in public repository and the private key as a well-guarded secret. Though public and private keys of the user are related, it is computationally not feasible to find one from another. This is referring to the strength of the scheme and related to the mathematical theory of complexity.

SK / PK comparison

The length of Key (number of bits), in SK encryption is smaller than in PK encryption and hence, process of encryption decryption is faster. Processing power required to run symmetric algorithm is thus generally less greedy.

Yet, there are two major challenges linked to SK cryptography:

- Key establishment − Before any communication, both the sender and the receiver need to agree on a secret symmetric key. This requires a secure key establishment mechanism in place;
- Trust Issue – Since the sender and the receiver use the same symmetric key, there is an implicit requirement that the sender and the receiver “trust” each other. For example, it may happen that the one party has given (intentionally or not), the key to an attacker and the others are not informed.

These two challenges are strong roadblocks in our hyper-connected world. Today, people need to exchange information with a multiplicity of trusted and non-trusted parties. The SK schemes are hence strongly impractical for e-commerce issues, for example.

ii. Synergies with other emerging technologies

Cryptography is, of course, the fundamental constituent of **Digital Identity** (see the chapter on the Identification & Authentication emerging market), and **e-secure elements**. Yet, cryptography has synergies with many other domains of this study:

More-Moore. The synergies are multiple, from hardware implementation of crypto-algorithms in dedicated ICs or IPs to multiply the computational efficiency versus pre-software, to dedicated SIPs for Quantum Key distribution or PUFs, (Physically Un-clonable Functions: an enabling technology producing un-clonable and inherent instance-specific measurements of integrated circuits, comparable to human fingerprints and helping to generate high-quality random numbers), nonce (non-repeating numbers), and forgery-proof unique IDs.

Blockchain. The links and cryptographic challenges are explained in the blockchain section of this report.

Quantum computing. The synergies are great between quantum computing and cryptography, as both QKD (Quantum Key Distribution), and post-quantum cryptography are important R&D topics, in relation with new optical communication networks and development of quantum computers respectively.

Edge IA and AI. Traditionally, neural networks have not been considered suitable for cryptographic operations as they have a hard time performing simple Boolean operations. It turns out nevertheless that neural networks can learn to protect the confidentiality of their data from other neural networks: they can benefit from supervised learning forms of encryption and decryption, without being taught specific algorithms for these purposes. Yet, in situations where privacy and security in distributed scenarios is critical, classical PK schemes might not be convenient to develop multiparty efficient secure communication schemes. Pioneered by Google in 2016, adversarial neural cryptography or GAN (Generative Adversarial Neural Networks), cryptography is an emerging AI method that uses GAN to secure communication between different parties.

Biochips. DNA cryptography, a new branch of cryptography, utilizes DNA as an informational and computational carrier with the aid of molecular techniques. It is relatively a new field which emerged after the disclosure of computational ability of DNA. DNA cryptography has gained attention due to the vast storage capacity of DNA, which is the basic computational tool of this field. One gram of DNA is known to store about 10^8 TB, which surpasses the storage capacity of any electrical, optical or magnetic storage medium.

Emerging markets of IoT sensors. Lightweight cryptography is aimed at securing IoT architectures, especially when Size, Power, Costs are key design constraints.

iii. Technology roadmap: Maturity levels and expected impacts by application area

Technology maturity. A large number of cryptographic tools are already mature and largely integrated in end-user electronic markets. The main emerging trends opening new research directions in cryptography are the following:

- **Lightweight cryptography**. The rapid development of IoT has a tremendous impact on all related cybersecurity aspects. Recent massive attacks on IoT configurations have shown that strong cryptographic techniques must be used to ensure a global system security. Unfortunately, in the case of IoT, cryptography usage can be limited by size, power, local computing performance of the objects. This has given rise to a very active field of research around the so-called lightweight Cryptography. In short, lightweight cryptography searches for new cryptographic algorithms or protocols tailored for implementation in constrained environments including RFID tags, sensors, contactless smart cards, health & care devices;

- **Quantum cryptography.** The development of high-speed communication systems has opened new Key distribution systems using photonic technologies: this is known as the domain of Quantum Cryptography;

- **Post-Quantum cryptography**. Finally, the potential advent of quantum computing is putting at risk some of the most used PK algorithms used today, such as RSA, ECC, TLS and other. The post-quantum cryptography seeks for cryptographic algorithms or primitives (usually public-key algorithms), that are thought to be secure against an attack by a quantum computer. As of 2019, there is no strong evidence that the most popular public-key algorithms, could be efficiently broken by a sufficiently strong quantum computer (although some quantum algorithms e.g., SHOR factoring algorithms have demonstrated its feasibility);

- **Homomorphic encryption**. The huge development of cloud computing has generated a very active field of research around the so-called functional encryption and homomorphic encryption: functional encryption is a novel paradigm for public-key encryption that enables both fine-grained access control and selective computation on encrypted data, as it is necessary to protect big and complex database in the cloud. In its most complete version, Fully Homomorphic Encryption (FHE) enables computation on encrypted data without leaking any information about the underlying data. In short, a party can encrypt some input data, while another party, that does not have access to the decryption key, can blindly perform some computation on this encrypted input. The final result is also encrypted, and it can be recovered only by the party that possesses the secret key;

- **Generative Adversarial Neural Networks (GAN) cryptography**, an emerging AI method that uses GAN to secure communication between different parties.

Main applications.

Cryptography has key interactions with the majority of both emerging technologies and promising CPS markets and applications as it will secure the way new systems based on the interconnection between separate systems will work in the future. In this respect, the 5G area and its galaxy of IoT applications gathering many different telecommunication or business operators and service companies is a perfect example of the need for next generation cryptosystems, which may use multiplicity of basic crypto components. Connection between cryptography, AI, rebooting computing and IoT will represent a strategic field for the EU, generating huge new revenue opportunities which could also help developing future European champions. More specifically, in a 2018-2023 industrial perspective:

- **Public Key (PK) cryptography** is massively today used in all classical applications domains listed above and is an essential pillar of the global cybersecurity of the relative business domains;

- **Lightweight cryptography** is expected to become progressively used in all IoT domains where the SWAP concept (Size, Weight and Power), is aimed at becoming critical: home appliances, smart mobility, smart energy, wearables;

- **Post-Quantum cryptography** could be used as a substitute of PK in case quantum computers would be become a reality. The most sensitive domains in a five years perspective are Internet, Financial and Data Processing applications;

- **Homomorphic encryption.** In case the current limitations of this technology would be overpassed, homomorphic encryption would have a strategic impact on PC and data processing and more precisely in the cloud computing area.

- Other technologies (**GAN, DNA cryptography**), should emerge on the long run, after 2023.

Technology Roadmap - Maturity of the technology at the global scale and by application area

<table>
<tr><th>N°</th><th></th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td colspan="2">Public Key Cryptography</td><td colspan="5">Industrial production</td><td colspan="16">Massive production</td></tr>
<tr><td colspan="2">Quantum Key Distribution (QKD)</td><td colspan="6">R&D</td><td colspan="3">Tests & prototyping</td><td colspan="6">Industrial production</td><td colspan="6">Massive production</td></tr>
<tr><td colspan="2">Lightweight cryptography</td><td colspan="8">R&D</td><td colspan="4">Tests & prototyping</td><td colspan="5">Industrial production</td><td colspan="4">Massive production</td></tr>
<tr><td colspan="2">Post-Quantum cryptography</td><td colspan="9">R&D</td><td colspan="4">Tests & prototyping</td><td colspan="5">Industrial production</td><td colspan="3">Massive production</td></tr>
<tr><td colspan="2">Homomorphic encryption</td><td colspan="9">R&D</td><td colspan="4">Tests & prototyping</td><td colspan="5">Industrial production</td><td colspan="3">Massive production</td></tr>
<tr><td colspan="2">GAN cryptography, DNA cryptography</td><td colspan="15">R&D</td><td colspan="3">Tests & prototyping</td><td colspan="3">Industrial production</td></tr>
<tr><td></td><td>Electronic Segment</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="5">Small impact (Public Key)</td><td colspan="16">Medium impact (Public Key)</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="5">Small impact (Public Key)</td><td colspan="16">Medium impact (Public Key)</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="5">Small impact (Public Key)</td><td colspan="16">Medium impact (Public Key)</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="21">Medium impact (Public Key, Secret Key)</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="7">Medium impact (Public Key, Secret Key)</td><td colspan="14">Critical impact (Public Key, Secret Key)</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="13">Medium impact (Public Key, Secret Key)</td><td colspan="8">Critical impact (Public Key, Secret Key)</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="13">Medium impact (Public Key)</td><td colspan="8">Critical impact (Homomorphic encryption) + Medium impact (Public Key, QKD)</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="13">Medium impact (Public Key, Secret Key)</td><td colspan="8">Critical impact (Homomorphic encryption) + Medium impact (Public Key, Secret Key, Post-Quantum Crypto)</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="21">Medium impact (Public Key)</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="5">Small impact (Public Key)</td><td colspan="7">Medium impact (Public Key)</td><td colspan="9">Medium impact (Public Key, Lightweight crypto)</td></tr>
<tr><td></td><td>Crossed segments</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Data analytics / Big data</td><td colspan="15">No significant impact</td><td colspan="6">Critical impact (Homomorphic encryption) + Medium impact GAN by 2028</td></tr>
<tr><td>2</td><td>Smart home</td><td colspan="12">Medium impact (Public Key)</td><td colspan="9">Medium impact (Public Key, Lightweight crypto)</td></tr>
<tr><td>3</td><td>Smart mobility</td><td colspan="12">Medium impact (Public Key)</td><td colspan="9">Medium impact (Public Key, Lightweight crypto)</td></tr>
<tr><td>4</td><td>Smart energy</td><td colspan="21">Medium impact (Public Key)</td></tr>
<tr><td>5</td><td>Wearables</td><td colspan="12">Small impact (Public Key)</td><td colspan="9">Medium impact (Public Key, Lightweight crypto)</td></tr>
<tr><td>6</td><td>Finance sector</td><td colspan="13">Small impact (Public Key)</td><td colspan="8">Small impact (Public Key, Post-Quantum Crypto)</td></tr>
</table>

At the global scale, each technology is defined through four different stages of maturity.

- R&D: Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6
- Tests & prototyping: Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9
- Industrial production: Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)
- Massive production: Signify that production of systems integrating the technology has already reached steps that enable significant scale economies

The impact of the technology on each end-user segment is described as:

- A critical impact;
- A significant impact;
- No significant impact;

…in terms of competitive advantage and volumes of production…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. Cryptography markets

Cryptography is very often embedded in Electronic Components and Systems. It is therefore very complicated to provide specific market figures related to this segment.

Yet, estimates can be provided for the main aggregates, based on the existing public reports and experts' analyses:

Markets	2018 (B€)	2023 (B€)	CAGR 2018-2023 (%)
Hardware encryption	10-15	40-50	~30%
Software encryption	3-6	7-12	~16%
Quantum cryptography	<0.1	0.3-0.45	~30%
TOTAL encryption market	17 (13-21)	55 (47-62)	~30%

Source: DECISION Etudes & Conseil

1 - The Hardware encryption market

Hardware encryption refers to all electronic products embarking dedicated components able to perform encryption and storage of critical data. Such dedicated components can be either an ASIC or an FPGA. Major products concerned are embedded into: External Hard Disks, Internal Hard Disks, Inline Network Encryptors, Solid State Disks and USB Flash Drive.

Hardware encryption market also includes **Hardware Security Modules (HSM)**: physical computing devices that safeguards and manages digital keys for strong authentication and provides crypto processing. These modules traditionally come in the form of a plug-in card or an external device that attaches directly to a computer or network server. This is a relatively small sub-market with over 100 suppliers worldwide. The expected market was valued at nearly €1B in 2018 and is projected to reach €1.5B by 2023, at a CAGR of 10-15% during the forecast period. This is nevertheless a strategic segment where Europe has some strong leaders (Thales, Atos).

The global hardware encryption market is expected to benefit from a very strong growth of ~30% over the 2018-2023, in line growing number of end-user subsystems (External Hard Disks, Internal Hard Disks, Inline Network Encryptors, Solid State Disks and USB Flash Drive), embedding hardware encryption modules. Inline Network Encryptors should first drive the growth of the market in line with the growing needs of Telecommunication Networks in the most populated Asian Countries (China, India, Malaysia, Thailand, South Korea, etc.). Target applications for HW encryption include virtually all segments (IT, communications, Defence, Health, Automotive, Banking and Financial services), etc.

2 - Global SW encryption market

This market includes SW for disk encryption, file/folder encryption, database encryption, communication encryption, and cloud encryption segments. The cloud encryption segment is the fastest growing segment in the market, due to the increasing demand for securing sensitive data especially at the light of the most recent directives or regulations recently in the world (NIST, CLOUD, GDPR). These new regulations or directives have constrained operators to adhere strictly to regulatory standards and data privacy compliance, especially at the light of the financial penalties and liabilities in case of loss of critical data and also due to the exponential increase in the adoption of cloud and virtualization technologies as well as observed massive frauds. The market value is expected to be almost equilibrated in 2019 among the three major economic zones between 2018 and 2023.

3 - The Quantum cryptography market

This is clearly an emerging market but becoming under the hot spot due to some impressive experiments done recently in China. Quantum cryptography is expected to be applied principally in high-speed communication between computers, next generation wireless systems, sensitive or critical IoT applications.

B. Main players in the World and in the EU

As cryptography is very often embedded in Electronic Components and Systems and is not associated to any specific BtoB or BtoC market, there is no competitive landscape specifically dedicated to cryptography.

Yet, five sectors are particularly linked to cryptography, with players regrouping teams dedicated to the development of cryptographic applications. These five sectors are often interconnected, with players simultaneously present on several of them, and cross-sectoral purchases of companies (for instance Forcepoint / Websense have been bought by Raytheon in 2015).

As shown in the tables below, in each of these sectors, the European players accounted for around 7-15% of the total market in 2018, while the EU GDP accounted for 21% of the World GDP the same year. In other words, the EU industrial landscape is less strong compared to the EU average economic weight in the global economy. On the contrary, a relative supremacy of the USA can be observed, as well as a rise of the Chinese players.

1. Hardware encryption manufacturers

The table below shows twenty of the main hardware encryption manufacturers and their total sales in 2018.

Nationality of capital ownership	Company name	Sales 2018 (M€)
South Korea	Samsung Electronics	181 800
The USA	IBM	66 326
Japan	Toshiba	29 026
The USA	Micron	25 326
The USA	Western Digital	17 206
France	Thales/Gemalto	15 855
France	Atos / Bull	12 258
Ireland	Seagate Technology	9 315
The USA	NetApp	4 926
The USA	Symantec	4 143
The USA	Idemia	2 640
The USA	Maxim Integrated Products	2 000
The USA	Kingston Technology	120
Japan	Hitachi ID Sysems	<60
The USA	GlassBridge Enterprises	40
The USA	Kanguru Solutions	<35
The USA	WinMagic	<30
The USA	Certes Networks	<20

Source: DECISION Etudes & Conseil

2. Cybersecurity software & service providers

The table below shows around thirty industrial players that are among the world TOP cybersecurity software & service providers, and their total sales in 2018. These players are particularly linked to the software encryption business. Idemia is owned by the American fund Advent International, but the management is French as well as the main offices.

Nationality of capital ownership	Company name	Sales 2018 (M€)
The USA	Microsoft	91 967
The USA	IBM	66 326
The USA	Cisco Systems	41 108
The USA	EMC Corporation	24 000
France	Thales / Gemalto	15 855
France	Atos / Bull	12 258
The UK	Micro Focus	3 962
The USA	Idemia	2 640
The USA	McAfee (TPG Capital)	2 083
The USA	Symantec	4 143
Israel	Checkpoint Software technologies	1 597
The USA	Fortinet	1 501
Japan	Trend Micro	1 186
The USA	Tibco (Vista Equity Partners)	917
The USA	Fireeye	693
The UK	Avast	689
The USA	Proofpoint	598
Russia	Kaspersky	583
The USA	Forecepoint / Websense	567
The UK	Sophos Group	534
China	Bluedon	290
The USA	Crowdstrike	200
Slovaquia	Eset	200
Roumania	Bitdefender	100
The USA	Ciphercloud	<70
The USA	Bloombase	<60
The USA	Winmagic	<30
Denmark	Crypromathic	<30

Source: DECISION Etudes & Conseil

3. Software editors

The table below shows the world TOP 10 software editors, and their total sales in 2018.

N°	Nationality of capital ownership	Company name	Sales 2018 (M€)
1	The USA	Microsoft	91 967
2	The USA	Oracle	32 917
3	Germany	SAP	22 833
4	The USA	VMWare	6 583
5	The USA	Adobe	6 417
6	The USA	Salesforce	8 750
7	India	HCL	6 500
8	The USA	Fiserv	4 750
9	Spain	Amadeus	4 583
10	The USA	Intuit	4 500

Source: DECISION Etudes & Conseil

4. Information Technology Consulting (ITC) firms

The table below shows the world TOP 12 Information Technology Consulting (ITC) firms, and their total sales in 2018.

N°	Nationality of capital ownership	Company name	Sales 2018 (M€)
1	The USA	IBM	39 000
2	The USA	Accenture	34 250
3	The USA	Amazon Web Services	21 417
4	Japan	Fujitsu	19 833
5	The USA	DXC	18 167
6	India	TCS	17 083
7	Japan	NTT Data	16 083
8	The USA	Cognizant	13 417
9	France	CapGemini	13 000
10	France	Atos / Bull	12 083
11	India	Infosys	9 583
12	Canada	CGI	7 500

Source: DECISION Etudes & Conseil

5. Defense companies

The table below shows the world TOP 20 Defense companies, and their sales in the Defense sector in 2018.

N°	Nationality of capital ownership	Company name	Defense Sales 2018 (M€)
1	The USA	Lockheed Martin	42 113
2	The USA	Boeing	28 375
3	The USA	Northrop Grumman	21 083
4	The USA	Raytheon Company	20 970
5	China	Aviation Industry Corporation of China	20 752
6	The USA	General Dynamics	20 046
7	The UK	BAE Systems	18 731
8	China	China North Industries Group Corporation Limited	12 315
9	France/Germany/spain	Airbus	10 887
10	China	China Aerospace Science and Industry Corporation	10 109
11	China	China South Industries Group Corporation	9 970
12	China	China Electronics Technology Group	8 563
13	Italy	Leonardo	8 191
14	China	China Shipbuilding Industry Corporation	8 163
15	Russia	Almaz-Antey	8 050
16	France	Thales / Gemalto	7 980
17	The USA	United Technologies	7 758
18	The USA	L3 Technologies	6 874
19	China	China Aerospace Science and Technology Corporation	6 782
20	The USA	Huntington Ingalls Industries	6 473

Source: DECISION Études & Conseil

6. Public Agencies involved in cybersecurity activities

Finally, many public agencies around the world regroup significant cryptographic skills: The American NSA, the UK Government Communications Headquarters (GCHQ) and National Cyber Security Centre (NCSC), the German BSI, the Russian Special Communications Service (Spetssvyaz), the French ANSSI (involving 400 skilled workers in cybersecurity and cryptography activities and research), the Cyberspace Administration of China (CAC), and many more.

Impact of cryptography by end-user electronic applications in 2023

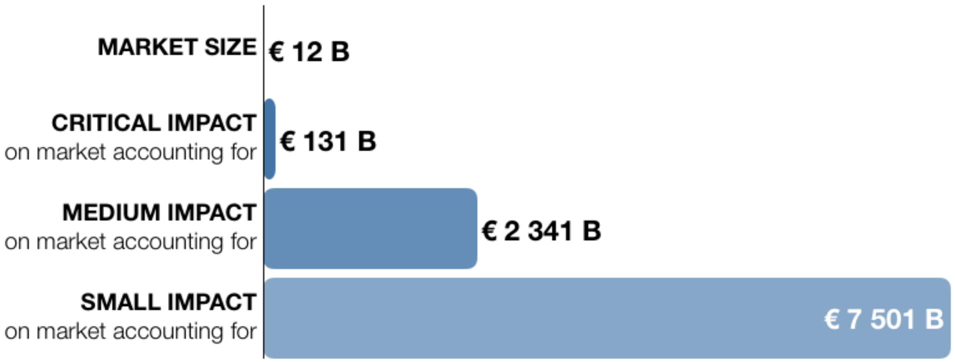
	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Medium	Medium	Medium	Medium	Critical	Medium	Medium	Medium	Medium	Medium

Corresponding quantitative impact of cryptography in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
12	131	2 341	7 501	131	2 341	0	0	0	7 501
				External Hard Disks, Internal Hard Disks, Inline Network Encryptors, Solid State Disks, USB Flash Drive, as well as sub-electronics segments dedicated to cybersecurity applications	Every other electronic end-user segment	-	-	-	Finance sector and gaming sectors. Markets where the pay-as-you-go unit will become the rule (music, video, software, etc.), although too complex to be quantified in this study

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

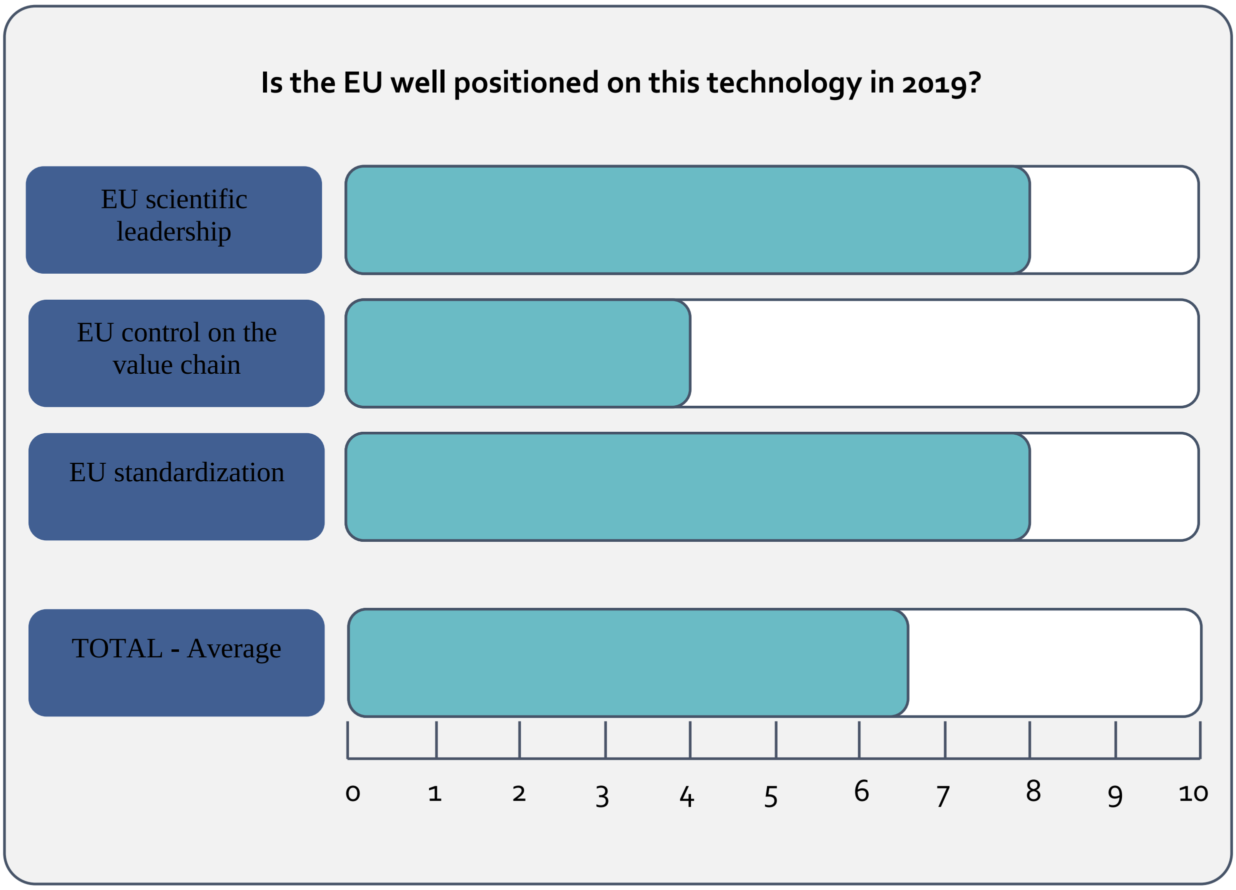
Estimated economic impact of cryptography in 2023

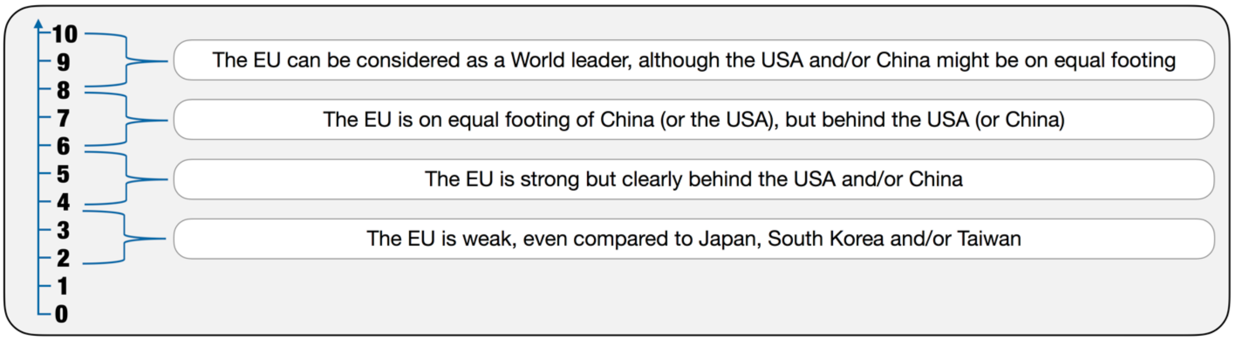


Source: DECISION Etudes & Conseil

V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

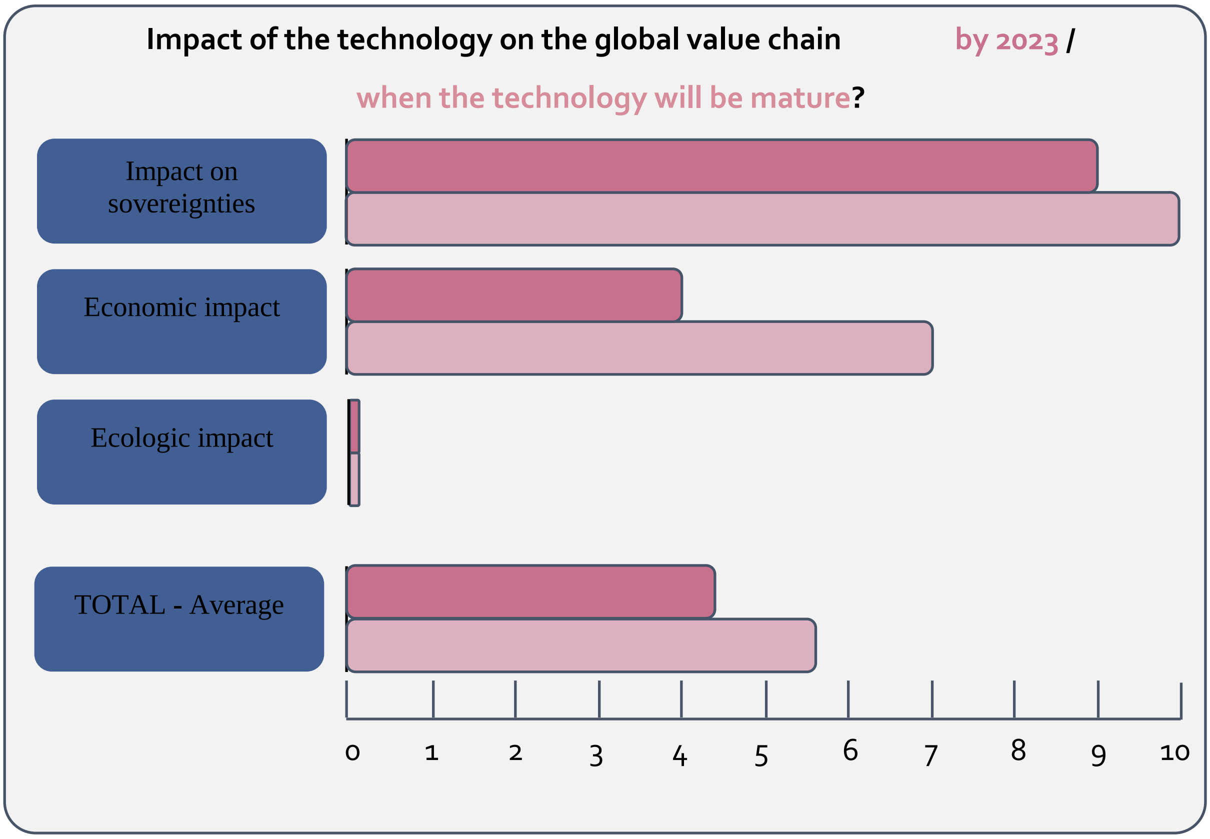
A. Position of the EU in the World in 2019





Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

Europe has a long and proven track record in cryptographic research, sustained by a solid industrial expertise in the field. European labs are working on almost all future challenges of cryptography at top levels even compared to the USA and China. To maintain this scientific expertise, Europe must continue to invest in the following areas:

<u>Generic recommendations</u>

- Maintain a state-of-the-art position in physical/logical methods to assess security of algorithms implementation, and ensure general monitoring of potential attacks;
- Develop strong White-box crypto techniques;

- Develop software obfuscation methods;
- Investigate new fields such as DNA cryptography and AI-based techniques (such as GAN, Generative Adversarial Networks).

Lightweight cryptography (LW) (Especially for IoT applications)

- Develop the essential libraries in LW scripting languages;
- Evaluate Power drainage issues over introduced overheads by the adoption of conventional cryptography over smaller footprints for LW scale;
- Develop/standardize assessment methods to investigate the overall performances, especially contribution to the SWAP aspect (Size, Weight and Power);
- Develop security insurance tools and methods of the whole four-layer IoT architecture;
- Develop control mechanisms to prevent privacy violations through open source IoT devices;
- Integrate cost/efficiency considerations, in relation with SaaS and cloud platforms;
- Develop cryptography cloud security insurance tools.

Quantum cryptography

- Propose new efficient QKD (Quantum Key Distribution) protocols;
- HW QKD implementation: develop dedicated HW for distance transmission;
- Network QKD;
- Work on cost and robustness of the whole solution.

Post-Quantum cryptography

- Hash-based: interoperability and efficiency (slow key generation for state-full HBS, long signatures for stateless HBS);
- Code-based (Linear codes): work on efficiency, indistinguishability of peers;
- Other schemes: extend research on applicable schemes: multivariate, isogeny, lattice, etc.

Homomorphic cryptography

- Performance optimization of existing algorithms;
- Develop Full homomorphic encryption.

Cryptographic standards

- Ensure a strong industrial presence in all related committees.

EU control on the value chain

Besides R&D, the EU has a reasonable control of the basic industrial value chain, with some leaders in the Chip design, algorithm design, software implementation, Hardware Security Modules, Integrators and full solution suppliers. The least satisfactory domain is the hardware encryption, where only American and Asian suppliers (mostly Korean and Japanese), are visible in top 10 vendors. The EU also misses some strong cryptographic software vendors, as current European ecosystem is mostly composed of a lot of SMEs competing with each other without global footprint. As a consequence, European cryptographic products developed by SMEs represent a small part of the purchases of the European buyers, despite a similar quality level as non-domestic products made by large American or Chinese industrial players or government bodies. This is for sure lowering the global control of the value chain and represents a threat.

Standard analysis

The EU is well represented in all the major cryptography standardization committees and is a strong contributor to challenges related to cryptography (e.g., the recent challenge from the NIST on post-quantum cryptography where a significant portion of proposals came from the EU).

A specific point of warning is to keep the European leading position of cryptographic product certification, where European products have been able to achieve the highest Security Insurance levels, according to the ISO/IEC 15408 Common Criteria standards.

New security certification schemes are, however, needed for future cryptographic enabled products, based on current Common Criteria experience and expertise, but offering more flexibility and agility (e.g., for IoT of short life cycle products). The availability of such new Certification Scheme framework at the EU level (with mutual recognition), will be an important business enabler for a lot of new applications.

Impact on sovereignties

Ensuring protection of government and business applications is clearly a major sovereignty objective, relying on holistic approaches mixing regulatory, governance and technology frameworks. Cybersecurity and cryptography in particular are a key ingredient contributing to this goal.

While the EU currently misses strong central agencies in charge of this aspect (like the USA with the NSA and the UK with the GCHQ -now leaving EU due to the Brexit), some EU members are managing at the highest strategic and sovereignty level all issues related to cryptography, such as the French ANSSI and the German BSI.

The use of cryptography represents a key enabling technology and contribute reinforcing EU sovereignty in three recently adopted European directives: the NIS (for Information and Communication Network security), the GDPR (for privacy management), and the DSP2 (for payment). This common framework should be reinforced and for example, there is a clear need for a European common answer (cryptographic enabled), to the recently adopted CLOUD (Clarifying Lawful Overseas Use of Data) act in the USA. The new mandate of the ENISA agency, partnering with all major national security agencies, should be a key factor for defining the basis of a European cryptography strategy (in synergy with the national ones from the EU State members), with sovereignty impact in mind.

Economic impact

Cryptography is becoming a more and more important constituent of the business and becomes a key enabler for most applications (connected cars, IoT, cloud services, health, and industry 4.0 to name a few). Cryptography is also heavily used in Bank and Finance, Identity protection in computer and communication networks, Health, Government and defense. With the expected development of password-less technologies, it will become the key technology for establishing and maintaining trust in a more and more interconnected world. Besides the direct economic impact of developing and selling cryptographic products and services, the EU will be able to develop new sustainable applications by introducing the appropriate highly secure cryptographic protection mechanisms, following high ethical, privacy compliant and interoperable standards.

Ecological impact

No positive ecological impact can currently be and should be in the future associated to cryptography. Cryptographic tools are ecologically costly to design and to set up but are essential for both sovereignties and personal data privacy.

Specific interaction between cryptography and pollution are linked to blockchain (see the associated discussion in the chapter dedicate to blockchain).

C. Blockchain

i. Definition

Blockchain (also named Distributed Ledger Technology, DLT), is a way of storing the information related to all transactions between multiple parties in a trustable and not revocable way. The two main characteristics of blockchain are the following:

- Both the recording, sharing, storing and redistribution of the transaction content are done in a secure (cryptographically protected), and decentralized way;
- Blockchain systems are owned, run and monitored by all actors in the system (*at least theoretically),* without any party controlling it, hence avoiding modifications or abuses from a central authority.

Basic Components of the blockchain

- **Nodes.** The participants of the blockchain are nodes (computers and users), that form a peer-to-peer network. Each node has a local copy of the whole blockchain (or the most recent part of it). When retrieving the blockchain, a node verifies the integrity of the blocks by computing a set of cryptographic challenges named hashes. Every node can send transactions and ask the network to add these transactions to the blockchain, these pending transactions are then validated by some special nodes called the miners.
- **Miners** (also known as block generators or validators). Miners are nodes that are willing to share their computational power to add blocks to the blockchain, usually in exchange for tokens or crypto money. The way they are paid depends on the implementation of the blockchain (e.g., in the case of Bitcoin, the blockchain creates cryptocurrency and gives it to the miner who has added a block).

  In public blockchains (such as Bitcoin), as Miners are paid, they are in competition: they all want to add the next block but only one of them will achieve it, in a random way for each new block. This randomness is very powerful to guarantee the security of the blockchain: since no one knows which miner will be selected, an adversary miner has a low probability to be selected, thus has low interest into trying to attack the system. Yet, this system has a potential failure: if miners owning more than half of the validation power of the blockchain network form an alliance and launch a common attack, there is more chance that the attack succeeds than fails, so the network can be considered under the control of this group of miners. This failure is known as the "51% attack". As currently, more than 51% of the mining capabilities for the Bitcoin system are in China, the Bitcoin system can be considered as vulnerable to a potential organized Chinese attack.
- **Consensus.** Consensus are protocols to enable a true randomness selection of the miners.

  Public blockchain (i.e., anyone can access it, also named permissioned blockchain), usually use a Proof of Work (PoW) consensus, whereby the more computation power miner has the highest probability that their block will be selected. As computation power is expensive, the cost of acquiring 51% of the network computation power is high. This is a way to secure the network. To add a block of data into the blockchain, each miner has to validate the current block's data and its consistency with the previous blocks and solve a cryptographic puzzle.

  Private blockchains (nodes belong to a same user) or semi-private blockchains (nodes belong to a consortium of different users) don't need such a costly consensus mechanism, because the participants are known (i.e., no one can freely join the network, hence they are also names permission-less blockchains). In this case, the consensus mechanism is much simpler. The consensus protocol is based on a Proof of Stake (POS) concept, relying on the idea that the more currency a user owns on the blockchain, the less he is likely to attack the system. As it could be seen as an unfair protocol since a small number of rich people would dominate the entire network, POS is often combined with different selection criteria.

Blockchain additional components

- Additional protocols can enhance the trust in private blockchains such as Practical byzantine fault tolerance (PBFT) and Delegated proof of stake (DPOS);
- Smart contract: The concept of smart contract (also referred as "chain code") has been implemented first by Ethereum. These are computer programs executed by the miners. Their deployments and executions are triggered by users through transactions. Like any other transaction, smart contracts executions also benefit from the properties of the blockchain: security, integrity, no intermediary, transparency and availability. For example, a smart contract could implement an asset representing some kind of ownership (not necessarily of financial nature), that one can sell or buy in an auction manner;
- Oracles: smart contracts enable the automation of transactions according to programmatically coded conditions. However, the conditions are limited to the internal state of the blockchain: information about transactions and the smart contract's source code. This is where oracles step in. They provide a service that enables communication between the blockchain and the open world through Internet. Technically speaking, they allow the smart contract to call web services using REST protocol. This concept was first introduced by Microsoft with the "Cryptlet" part of the Microsoft Bletchey project. This way, a smart contract can be aware in real time of the weather, the results of a sports competition, flight information of a specific plane and so on. It is also possible to output data to the real world from the blockchain. For example, in order to notify some user by email of the execution of the contract.

Historical development of the technology

The earliest form of the blockchain concept probably dates back from around the 13th century, with the *Messar*i double entry system of the Republic of Genoa. In our electronic era, the pioneering work of (pseudonymous?) Satoshi Nakamoto in 2008 on distributed ledger was almost immediately after followed by the first Open Source implementation of the Bitcoin system, which attracted immediately the attention of the financial community (and of the regulator and governments), on the potential use of the blockchain in the financial sector.

Five major steps that paved the way of the blockchain technology:

1. The definition of the initial Bitcoin architecture: simple transactions, single blockchain, Public and POW consensus protocol;
2. The development of the blockchain 2.0 concepts departing from the Bitcoin architecture with the introduction of generic contracts, multiple and linked blockchains, public, private or hybrid ownership, new consensus protocol (Ethereum, Corda, Hyperledger, Sawtooth Lake, etc.);
3. The introduction of the smart-contract concept (Ethereum) and Proof of Stake mining concept;
4. The introduction of the Oracle or cryptlets (Microsoft Bletchley project) to access external data securely, while maintaining the integrity of the blockchain;
5. Blockchain scaling architecture as magnified by the DPOS protocol, dramatically accelerating the speed of transactions, and introduction of the "Blockchain as a Service" by all major SW editors (IBM, Microsoft, etc.).

ii. Synergies with other emerging technologies

Cryptography. Several cryptographic tools are used to guarantee the participant identity, the blockchain integrity, the transactions authenticity and (sometimes) the content privacy. The two main cryptographic tools are cryptographic identity (defined by a pair of keys), and cryptographic signature (in order to be checkable, the blockchain transactions (data) must be signed by a cryptographic function so that the miner can identify the sender for sure). Cryptography is therefore an essential constituent of the blockchain technology, and conversely blockchain can be considered as an innovative cryptographic application.

Edge AI. There are several ways blockchain and edge AI could interact:

- A first investigation field consists in trying to understand how blockchain can make AI algorithms more coherent and understandable, possibly less discriminatory in explaining decisions made by machine-learning algorithms. Thanks to its ledger capabilities, blockchain can indeed record all data and variables that go through a decision made under such algorithms;
- In addition, as blockchain allows for the encrypted storage of data on a distributed ledger, it has all the characteristics required to facilitate the creation and qualification of large databases necessary for running AI algorithms. Blockchain allows for the creation of fully secured and qualified databases which can be looked into by parties who have been approved to do so and suitable for the training artificial intelligence algorithms. The combination of blockchain with AI is generating backup systems for sensitive and highly valuable personal data of individuals;
- Conversely, AI could boost blockchain's efficiency by making mining computations more efficiently (following "rules" improving through a supervision process), much better than humans, or even standard computers.

More-Moore technologies, beyond CMOS and / or neuromorphic computing. A key concern about blockchain is the time to validate transactions and the energy requested to do so. It is very likely than in the future, dedicated chips will appear to accelerate the mining process implemented by the variety of consensus protocols which will become available. For example, the giant Chinese Bitmain mining company announced some time ago they were ready to release a 7v nm Bitcoin mining chip using Taiwan Semiconductor Manufacturing Company's FinFET technology. This announcement has, however, been proven to be false and Bitmain was recently announced close to bankruptcy. But the concept of "low-power mining" HW accelerators is still very promising.

iii. Technology roadmap: Maturity levels and expected impacts by application area

A wide range of blockchain-related applications, covering almost all business segments have been or are under development. Blockchain should change the way people interact, prove their identities and do business together. Using a blockchain may help to:

- Reduce the need for trust between stakeholders;
- Build a secure value exchange system;
- Streamline business processes across multiple entities;
- Increase record transparency and ease of auditability.

These assets lead blockchain to impact the following markets:

Applications in electronic markets

Automotive. Almost all automotive manufacturers are now teaming up with blockchain start-ups companies to develop and test blockchain applications. For instance:

- Daimler is teaming with LBBW for B2B business payments;
- Porsche with XAIN to allow users to unlock their vehicles with an application as well as provide easier automated payment systems;
- Toyota with Massachusetts Institute of Technology (MIT) to build safer autonomous vehicles, in order to enable better autonomous vehicle data management);
- Although no tangible output is visible yet, MOBI, a new consortium made up of 37 major automotive and technology companies to build blockchain solutions for the automotive industry was created in 2017. Key members include BMW, General Motors Groupe Renault, Honda, Bosch, IBM, Accenture, etc.

Governments' public databases (Data analysis / Big data). Blockchain will have a critical impact on big data within the coming years in securing the large public and private data base being created through the world digitalization process. For instance, Guardtime is an Estonian company headquartered in Switzerland that uses blockchain to secure public and private data. It has signed a deal with the Estonian government to secure all the country's 1 million health records with its technology. Guardtime technology (KSI or Keyless Signature Infrastructure) is distinct from Bitcoin, making impossible for the government or doctors or anyone else to hide any access or change to healthcare records.

Defense & Security. The applications of blockchain in defense & security are numerous: cybersecurity, but also military supply chains and infield as well as inter-branch communications could benefit from facets of blockchain technology.

- Cybersecurity: Tracing defense-related shipping and procurement contracts, protecting critical infrastructure against cyber-attacks;
- Secure communications: For example, the DARPA has recently signed a 1.8 M$ contact with the US Galois firm to evaluate Guardtime technology to build the DoD new secure blockchain based messaging platform for securing the complete nuclear weapon launching chain;
- Identity and Authentication. Blockchain is expected to have a critical impact on Identification & Authentication applications. By combining the decentralized blockchain principle with identity verification, digital identities can be created, acting as unforgeable marks or tags assigned to every online transaction. Blockchain can help organizations to check the identity of every transaction in real time, hence lowering the fraud rate. Through blockchain solutions, consumers can simply use an app for authentication instead of using traditional methods, such as a username and password. Blockchain stores the encrypted identity, allowing the user to share its data with companies and to manage it on his/her own terms. Finally, blockchain could also be a valuable solution enabling the users to generate personal identities from their blockchain identities.

Telecommunication infrastructure. The business opportunities that blockchain creates for the operator business are diverse and extensive, including for the future 5G and IoT connectivity networks. The GSMA association has identified a lot of use cases where blockchain could improve or replace existing processes such as:

- Fraud reduction: Blockchain could for instance be used to govern access to fraud detection information shared between operators. Fraud detection and prevention continue to be topics of relevance for most operators as a result of fraud costs in the industry is over USD 38 billion annually, with no efficient solution find so far;
- Wholesaling, roaming process & interconnect billing: Customers require to roam/ interconnect on each other's networks, an indispensable service, but requiring a lot of interaction between operators. The current system of storing CDRs, clearing and settling these records is a costly process, which blockchain could dramatically simplify;
- Automation: Access control via blockchain, smart contracts and / or access coins could remove intermediaries and allow hot spot users to interact directly with the access points, paying (if needed) for the bandwidth they are using in real time;
- Content distribution: Delivering content directly from content providers (e.g., Disney, Netflix, etc.), straight to CSP customer devices, removing intermediaries from the process.

Smart Energy. Blockchain technologies could be applied to a variety of use cases related to the operations and business processes of energy companies. Existing literature dictates potential applications and aspects of business models that might be affected, as summarised below:

- Billing, sales & marketing: Blockchain and smart contracts can realise automated billing for consumers and distributed generators. Utility companies could experiment new business models based on micropayments, pay-as-you-go solutions or payment platforms for prepaid meters. Blockchain, in combination with AI techniques such as machine-learning, can also identify consumer energy patterns and therefore enable tailored and value-added energy products provision

- Wholesaling, roaming process & interconnect billing (see the description above for telecommunication infrastructures);
- Smart grid applications, data transfer & sharing of resources: Blockchain can potentially be used for transaction recording between networked smart devices, data transmission or storage between intelligent devices in the smart grid such as smart meters, environmental sensors, network appliances, control and energy management systems. In addition to providing secure data transfer, smart grid applications can further benefit from data standardisation enabled by blockchain technology. Blockchain could also improve control of decentralised energy systems and microgrids, offering charging solutions for sharing resources between multiple users, especially in the renewable sector: the adoption of local energy marketplaces enabled by localised P2P energy trading or distributed platforms can significantly increase energy self-production and self-consumption;
- Regulatory control: Immutable records and transparent processes can significantly improve auditing and regulatory compliance.

Applications in other markets

The Financial sector. The financial sector has been the first to endorse the blockchain technology. The interest of the Financial Community in blockchain goes far beyond the single cryptocurrency domain, as blockchain's applications in finance encompass[24]:

- Financial operation simplification. Blockchain reduces manual efforts required to perform reconciliation and resolve disputes in financial transactions as it disintermediates third parties that support transaction verification;
- Fraud minimization. Blockchain enables asset provenance and full transaction history to be established within a single source of truth. For instance, blockchain reduces the counterparty risk as it challenges the need to trust counterparties to fulfill obligations as agreements are codified and executed in a shard immutable environment;
- Regulatory efficiency improvement. Blockchain enables real-time monitoring of financial activities between regulators and regulated entities;
- Liquidity & capital improvement. Blockchain reduces locked-in capital as it provides transparency into sourcing liquidity for assets;
- Cryptocurrency. As a cryptocurrency, blockchain can be used as a medium for payment as well as a funding tool (through Initial Coin Offering, ICO).

The finance sector represented €6,350 B in 2018 and should account for €7,361 B in 2023. In 2017, 80% of the banks interrogated by experts of the World Economic Forum were initiating a blockchain-related internal project.

Game Industry. The gaming industry has grown dramatically in recent years, partially because the world of video games is keeping up with the latest technological advances and even tries to get ahead of them. As such, it couldn't bypass blockchain. Recent announcements show the interest of the sector for this technology, such as the launch of the Blockchain Game Alliance which promotes a universal standard in the blockchain gaming landscape in 2018. For example, the French market leader Ubisoft is working on a blockchain-based game called HashCraft.

The game console market is estimated to account for €60 B in 2023 and the video games market is expected to account for €80 B in 2023.

Other applications. Automation of the transaction process tends to reduce the unit costs and the marginal costs allowing the multiplication of the transactions associated with frequent use. The arrival of these micropayments will certainly revolutionize markets where the pay-as-you-go unit will become the rule (music,

[24] Elements presented at the WEF of Davos in 2017.

video, software, etc.). Blockchain coupled with connected objects will open new markets, for the management and sharing of data generated by these objects.

Future developments

- Open source. Blockchain blocks are generally and more and more available under an open mode source;
- Blockchain as a Service (BaaS). Blockchain blocks are more and more available under BaaS. BaaS is essentially a back-end infrastructure including "development tools-as-a service" and targeting application and solution developers at an individual or enterprise scale. This method eliminates the purchase of the software or the payment of licenses fees, but it is currently still very fast to version multiple blockchain and it pose a problem of stability of the applications built on top of these software blocks. The EU is, however, currently lacking major actors in the BaaS field as this type of infrastructure essentially targets service providers who provide advisory and consulting services, custom development, system implementation and integration services, as well a managed service to end users. Key BaaS vendors include Microsoft, IBM, Amazon, HP, SAP, Oracle.
- Consensus algorithms. Most popular blockchain implementations (e.g., Bitcoin and Ethereum), provide a weak form of consensus. Beyond the complexity introduced by the consensus executions, the main issue comes from the fact that all important decisions are solely under the responsibility of (a quorum of) peers, and the membership of the quorum is decided by the quorum members. This magnifies the power of malicious peers. Additional R&D is then needed to assess the security and consistency of mechanisms alternative to Proof-of-Work, such as *Proof of Stake*, *Proof of Activity, Proof of Memory, and related consensus algorithms built upon, such as* Practical Byzantine and Delegated Byzantine Fault Tolerance protocols.

Limitations and technological barriers

Finally, below are the five main reasons hampering large blockchain adoption:

- **Negative ecological impact**. The mining processes (mostly for the POW protocol consensus of Bitcoins), are extremely energy consuming and lead to a disastrous ecological footprint;
- **Long transaction times at the technical level** (for instance in the case of Bitcoin with 2.75 transactions per second in 2016) and verification times (10 minutes to validate a block and to write it within the next block in Bitcoin), preventing real-time processing capabilities;
- **Size.** By November 2016, the Bitcoin blockchain measured roughly 92 GB (with 2,075 transactions per block. With latency and throughput limitation solved, this size could grow up to 214 PB each year (if assumed to be as fast as other traditional payment platforms). If the blockchain-based application needs to control more data (as for smart contracts or any other digital assets written within the blockchain), this growth can be even faster. In the Bitcoin community, this problem is known as "bloat" and is usually solved by reducing the size of the blockchain. However, whilst this is a valid short-term solution, it will not scale to huge networks such as for application targeting the Internet of Things. In this case, the long-term solution is rather to design a faster and more efficient way to manage large blockchain;
- **Security.** The blockchain technology is usually seen as an inherently secure technology. However, there is no formal proof that the three classical security properties (confidentiality, integrity, and availability), are enforced by blockchain technologies. In the IoT, unmanaged and unsupervised case, devices could be running on top of blockchain technology thus being exposed to key theft or information stealing attacks.
- **Governance and legal issues** to prevent risks of fraud and / or of abusive uses of blockchain, such as money laundering and speculative use of cryptocurrencies.

Technology Roadmap - Maturity of the technology at the global scale and by application area

<table>
<tr><th>N°</th><th></th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td></td><td>Maturity level of the technology</td><td colspan="13">Industrial integration</td><td colspan="8">Massive integration</td></tr>
<tr><td></td><td>Electronic Segment</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Automotive applications</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>2</td><td>Industrial & robotics applications</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>3</td><td>Health & Care applications</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>4</td><td>Aerospace applications</td><td colspan="13">No significant impact</td><td colspan="8">Small impact</td></tr>
<tr><td>5</td><td>Defense & Security applications</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>6</td><td>Phones applications</td><td colspan="13">No significant impact</td><td colspan="8">Small impact</td></tr>
<tr><td>7</td><td>Telecommunications infrastructures applications</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>8</td><td>PC & data processing applications</td><td colspan="13">No significant impact</td><td colspan="8">Small impact</td></tr>
<tr><td>9</td><td>Audio & Video applications</td><td colspan="21">No significant impact</td></tr>
<tr><td>10</td><td>Home appliances applications</td><td colspan="21">No significant impact</td></tr>
<tr><td></td><td>Crossed segments</td><td colspan="21">Penetration rate by technology - Impact on the value chain of the segment in terms of competitive advantage and perspective of volumes of production</td></tr>
<tr><td>1</td><td>Data analytics / Big data</td><td colspan="5">Small impact</td><td colspan="8">Medium impact</td><td colspan="8">Critical impact</td></tr>
<tr><td>2</td><td>Smart home</td><td colspan="21">No significant impact</td></tr>
<tr><td>3</td><td>Smart mobility</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>4</td><td>Smart energy</td><td colspan="5"></td><td colspan="8">Small impact</td><td colspan="8">Medium impact</td></tr>
<tr><td>5</td><td>Wearables</td><td colspan="21">No significant impact</td></tr>
<tr><td>6</td><td>Finance</td><td colspan="21">Small impact</td></tr>
</table>

At the global scale, each technology is defined through four different stages of maturity.

- **<u>R&D:</u> Signify that no prototype has yet been demonstrated in a real environment. Technology Readiness Level (TRL) 1-6**
- **<u>Tests & prototyping:</u> Signify that no producer has yet launched the industrial production of a product using that technology (excluding prototypes for demonstration in real environment). Technology Readiness Level (TRL) 7-9**
- **<u>Industrial production:</u> Signify that at least one producer launched the industrial production of a system using that technology (excluding prototypes for demonstration)**
- **<u>Massive production:</u> Signify that production of systems integrating the technology has already reached steps that enable significant scale economies**

The impact of the technology on each end-user segment is described as:

- **A critical impact;**
- **A significant impact;**
- **No significant impact;**

…in terms of <u>competitive advantage</u> and <u>volumes of production</u>…

…on the global electronic value chain.

Source: DECISION Etudes & Conseil

Impact of blockchain by end-user electronic applications in 2023

	Industrial & Robotics	Automotive	Consumer PC	Mobile phones	Telecommunication infrastructures	Defense / Security	Audio / Video	Health & Care	Professional PC	Home appliances	Aerospace
Market size in 2023 (B€)	576	430	344	244	219	203	198	126	85	52	49
Impact on the markets*	Medium	Medium	Small	Small	Medium	Medium	No	Medium	Small	No	Small

Corresponding quantitative impact of blockchain in 2023

Market size of the technology (B€)	TOTAL impact			Electronic end-user markets			Other markets		
	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)	Critical impact in market accounting for (B€)	Medium impact in market accounting for (B€)	Small impact in market accounting for (B€)
19	0	1 554	8 223	0	1 554	722	0	0	7 501
				-	Automotive electronics, Industrial & Robotics electronics, telecommunication infrastructures, Defense & Security electronics and Health & Care electronics	Consumer & Professional PC, Mobile Phones, Aerospace	-	-	Finance sector and gaming sectors. Markets where the pay-as-you-go unit will become the rule (music, video, software, etc.). Too complex to be quantified in this study

* Economic impacts in terms of competitive advantage and volumes of production, thanks to improvement in terms of computing capacity and energy efficiency

Estimated economic impact of blockchain in 2023

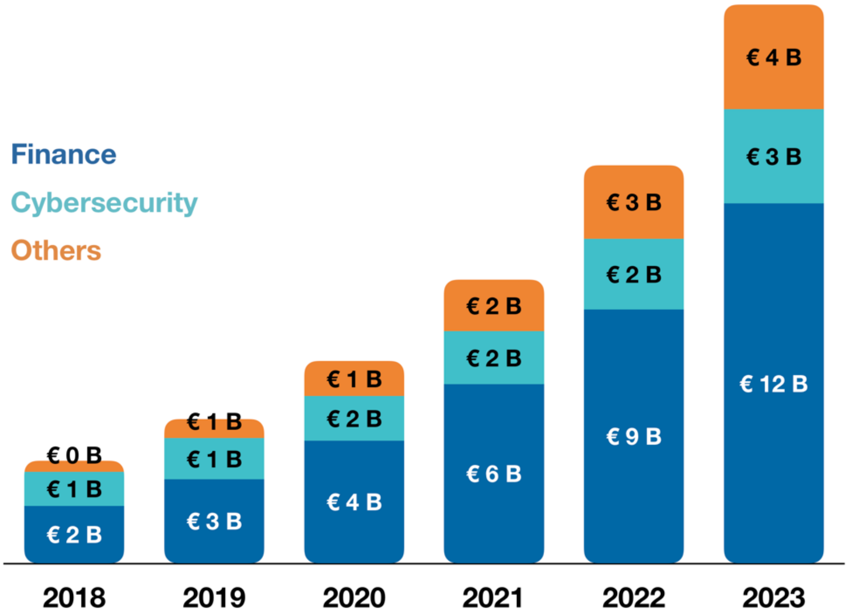
Source: DECISION Etudes & Conseil

iv. Main players in the World and in the EU

A. Market value

After many years over relative stagnation for an emerging technology (8-12%/year), the growth of the global blockchain market expected to rise significantly with an expected Compound Annual Growth Rate (CAGR) of 40% per year over the 2018-2023 period. The blockchain market should therefore move from €3.5 B in 2018 to €19 B in 2023.

Blockchain Market 2018-2023 (€B)



Applications	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
Finance	2,0	2,9	4,2	6,1	8,6	12,2	44 %
Cybersecurity	1,2	1,4	1,5	1,8	2,4	3,2	23 %
Others	0,4	0,6	1,2	1,8	2,5	3,6	57 %
TOTAL	3,5	5	7	10	14	19	40 %

Source: DECISION Études & Conseil

The digital identity application segment is expected to be the fastest-growing application in the blockchain market, as it eliminates the need for central authority and third party thereby making it easier for individuals to manage and control over personal information and access.

Based on figures from Markets and Markets, the Blockchain as a Service market (BaaS) was valued at €600 Million in 2018 and is expected to reach €12.9 B by 2023, at a Compound Annual Growth Rate (CAGR) of 88% during the forecast period (that is moving from 15% to 68% of the blockchain market). The Blockchain as a Service Market includes Blockchain as a Service platform vendors (Microsoft, AWS, etc.), and service providers.

Private investments into blockchain companies reached €800 M in 2018, and blockchain start-ups have raised a total of nearly €700 M during the first half of 2019[25].

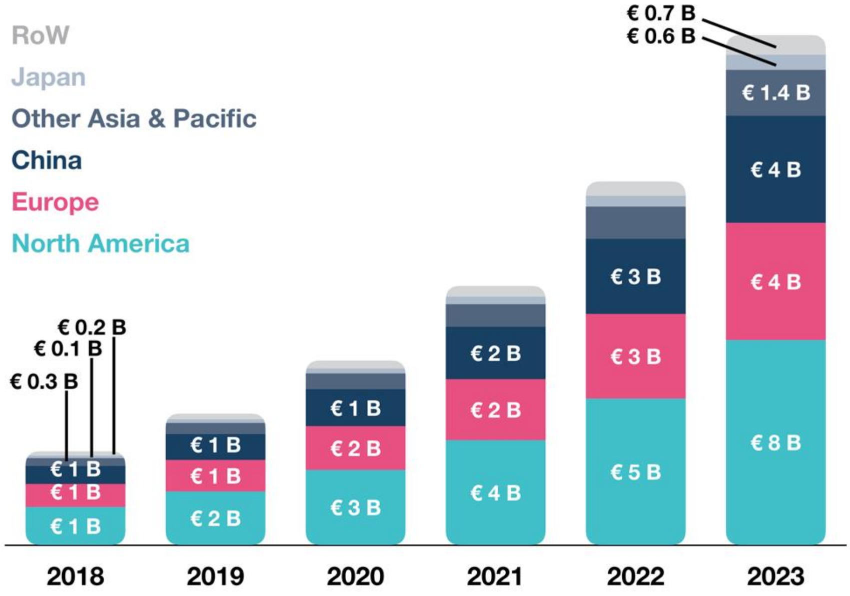
[25] Estimates based on a report from venture capital firm Outlier Ventures.

B. Country analysis

Regional comparison

Over the period, the EU should remain the second region after North America for revenue generation, but clearly lacks business leaders except in some focused areas. Indeed, IBM and Microsoft are driving blockchain as their clients are making the transition to cloud services. Accenture is one of the other market leaders as well.

Blockchain revenue by region, 2018-2023



Region	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
North America	1,4	2,0	2,8	3,9	5,5	7,6	40 %
Europe	0,8	1,2	1,6	2,3	3,1	4,4	39 %
China	0,7	1,0	1,4	2,0	2,8	4,0	43 %
Japan	0,1	0,1	0,2	0,3	0,4	0,6	43 %
Other Asia & Pacific	0,3	0,4	0,6	0,8	1,2	1,7	43 %
Rest of the World	0,2	0,2	0,3	0,4	0,5	0,7	36 %
TOTAL	4	5	7	10	14	19	40 %

Source: DECISION Études & Conseil

To date, the European Commission has granted approximately €80 M per year to the EU projects dealing with blockchain in many sectors and has announced plans to increase funding by up to €300 M by 2020.

Regarding the intra-European situation, developers from the UK and Germany are among the most active in the blockchain field on the world leading software development platform GitHub (around 3,000 developers together), with strong developer activity in other European countries (France, the Netherlands, Spain and Switzerland). In terms of cities, London (2nd place), and Paris (6th), were among the top 10 cities for blockchain development based on the number of projects started worldwide in 2017, according to the GitHub ranking.

C. Research players

The table below from WSGR (see the related study), shows the TOP 30 worldwide blockchain research players in July 2018 regarding the total number of patents granted and pending patent applications published related to blockchain, cryptocurrencies and cryptographic tokens during the 1998-2018.

TOP Research players: Blockchain Patents Granted and Applications Published Worldwide over the 1998-2018 period

N°	Nationality of capital ownership	Company	Number of patents granted & Applications published
1	China	Tsinghua Univ.	18
2	China	Univ. of Electronic Science of China	18
3	China	Beihang Univ. Beijing	18
4	The USA	Duke Univ.	13
5	China	Jilin University	12
6	China	Nanjing Univ.	10
7	China	Zhejiang Univ.	10
8	South Africa	Stellenbosch Univ.	9
9	China	Sichuan Univ.	9
10	China	Fudan Univ.	9
11	China	Guangdong Univ.	9
12	China	Huazhong Univ. Of Science	8
13	China	Sun Yat-sen Univ. Guangzhou	8
14	China	Chongqing Univ.	8
15	China	South China Univ.	7
16	China	Hanghzou Dianzi Univ.	7
17	China	Chengdu Univ.	6
18	China	Tianjin Polytechnic Univ.	6
19	China	Guangxi Normal Univ.	6
20	China	National Univ. of Defense	6
21	China	Harbin Engineering Univ.	6
22	China	Peking Univ. Shenzhen	6
23	China	Anhui Univ.	6
24	China	Hefei Univ. of technology	6
25	China	Beijing Univ. Of Technology	5
26	China	Nanjing Univ.	5
27	China	Xidian Univ.	5
28	China	Southeast Univ. Nanjing	5
29	China	Tsinghua Univ.	5
30	China	Beijing Univ. Of Posts & Telecom.	5

Source: Wilson Sonsini Goodrich & Rosati (WSGR)

D. Industry players

Global landscape. The table below from WSGR (see the related study), show the TOP 30 worldwide blockchain industrial players in July 2018 regarding the total number of patents granted and pending patent applications published related to blockchain, cryptocurrencies and cryptographic tokens during the 1998-2018.

TOP Industrial players: Blockchain Patents Granted and Applications Published Worldwide over the 1998-2018 period

N°	Nationality of capital ownership	Company	Number of patents granted & Applications published
1	The USA	IBM	225
2	The USA	Mastercard	140
3	Japan	Sony	80
4	The USA	Microsoft	78
5	Japan	Panasonic / Matsushita	75
6	South Korea	Coinplug	73
7	China	Alibaba	72
8	Japan	Canon	71
9	Netherlands	Philips	70
10	Japan	Hitachi	69
11	Japan	Fujitsu	64
12	The USA	Bank of America	55
13	China	Huawei	54
14	Japan	NEC	53
15	China	Nchain Holdings	52
16	The USA	Amazon	51
17	South Korea	Samsung	50
18	China	ZTE	45
19	Japan	Toshiba	44
20	The USA	Intel	41
21	The USA	HP	41
22	Japan	Fuji JP	39
23	The USA	Accenture	38
24	The USA	Walmart	36
25	Canada	Toronto-Domin. Bank	33
26	The USA	Oracle	31
27	The USA	Qualcomm	30
28	Finland	Nokia	27
29	The USA	Google	25
30	China	China Unicom	22

Source: Wilson Sonsini Goodrich & Rosati (WSGR)

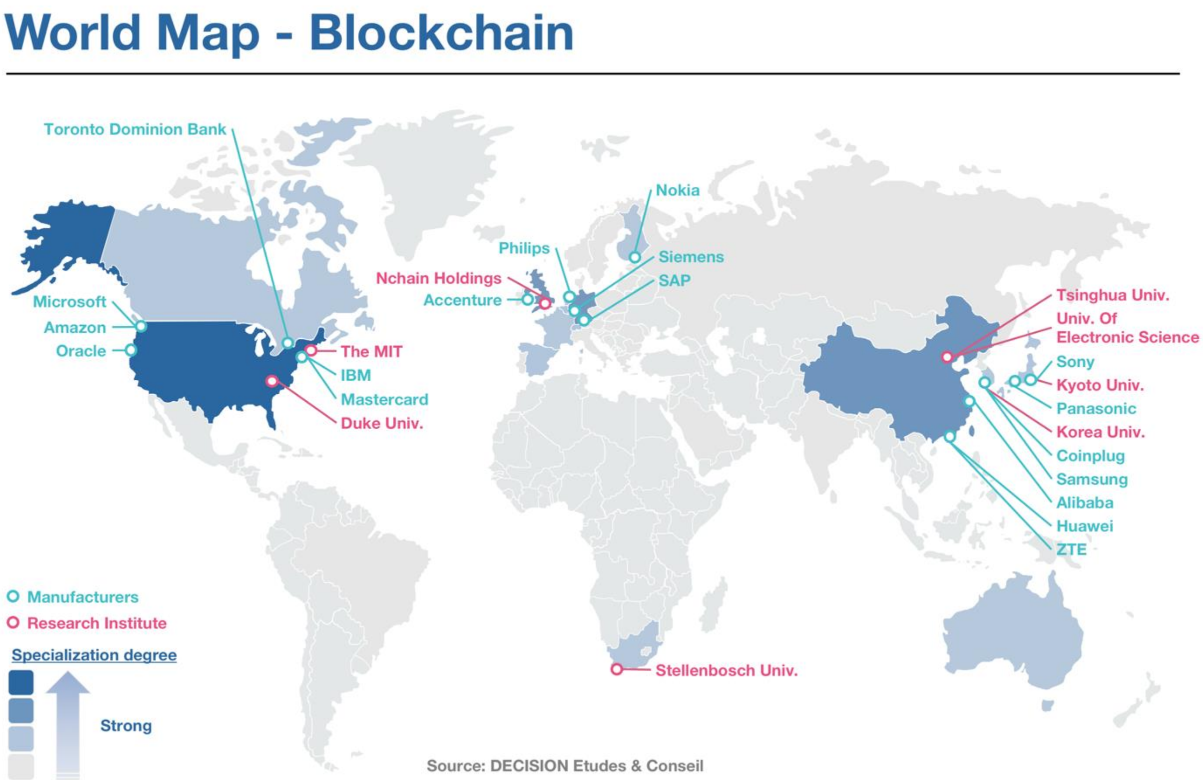
Blockchain applications in the Finance Industry. The picture below from BSI Intelligence enlightens the relatively smaller presence of the EU in the major blockchain initiatives visible so far on the financial markets compared to the position of the American players.

Out of the 44 partners of R3 CEV, which aims at setting up the bases and the norms of a worldwide shared blockchain between banking institutions, 10 are in the EU and 15 are in Europe, against 15 in North America, 4 in China and 3 in Japan;

Among the 15 investors of Digital Asset Holdings, a leading financial technology company that builds products based on blockchain for regulated financial institutions, 4 are in the EU against 9 in the USA.

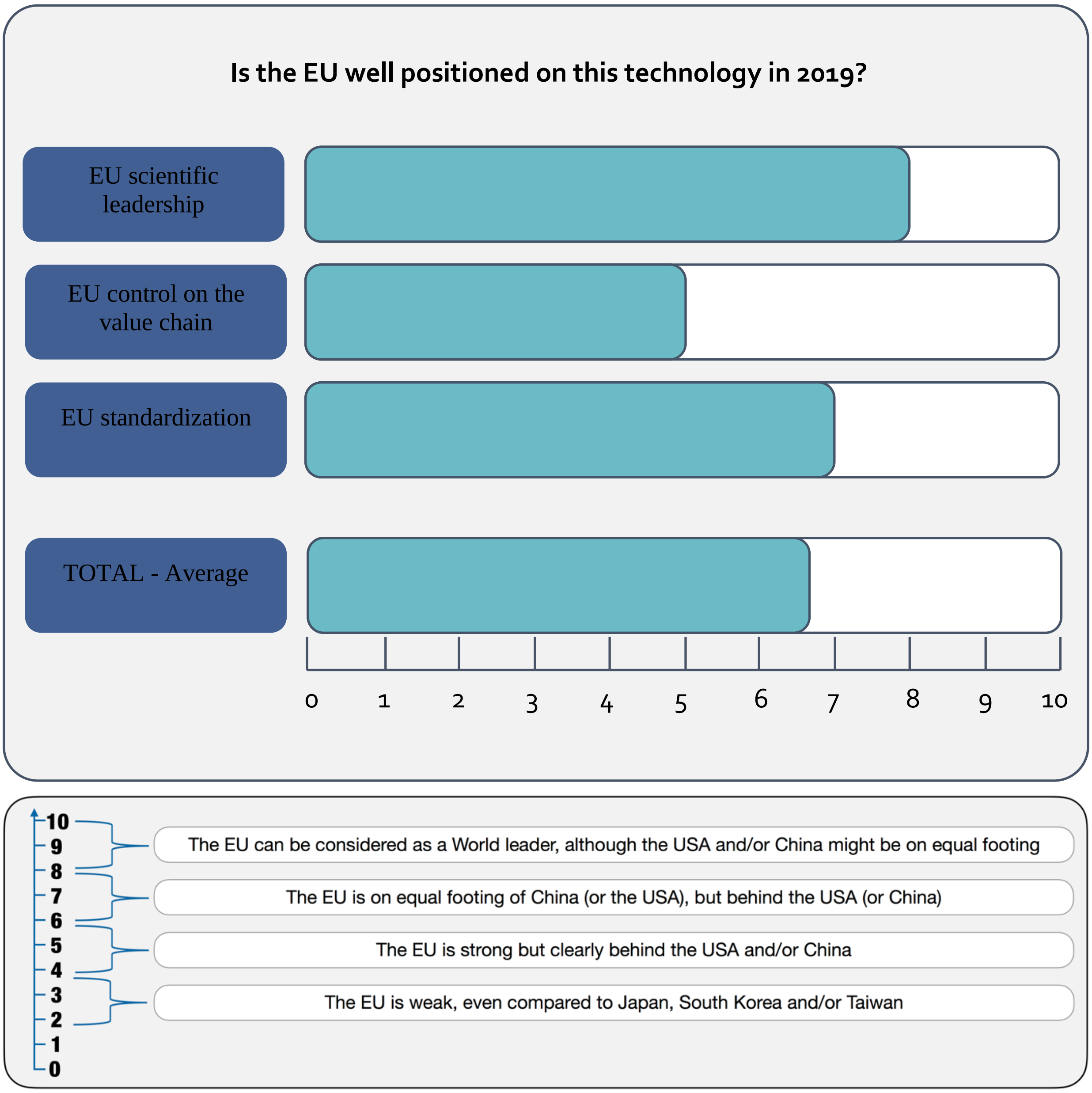
Among the 17 members of the Hyperledger Project (a multi-project open source collaborative effort hosted by The Linux Foundation, created to advance cross-industry blockchain technologies), 4 are in the EU, against 10 in the USA;

Among the 11 members of the Ripple project, 2 are in the EU against 2 in Canada, 2 in Australia and 2 in Asia.



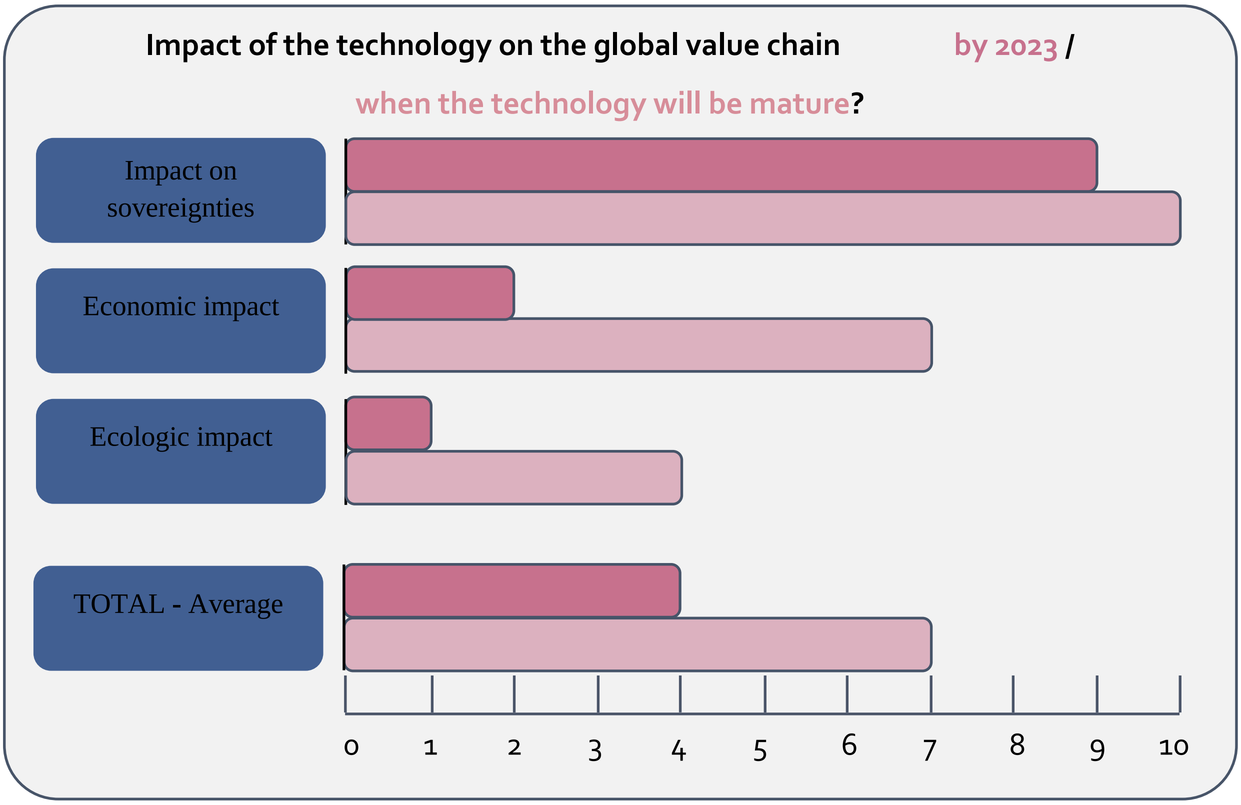
V. Quantitative and qualitative analysis of the technologies under consideration with regard to their relevant support under Horizon Europe

A. Position of the EU in the World in 2019



Source: DECISION Etudes & Conseil

B. Expected impacts of the technology



Source: DECISION Etudes & Conseil

- Impact on the EU sovereignty: Close to 0 if the technology is not related to any sovereignty issue for the EU. Close to 10 if the mastering of this technology appears as crucial to maintain and / or enforce the EU sovereignty.

- Economic impact: Close to 0 if the existing market of the technology is nonsignificant and / or if the indirect positive economic synergies that might be enabled by the technology are nonsignificant **by 2023 / when the technology will be mature**. Close to 10 if the existing market of the technology is outstanding and / or if the indirect positive economic synergies that might be enabled by the technology are outstanding **by 2023 / when the technology will be mature**.

- Ecological impact: Close to 0 if the technology cannot directly and / or indirectly be useful to fight Anthropocene (characterized by the climate change and the 6th mass extinction). Close to 10 if the technology should be directly and / or indirectly very useful to fight Anthropocene, either as a complement of existing technologies or by replacing existing technologies.

EU scientific leadership

According to the report "Blockchain Innovation in Europe", from the EU Blockchain Observatory and Forum, the EU is very active in blockchain R&D. The EU blockchain R&D is benefiting from good EU strengths in domains adjacent to blockchain such cryptography or artificial intelligence. The USA are leading the blockchain R&D landscape, yet the EU is in second position along with China and ahead of Japan.

EU control on the value chain

In April 2018, 22-member states (joined in 2019 by 5 additional members), signed the Declaration for a European Blockchain Partnership (EBP) in order to cooperate on the development of a European Blockchain Services Infrastructure. The goal is to support the delivery of cross-border digital public services, with the highest standards of security and privacy and to identify initial use cases and develop functional interoperable specifications. EBP should be an important catalyst for the use of blockchain technology by European government agencies, helping them controlling the value chain at a certain extent. The EU Blockchain Observatory and Forum provides am impressive list of start-ups, SMEs or Initiatives working on the blockchain technology in the EU (over 500 companies or initiatives mentioned). This may give the impression that the EU has the control of the whole value chain, but in fact, with a few exceptions, most major blockchain software editors are American. Software edition is for sure the delicate point of the European global blockchain ecosystem.

Standard analysis

Standardization in blockchain will represent an important factor for the development of the technology. An international set of working groups was created as part of the International Standards Organization, with a first meeting being held in April 2017. The group has been since labeled as ISO TC 307 "Standardization of blockchain technologies and distributed ledger technologies". The TC 307 includes now 43 members, 12 observers, and has established relationships with the European Union, the OECD, the SWIFT international network, the Ethereum Alliance and the ITU. Participation of national countries is through delegates from their national standard organisations (e.g., AFNOR for France). From this perspective, with about 25 members of the EU participating to the TC307, the EU position is good.

Impact on sovereignties

Blockchain will very significantly impact on sovereignties through its impacts on multiple sovereign fields: monetary transactions, cybersecurity, identification & authentication and secure communications. New features could even appear based on the strengths of the blockchain technology (transparency, auditability, non-repudiation, security, resilience) as for example the electronic votes that could evolve towards more complexity of choices today limited by the physical support for the choices of the citizen.

Economic impact

The blockchain market (outside cryptocurrencies), cannot be considered as an established market and the usability and mass deployment of the technology stays at the prototype or concept level for a lot of domains, due to government regulation or legal issues. Yet, market positions should so dramatically change in the future, even if the American software editors currently have the lion's share. The blockchain market will remain small by 2023 (€19 B), with a medium impact on the majority of the electronic end-user segments and significant impacts on the video game / game console markets and the (very large) finance sector.

Ecological impact

The most visible impact of cryptography on ecology relates to the cryptocurrency mining process. Cryptocurrency "mining" is currently on the spotlight for its negative environmental impacts associated with it. According to Digiconomist, Bitcoin alone (due to the POW mining process), has the same environmental impact as approximately 2.358 million cars annually in terms of CO2 emissions (that is the vehicle fleet of Ireland, Slovakia, Israel or Vietnam). This energy usage is only set to increase with blockchain's development. This aspect is probably the hardest challenge blockchain has to face for its mass adoption and the EU needs to take part to the global effort to mitigate crypto-mining activities' impact on the public energy sector and create the appropriate regulatory environment. There are nevertheless two applications where blockchain could be envisaged for having a positive ecological impact:

- Tracking products from origin to source, hence reducing carbon footprints & unsustainable practices, and incentivising recycling schemes. For instance, while tracking the carbon footprint of products, blockchain might also help to determine the amount of carbon tax to be charged;
- Blockchain should ease smart-energy development, e.g., through peer-to-peer localised energy with blockchain managed networks.

ANNEX 2 - ELECTRONICS ECOSYSTEM

EUROPE'S POSITION IN TERMS OF PRODUCTION AND FORECASTS

Methodology

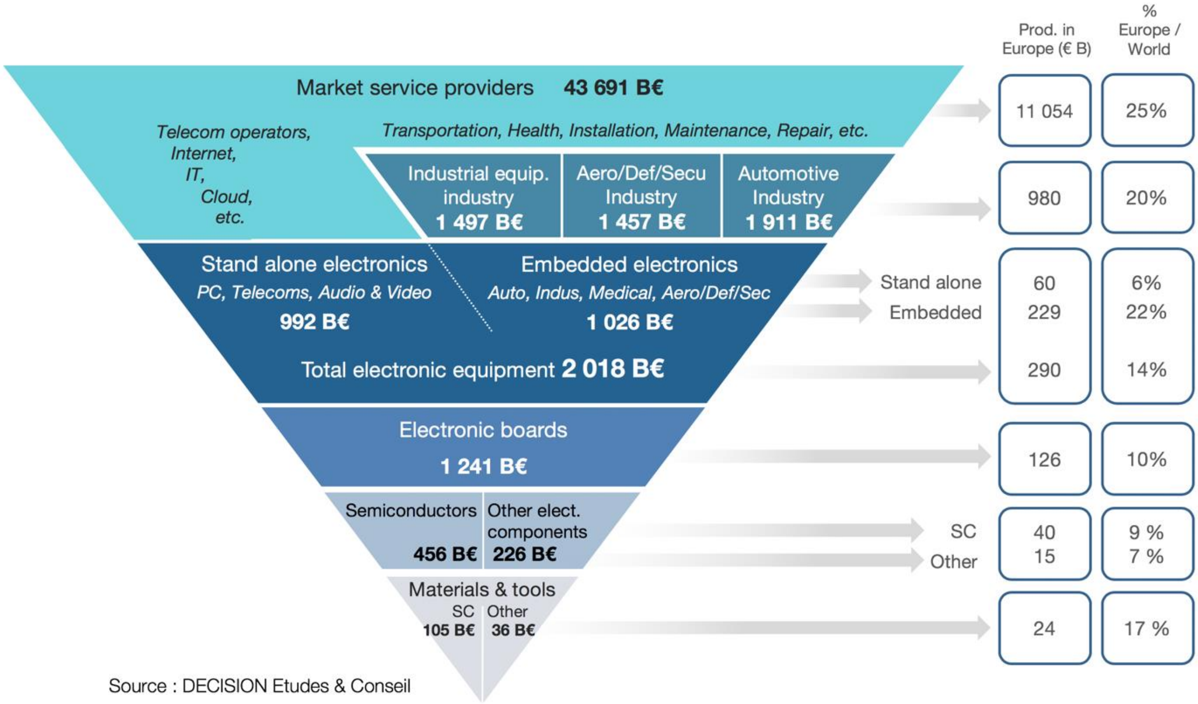
The market and forecasts values presented in this part are based on almost 30 years of expertise on the electronics industry worldwide. Especially through analyses, studies and databases carried out by DECISION and in particular:

- Figures related to electronics markets and production localizations are based on the study undertaken in 2018 for the DG CONNECT entitled "Study on the electronics ecosystem: Overview, Developments and Europe's position in the World" – SMART 2016/0007.
    - **Electronics equipment.** The figures related to electronics equipment are directly computed from an internal database updated yearly since 2001 by DECISION and measuring (and covering) the worldwide production of electronics equipment by segment (Automotive electronics, Industrial & Robotics, Data Processing, Telecommunications, etc.), and for all regions of the world: Europe, North America, Japan, China, Other Asia Pacific and RoW. This work is set up from different sources: interviews of experts by DECISION's analysts, companies' annual reports, international or regional professional associations, various government statistics (Eurostat Prodcom, US Census, Japanese Census, etc.). For the segments without public statistics (for instance automotive electronics), the annual reports of the main industrial players are computed and analyzed. Then the list of their factories worldwide is identified, along with their associated products. Finally, the figures associated to each factory (number of employees and turnovers), are either found or estimated. The data are then computed and adapted to fit with Prodcom standards. The Prodcom database measures the quantities and values of the electronic systems sold by suppliers. The purpose of this statistic is to report, for each product in the Prodcom List, how much has been produced in the reporting country during the reference period. This means that Prodcom statistics relate to products (not to activities) and are therefore not strictly comparable with activity-based statistics such as Structural Business Statistics. The link to the turnover of an enterprise is tenuous, since some enterprise's activity does not result in new products and are therefore not be recorded in Prodcom. The NACE codes on which Prodcom codes are based merely serve to identify the enterprises that should be surveyed to determine the production of products.
    - **Semiconductors.** The figures related to semiconductors are based on the most recognized institutes and / or professional associations worldwide, like WSTS (World Semiconductor Trade Statistics), SEMI, SIA (Semiconductor Industry Association), JEITA (Japan Electronics and Information Technology Industries), etc.
    - **Passive components.** Passive components figures are based on the Worldwide Passive & Interconnection Component Market database carried out by DECISION**.** The passive & interconnection component market database is based on the component content of the various segments of electronic products. The values in the database are obtained by a thorough, two-pronged analysis of the European electronic markets. Once the end markets have been established and forecasts made, a top-down, input/output methodology is employed to calculate the passive component content of the end products.
    - **Non-electronic segments.** The figures related to end users' non-electronic services and industries (services, automotive industry, robotics industry, etc.), are based either on international statistics (OECD, the World Bank), and / or on the most recognized institutes and / or professional associations worldwide (the OICA and the ACEA for the Automotive industry, etc.).
- Figures related to Defense & Security (in particular the Identification & Authentication market), are based on studies undertaken by DECISION in defense & security. DECISION has been in charge for many years of the French Observatory of the industries of Security and of the Observatory of the French Alliance for Digital Trust (ACN). DECISION collects corporate accounts of the main companies on an annual basis as well as annual reports and segment their activity by-products and applications, to set up consistent figures. The data are then computed by segment and by region.
- Finally, figures related to emerging markets linked to technologies for which DECISION and Yole Développement do not have a particular database (examples: Digital identities, smart sensors, HPC, AI chips, AI algorithms, secure elements, cryptography, blockchain and integrated photonics), figures are built

as follows. First, DECISION's industrial experts identify the main industrial players by region. Then, the annual reports and financial information on these players are collected and computed to have a baseline of analysis and comparison. Then, the existing public data related to the market are collected whenever they exist (Eurostat, OECD, World Bank, etc.). Then, a literature review on the emerging market is undertaken, to collect the main reports that provides market values. The final step consists in comparing and challenging our internal inputs, the knowledge of our experts, the existing public databases and the different reports to set up the most consistent market values.

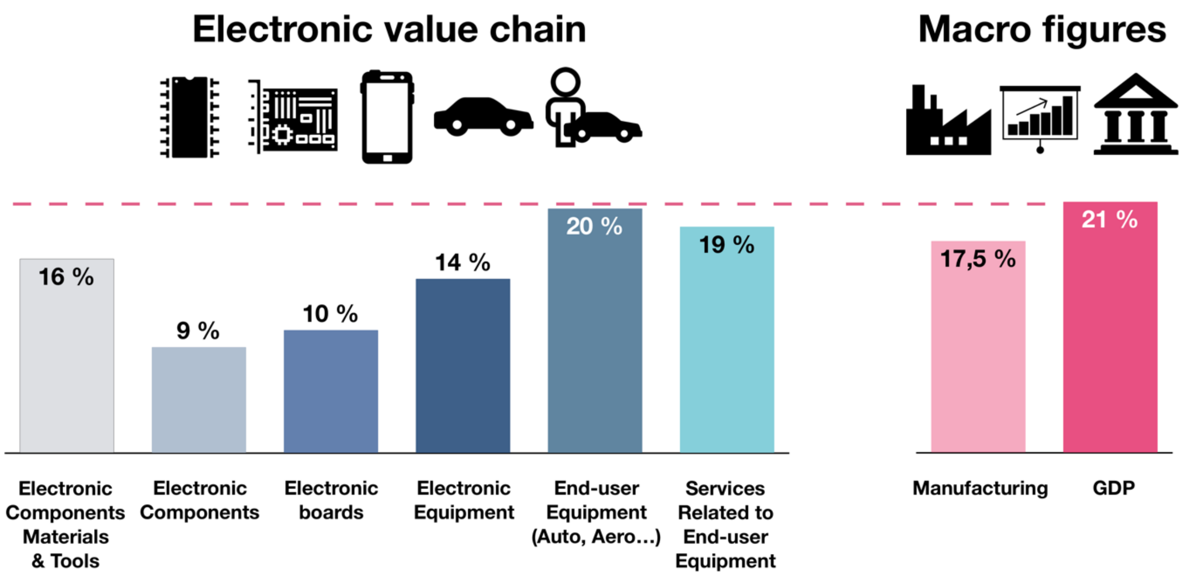
1. The World electronics value chain in 2018

The electronics value chain in 2018 – production values (in euros)



The EU electronic value chain shows that Europe still holds a good share in materials and tools for the production of electronic components, although Europe's production share is lower at levels such as electronic equipment, electronic boards and electronic components (including semiconductors).

Electronics value chain in 2018 – EU share of total production (1/4)



Source: DECISION Études & Conseil, see III)1) Methodology

Yet, in the professional/embedded electronics segments, the EU holds very strong positions.

The relative importance of the end user segments in the European Electronics Ecosystem is significantly different from the world configuration. In Europe the leading end-user segments are industrial electronics, aerospace defense and security, and automotive electronics, whereas the industrial ecosystem in Phones, Consumer PCs and Audio/Video is weaker. At the worldwide scale, consumer PCs and Phones remain the third and the fourth electronic markets.

Europe's share in world production, unsurprisingly, is also highest in those segments where Europe is strongest.

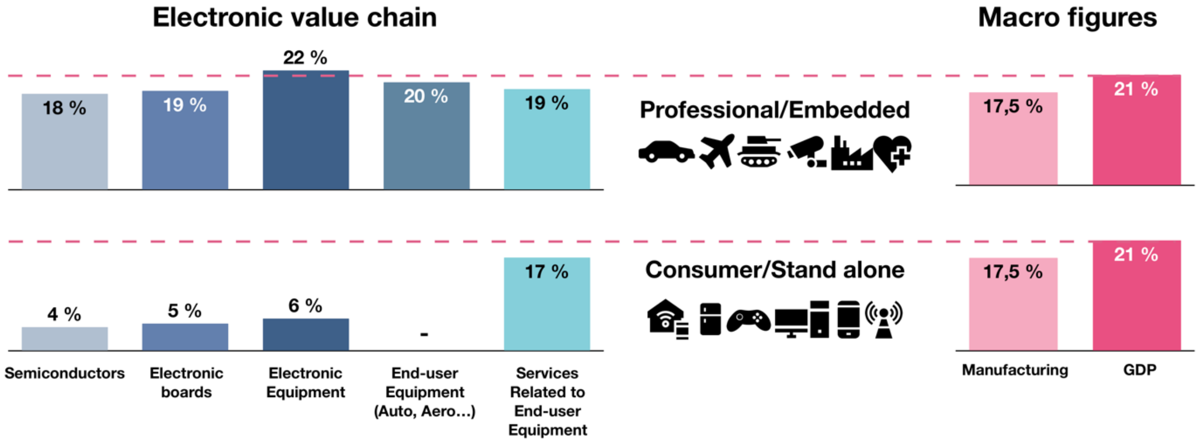
- The EU automotive industrial base is very strong. Yet, the EU automotive electronics sector is even stronger, not only in terms of high value-added activities (engineering, R&D, etc.), but also in terms of factory production. The EU produces 27% of the global automotive electronics. The EU is the first region in the world ahead of China (21%), and North America (17%);
- The EU also holds strong positions in industrial electronics. The EU produces 20.1% of the global industrial electronics. The EU is the second region in the world after China (27%), and ahead of North America (20.9%);
- The EU aeronautics/defense/security electronic industrial base is strong. The EU produces 21.5% of the global Aerospace/Defense/Security electronics. The EU is the second region in the world after North America (41%), but ahead of China;
- The EU has a competitive Health & Care electronics industry. The EU produces 19.3% of the global Health & Care electronics. The EU is the second region in the world after North America (41%), but just above China (20%).

In the stand-alone / consumer electronics segments, the EU has weaker positions.

In comparison, the EU represented in 2018:

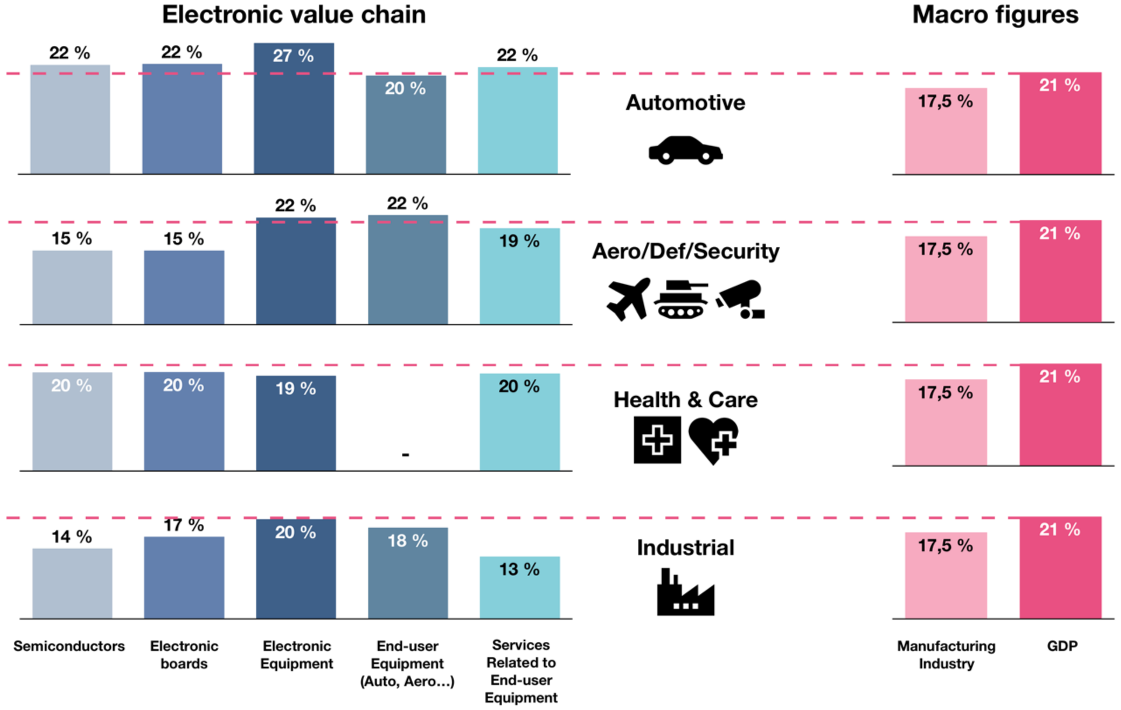
- 16.5% of the global home appliances production. The EU is the second region in the world after China (37.5%) but ahead of other Asia (12.5%) and the rest of the world (12.5%);
- 11% of the global audio & video production. The EU is the 4th (out of 6) region in the world after China (56%), other Asia (24%) and the USA (1.5%);
- 5.4% of the global computer production. The EU is the 3rd (out of 6) region in the world after China (53%), other Asia (32%);
- 3.7% of the global telecommunication electronics production. The EU is the 5th region in the world after China (51%), other Asia (29%), the rest of the world (7.6%) and the USA (5.4%).

Electronics value chain in 2018 – EU share of total production (2/4)



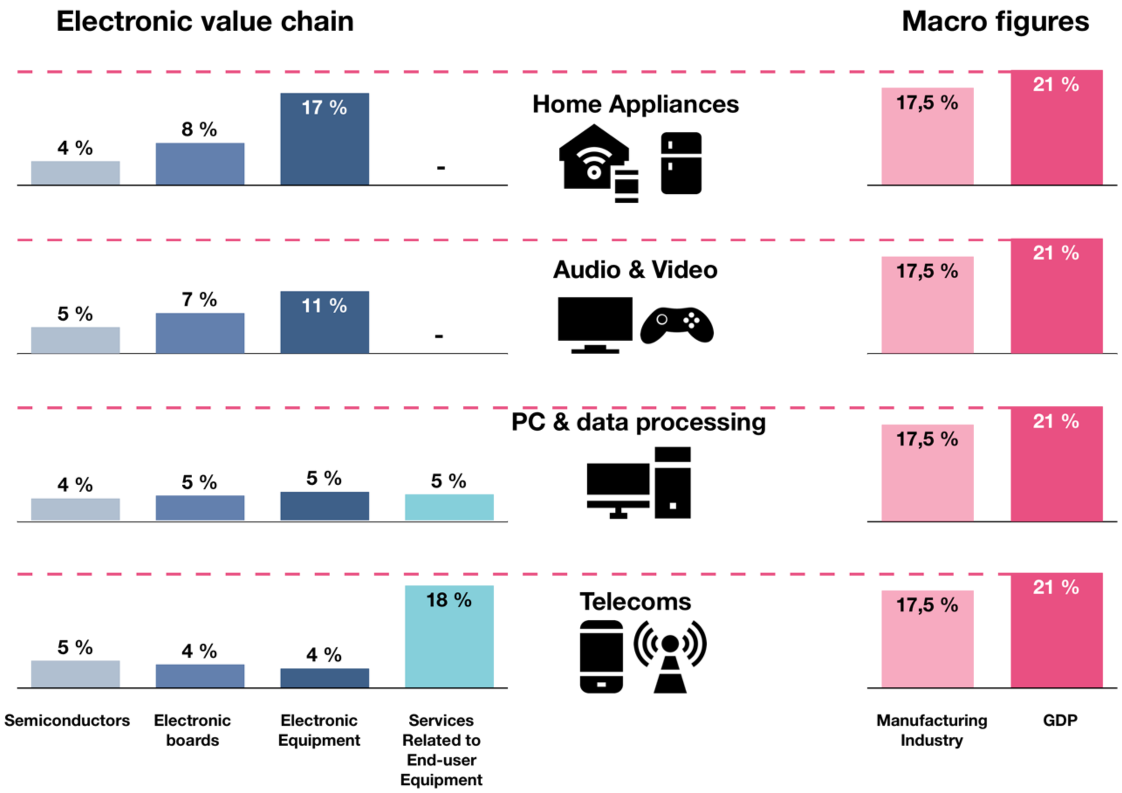
Source: DECISION Études & Conseil, (see Methodology)

Electronics value chain in 2018 – EU share of total production (3/4)



Source: DECISION Études & Conseil, (see Methodology)

Electronics value chain in 2018 – EU share of total production (4/4)

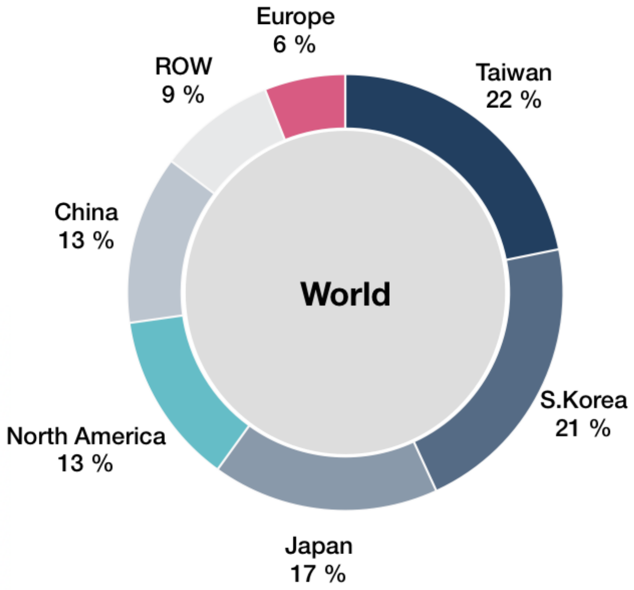


Source: DECISION Études & Conseil, (see Methodology)

2. The Semiconductor industry

The semiconductor market represents € 456 B in 2018. Regarding the semiconductor industry, Europe represents only 6% of the world in terms of monthly installed wafer capacity in 200 mm equivalent and this share is constantly declining since 2010. The EU also represents 9% of the worldwide semiconductor shipments.

Wafer capacity in 2018 – by geographic region (monthly installed capacity in 200 mm equivalent)



Source: IC Insights, DECISION Études & Conseil

Europe does not produce advanced semiconductor technologies anymore

- In terms of production of old technologies (> 22 nm), the EU remain well positioned;
- On the contrary, advanced technologies (currently below 22 nm), are no longer manufactured in Europe;
- Yet, the alternative technology, namely FDSOI, is an opportunity to regain production shares in advanced technologies.

Europe remains a world leader in terms of semiconductor equipment production

- ASML, based in the Netherlands and supported by research at IMEC, is a world leader in lithography with 11 B € turnover in 2018;
- SOITEC is a key player in SOI wafers and is gaining market shares thanks to its SDSOI technology;
- M + W is a world leader in advanced technology facilities with a turnover of 3,5 B € in 2018;
- Companies like ASML or AIXTRON are also gaining important market shares thanks to their deposition technologies;
- RECIF is one of the world leaders in robotic wafer handling.

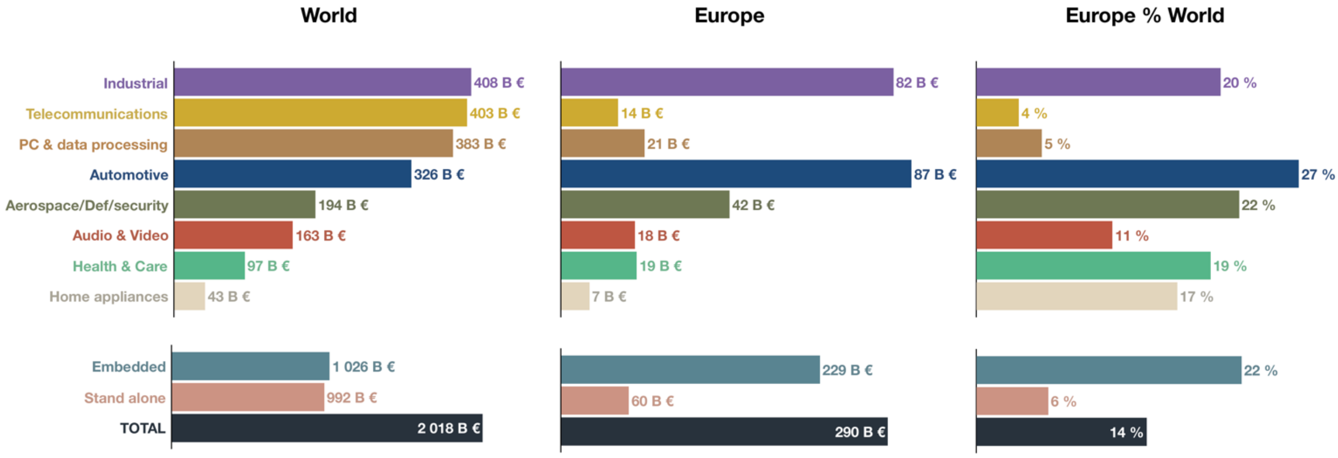
Europe is a world leader in R&D, mostly due to successful European Commission supported basic research

The Imec, the Fraunhofer Institutes and the CEA Leti are excellent R&D centers at the cutting edge of numerous MNE technologies.

3. Overview by segment in 2018

The following paragraphs and associated pyramids present the figures of the electronic value chains in 2018 by segment. In 2018, Europe represented 22% of the world embedded/professional electronic production, but only 6% of the world stand-alone/consumer electronic production.

Electronic systems production by segment in 2018 (B €)



Source: DECISION Études & Conseil, see III)1) Methodology

A. Industrial & Robotics

The second-largest user segment in Europe, and the third largest in the world

Industrial electronics is the second-largest end-user segment in Europe, and a segment where Europe's position is particularly strong. In 2018, European production represented 20% of the world market, well over the average for all end user segments (14%), and Europe ranks second in the world for the manufacture of industrial electronics, behind China, but ahead of the USA and Japan. Two European companies are world leaders (Siemens and ABB) in this field, and with Schneider three European companies are among the top five. Inside the EU, Germany is by far the leading country. The synergies between systems and components supplies are particularly strong in this field. The three large European semiconductor manufacturers (Infineon, STM and NXP) are among the top ten suppliers of analog ICs. Analog ICs correspond to a huge share of the industrial market (around 50%), far above their modest share in the total IC market (less than 20%). The same is true of discrete devices.

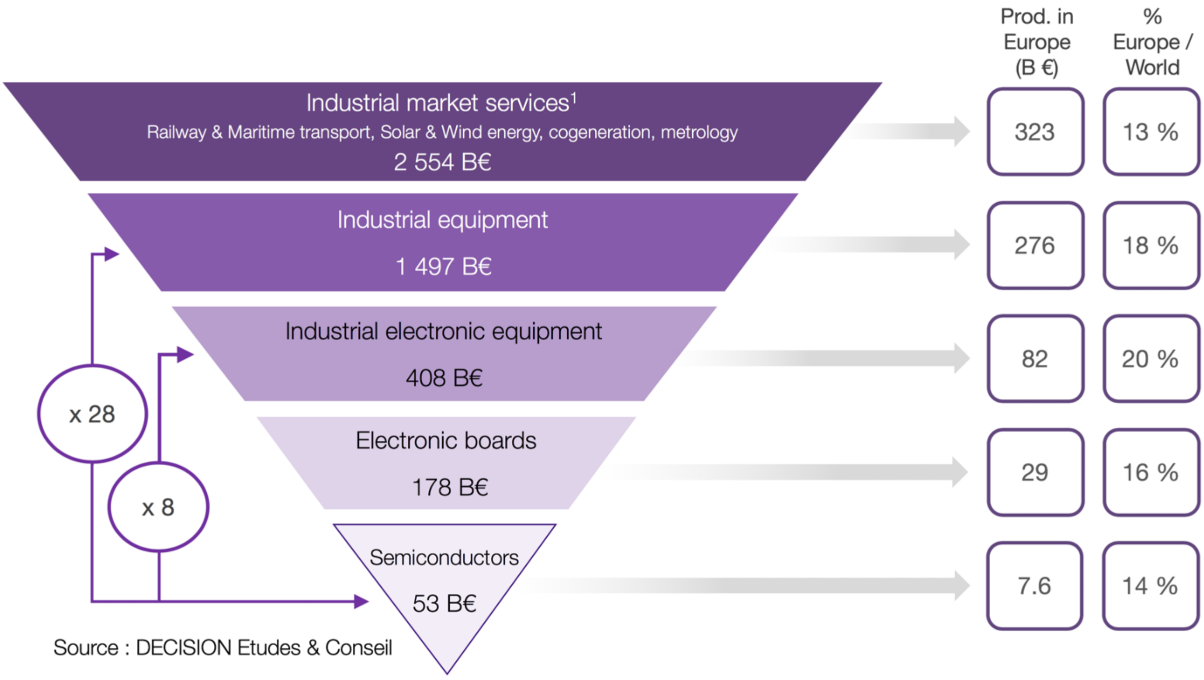
The strong growth in the past, should continue

The global market for industrial electronics has grown at 7.4% per year over 2010-2018, and this strong growth should last during the coming years, pulled by innovation (Industry 4.0, etc.) and the strong demand in Asian countries, as well as by the shift to renewable energies (wind and solar power). This global growth is very unequally distributed among regions. The "historic" regions are losing market shares and Asia, growing very fast, is gaining. European production of industrial electronics has grown at 4.1% over 2010-2018, falling back in market share in the world from 25% in 2010 to 20% today. In contrast, the production of the USA has grown at 6% during the same period, whereas Japanese production has shrunk by 3% per year.

China becoming leading manufacturing country

Chinese industrial electronics production has grown very fast over the recent years, at rates close to 20%. China is now the first country for industrial electronics manufacturing, with 33% of the world industrial electronics market, ahead of Europe (20%), and North America (21%).

World Industrial & Robotics electronics value chain in 2018 (B €)



Source : DECISION Etudes & Conseil

[1] The services measured in this diagram only corresponds to the "market services", that is the services produced for sale on the market at a price intended to cover production costs and to provide a profit for the producer. Yet, industrial equipment provide a majority of "non market services" once they are sold.

B. Automotive electronics

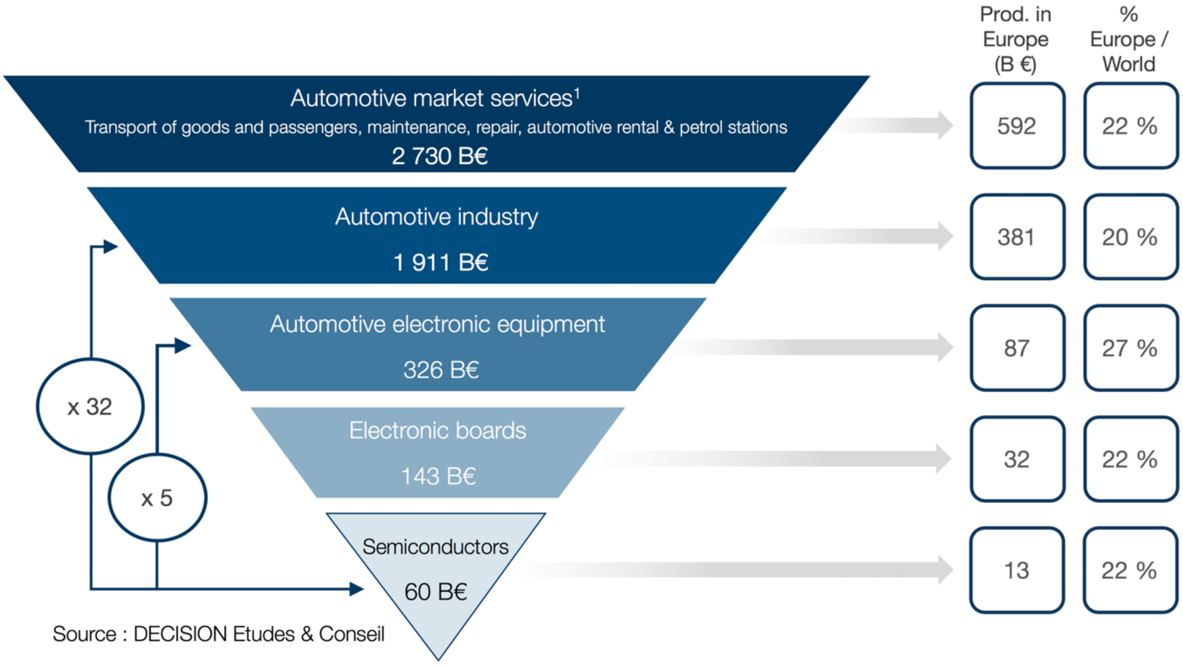
Automotive electronics production registered a strong compound annual growth rate (CAGR) within the 2012-2018 period compared to the other electronics applications, with a CAGR of 5.3%. Automotive electronics benefited from the third-highest CAGR after Health & Care (5.3% CAGR), and the industrial electronics segment (5.8% CAGR). Despite an expected downturn of the automotive industry over the 2017-2020, automotive electronics production is expected to register the third-highest CAGR within the 2018-2023 period compared to the other electronics applications, with an estimated CAGR of 5.7% (behind Professional PC and the Industrial segment). As a consequence, automotive is expected to represent € 430 B by 2023 and to outreach the telecommunication and the PC & data processing segments by 2022-2025.

The global automotive electronics production has two main components:

- The world automotive production in units, with an estimated average annual growth rate of around 1% over the 2018-2023 period;
- The average percentage of electronics in the added value of an automotive will also benefits from high growth over the period 2018-2023 (5% CAGR). Its main driver will be Advanced Driving Assistance Systems (ADAS) but also Infotainment and the main beneficiaries of this growth will be embedded software developers.

Automotive IC is the end-user application that is growing the fastest with 13.4% compound annual growth rate expected over the period 2016-2021. Although automotive IC sales represented only 8.3% of the total IC sales in 2018 (far less than computers, communications and consumer applications), this market is expected to account for nearly 10% of the total IC sales in 2021, which would make it the third-largest end-use application for ICs, slightly ahead of the consumer segment.

World Automotive electronics value chain in 2018 (B €)



[1] The services measured in this diagram only corresponds to the "market services", that is the services produced for sale on the market at a price intended to cover production costs and to provide a profit for the producer. Yet, industrial equipment provide a majority of "non market services" once they are sold.

i. Four leaders at the global scale

In 2018 at the global scale, the automotive electronics production was clearly dominated by four countries: China (19%), the USA (15%), Japan (10%), and Germany (10%). Their cumulated turnover accounted for 54% of the global turnover in 2018;

For already more than 10 years, China has been the first country in terms of automotive electronics at the global scale. In 2018, China's turnover represented 19% of the global turnover and 20% of the people employed in the world in automotive electronics. China is the first country in terms of automotive electronics factory production, but China is also the third country in terms of automotive electronics engineering, R&D and supporting function with nearly 13% market shares (on an equal footing with the USA), against 16% for Germany and 17% for Japan.

ii. Position of the EU

In 2018, the automotive electronics sector provided nearly 1,2 million jobs and generated a turnover of € 155 B[26]. In the EU. In other words, the EU automotive electronics sector contributes directly to 1% of the EU's GDP.

- With 27% of the world global output in 2018, Europe is the leading region in automotive electronics production;
- In 2018, the automotive electronics sector provided 324 000 high-skilled jobs in engineering offices, R&D offices and headquarters. These skilled jobs generated a turnover of € 58 B in the EU;
- In 2018, the automotive electronics sector provided 911 000 jobs in factories. These jobs generated a turnover of € 97 B in the EU;
- In 2018, 40% of the automotive electronics turnover was generated by firms whose principal shareholders were headquartered in an EU member state, which makes the European Union by far the first region at the global scale regarding that criterion before Japan (23%) and North America (17%). In comparison, in 2018, 40% of the automotive electronics turnover was generated by firms whose principal shareholders were headquartered in Asia (China, Japan and other Asia & Pacific), equaling the EU for the first time;
- The European automotive IC consumption represented € 9 B in 2018.

The predominance of Germany in the EU

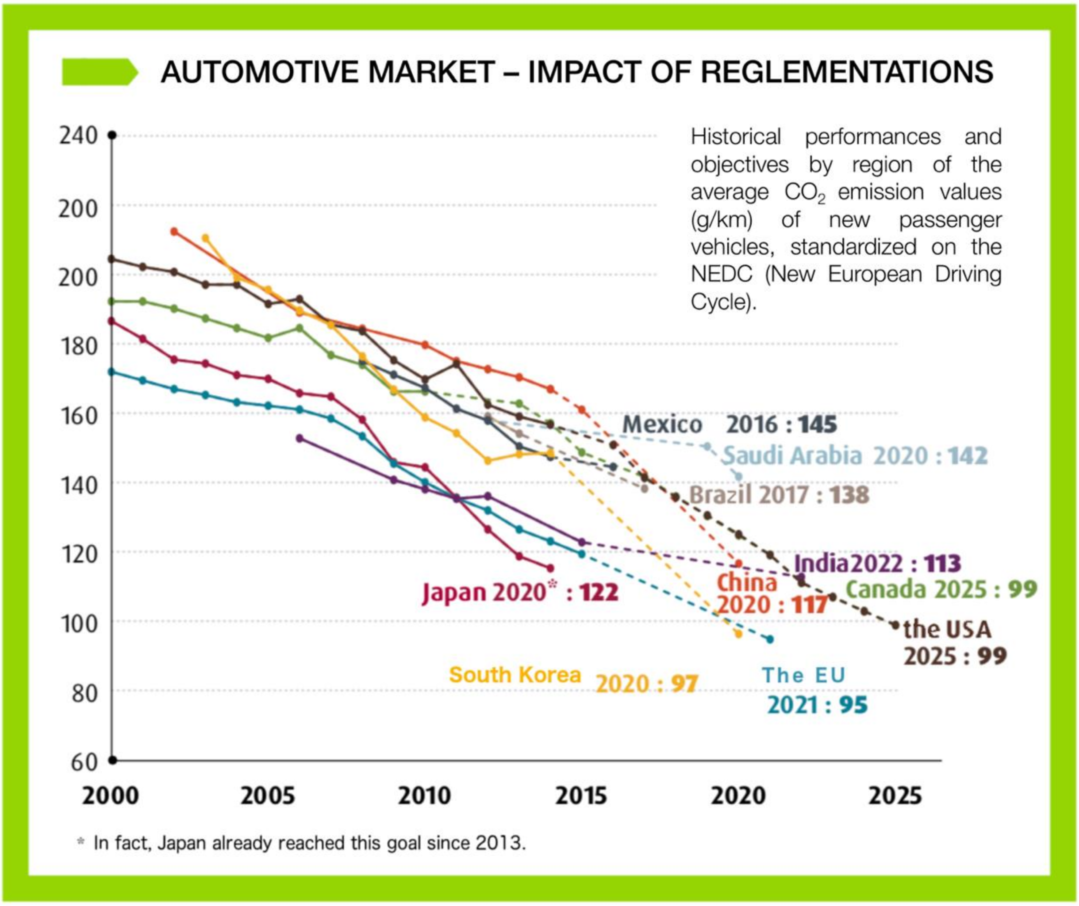
- In 2018 and for decades, the EU automotive electronics production has clearly been dominated by one country: Germany. Germany's turnover in automotive electronics accounted for nearly 40% of the EU total turnover in 2018. Besides, a third of the people employed in the EU automotive electronics industry in 2018 were in Germany;
- In 2018, in terms of engineering offices, R&D offices and supporting functions, Germany's turnover in automotive electronics accounted for 50% of the EU turnover and close to 45% of the jobs within the EU.

iii. The electrification of powertrains and its impact on automotive electronics

In 2014, automotive represented 18% of the global CO_2 emissions. To fight pollution, states are implementing very restrictive pollution emissions standards (see the diagram above). Such standards are fostering a trend of electrification of powertrains: in new cars produced, electric batteries are progressively gaining in importance. That electrification of powertrains leads to a slight increase of the electronic contents of cars and to a very high increase of automotive semiconductors contents.

[26] The figure "€ 155 B" corresponds to the total turnover generated in the EU from the production of automotive electronics. The figure "€ 87 B", included in the pyramid, is limited to a more restricted definition consistent with Prodcom figures: it corresponds only to the production cost of the automotive electronics goods produced in the EU territory (Production cost VS turnover generated).

Governments are setting ambitious targets for transport vehicle CO_2 emissions



Source: International Council on Clean Transportation

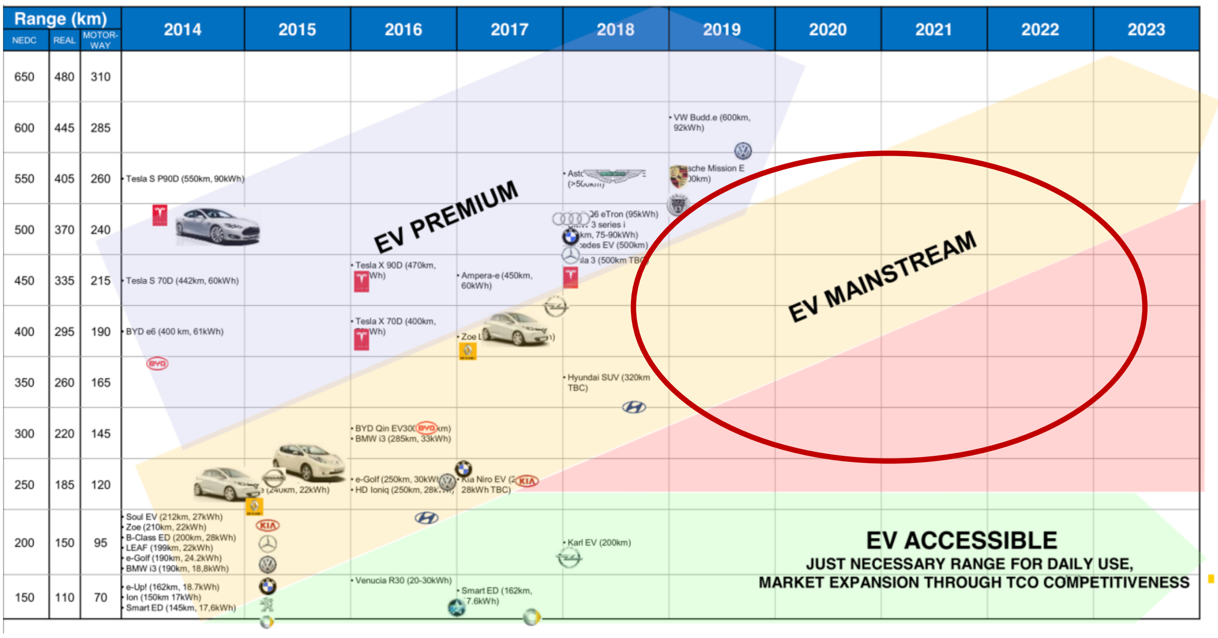
There is no strict frontier between petrol/diesel vehicles and electric vehicles. On the contrary, there is a continuum of types of cars leading to more or less petrol/diesel consumption and to more or less electrification of powertrains and therefore electricity consumption. Here is a list of the main motorization types by rising order of powertrains' electrification:

- **Petrol vehicles**
- **Diesel vehicles**
- **Mild hybrid vehicles.** Mild hybrid vehicles are composed of internal combustion engines equipped with an electric battery that is powerful enough to provide an assistance to the engine in specific driving phases. Mild hybrid vehicles employ batteries with higher voltage than traditional petrol/diesel vehicles (12 V), but with lower voltage than full hybrid vehicles, PHEV and BEV (> 60 V). Finally, mild hybrid vehicles do not have an exclusive electric-only mode of propulsion.
- **Full hybrid vehicles.** Full hybrid vehicles are hybrid vehicles designed with an exclusive electric-only mode of propulsion.
- **Plug-In Hybrid electric Vehicles (PHEV).** PHEV are full hybrid vehicles that can be plugged to recharge the electric battery.
- **Battery Electric Vehicles (BEV).** BEV are vehicles that are only powered with electric batteries.
- **Fuel-Cell Electric Vehicles (FCEV).** FCEV are vehicles that are only powered with hydrogen.

2017 has been the first year where more than 1 Million electric vehicles (BEV) were produced at the global scale (1.2 Million precisely). For nearly a decade, electric vehicles production rise at very high rates (more than 20%/year).

Furthermore, the global automotive electric vehicles production is currently reaching a critical development stage. Indeed, for the first-time electric vehicles are produced by carmakers with both ranges (300-400 km in real conditions), and prices that are competitive with petrol/diesel cars (with selling prices that remain higher but lower maintenance and fuel costs, and ever-decreasing batteries prices thanks to scale economies). According to Philippe Chain (former Chief Electric Vehicle Strategist of Renault and VP of Tesla Motors), the global cost of small urban BEV is already lower than their petrol/diesel counterparts, and this trend should reach larger vehicles within the next five years. This period is represented by the red circle in the following table and can be summarized as the emergence of "EV Mainstream" market.

Emergence of EV mainstream market: price and range-competitive with diesel/petrol



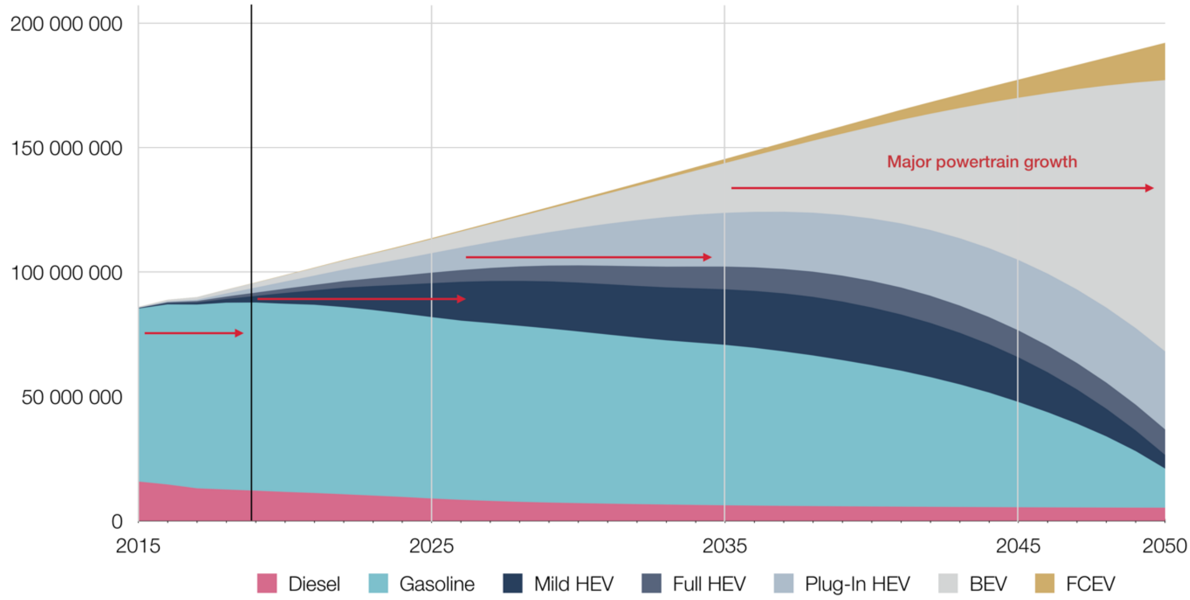
Source: Renault, DECISION Études & Conseil

Below is shown a forecast of the world light vehicles (Passenger cars and Commercial Vehicles) sales in units up to 2050. This forecast has been made in early 2019 based on the projected population growth (World Bank data), and a forecast of the evolution of the equipment rate by country over the period (based on the evolution of the previous equipment rates by countries over the 1960-2018 period analyzed in line with the evolution of GDP per capita, enabling transitions towards large equipment rate after reaching a certain threshold). The model also considers the estimated GDP growth country by country up to 2023 (World Bank data).

One can notice that in this scenario, New Energy Vehicles (Full Hybrid, PHEV, BEV, FCEV), should correspond to the majority of the world sales only by 2035.

BEV sales accounted for 1.6% of the world automotive sales in 2018 and are expected to represent 4% of the world sales in 2023. Hybrid vehicles production (Full Hybrid Electric Vehicles and Plug-in Hybrid Electric vehicles) accounted for 2.4% of the world automotive sales in 2018 and should not represent more than 8% of the world production up to 2023.

Light Vehicles Sales by powertrain type (Units)



Source: DECISION Études & Conseil

Impact of electric vehicles on the supply chain

The current middle term shift from diesel and petrol engines to hybrid and electric engines needs to be considered in this study and will have a significant and long-term impact on the automotive electronic supply chain.

Yet, only a few electronic embedded applications are different between a petrol/diesel car and a hybrid/electric car (2 out of 6).

- The applications impacted by the shift from diesel/petrol to hybrid/electric vehicles are powertrain and chassis;
- The applications not impacted by the shift from diesel/petrol to hybrid/electric vehicles are infotainment, Comfort / Body, safety and security.

In addition, as shown above, the sales of New Energy Vehicles (Full Hybrid, PHEV, BEV, FCEV), should remain small within the next five years, despite impressive growth rates.

Yet, the trend of electrification of powertrain could highly affect the European electronic automotive industry indirectly. Indeed, the strength of the European automotive electronics industry has come from the historical strength of the European automotive industry. If the move towards BEV were to be missed by the European automakers, it could largely question the competitive position of European automotive electronics leaders that are linked to European automakers.

iv. 2018-2023 Forecasts

Below is a forecast of the world automotive electronics growth over the 2018-2023 period. A slowdown of the growth is foreseen over the period. Yet, this slowdown is analyzed as short-term rather than structural and a rebound is estimated to occur in 2022-2023.

Automotive electronics growth 2018-2023

	2018	2019	2020	2021	2022	2023	CAGR 2018-2023
Automotive electronics growth	6,5 %	4,5 %	3,5 %	2,5 %	8,0 %	9,0 %	5,7 %
Growth interval		3-6%	3-4%	2-3%	6.5-9%	8-10%	5-7%

Source: DECISION Études & Conseil

As shown in the table below, the Chinese GDP growth is slightly decreasing since 2013 and the Chinese automotive market -which was benefiting from a significant average growth of 8.5%[27] over the 2013-2017 period, although volatile- entered in a recession phase in 2018 with -2.8% growth. The downturn of the Chinese market is the main cause of the downturn of the world automotive market, which in turn faced a -0.6% growth in units in 2018. Over the same period, the USA recovered a significant level of GDP growth after the Subprime crisis, tending towards 3% per year.

Definiton	Source	Country	2013	2014	2015	2016	2017	2018	CAGR 2013-2018
GDP growth	World Bank	World	2,7 %	2,8 %	2,9 %	2,6 %	3,2 %	3,0 %	2,9 %
		China	7,8 %	7,3 %	6,9 %	6,7 %	6,8 %	6,6 %	7,0 %
		The USA	1,8 %	2,5 %	2,9 %	1,6 %	2,2 %	2,9 %	2,3 %
Growth of the registration of all types of automotive (in unit)	IOMVM	World	4,2 %	3,2 %	1,5 %	4,7 %	1,9 %	-0,6 %	2,5 %
		China	13,9 %	6,9 %	4,9 %	13,7 %	3,0 %	-2,8 %	6,6 %

Source: DECISION Études & Conseil

The slowdown of the Chinese automotive market, started in 2017, is not structural and has four main causes (by decreasing order):

1. China is introducing “China V” and “China VI” standards against the registration of petrol / diesel revise vehicles (like those that the EU is planning for January 2020 but more constraining). Yet, the timescale of introducing of these standards is being regularly reviewed, leading to shorter implementations and in turn creating a short-term confidence crisis from Chinese consumers, delaying their purchases in order to be sure to meet the right regulations. For instance, the “China VI” standard was initially set to take effect nationwide from July 1, 2020. Yet, a three-year action plan on air pollution control released in July 2019 urged early implementation in major heavily polluted areas, the Pearl River Delta region, Sichuan Province and Chongqing Municipality.

2. According to the Chinese Association of Automotive Manufacturers (CAAM), several announcements of consumer support are also planned but not yet launched, which creates an additional wait-and-see attitude on the part of Chinese consumers.

3. For a few years now, the United States has become aware of the threat that represents the invasion of China at every step of the automotive electronic value chain. The trade reforms undertaken by Mr. Trump since early 2019 are a consequence of this awareness. A list of 5 745 Chinese products (including a large share of electronic products), has been set up by the USA. It represents $ 200 B dollars to compare with the total amount of the US importations: $ 505 B in 2017. These products are taxed at 10% since January 1st, 2019, and some tax rates might rise up to 25%. The USA is adopting the same policy as the one set up in the 1980s by Ronald Reagan towards Japan that was at that time on its way to become the first country in the world (in terms of GDP). The USA successfully imposed drastic raises of tax rates (up to 100%), on many Japanese products (mainly electronic products: cameras, camcorders, etc.). Under the current American pressure, the Chinese government already proposed several concessions, among which the possibility for foreign companies to hold more than 50% of the shares of a Chinese company (proposal made in May 2019). Since 2017, the US-China trade war has generated strong unstable variations in Chinese exports and therefore its growth potential, although it did not yet significantly impact Chinese GDP growth. China's August 2019 exports to the US fell 16% year-on-year, decreasing sharply from a decline of 6.5% in July. Meanwhile, imports from the US slumped 22.4%. This high volatility of commercial trades, the unpredictable behaviors of Donald Trump and the uncertainty of the results of the US election to come lead to an additional wait-and-see behavior from Chinese consumers.

4. Finally, Chinese growth has been slowly decreasing but surely for several years, which does not help.

[27] Source: World Bank national accounts data, and OECD National Accounts data files. Annual percentage growth rate of GDP at market prices based on constant local currency. Aggregates are based on constant 2010 U.S. dollars. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.

However, several signs remain positive:

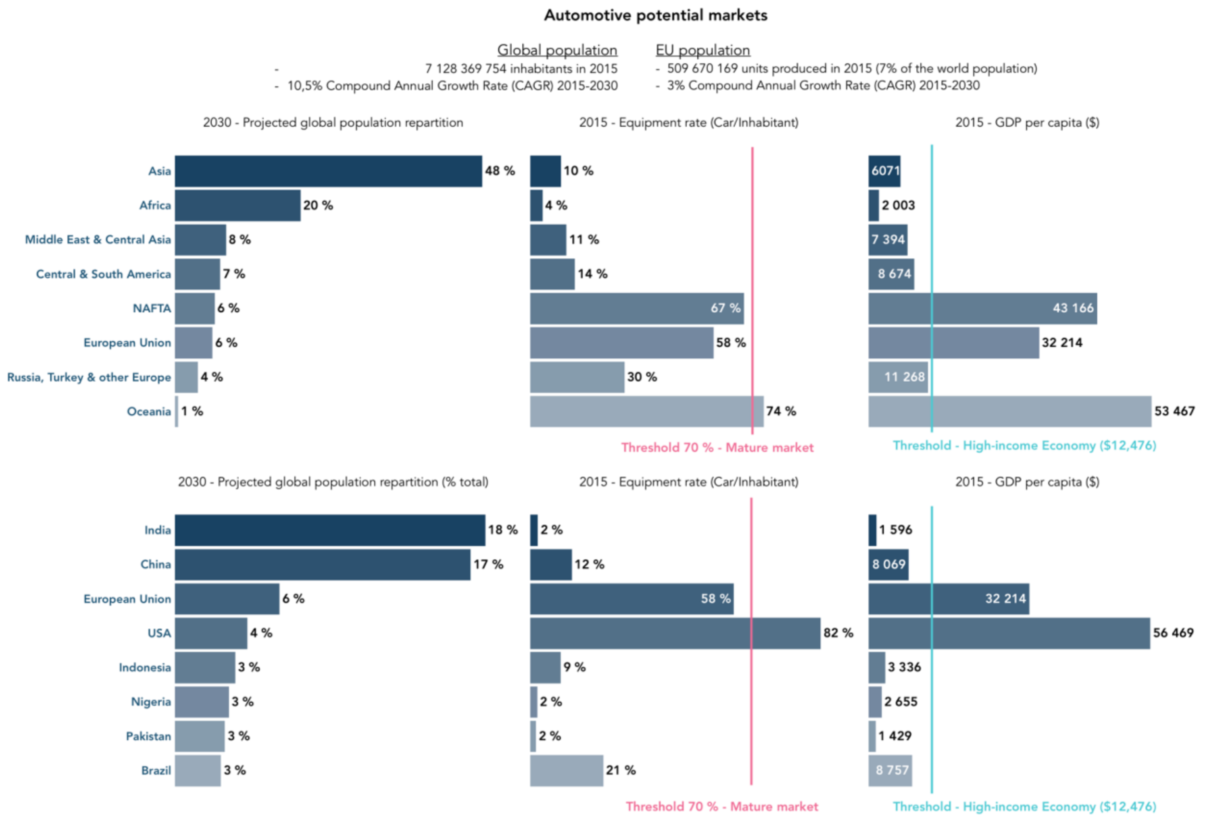
- The Chinese growth of New Energy Vehicles (NEVs), remain very significant, although not sufficient to compensate the global market downturn;
- The growth of Chinese professional vehicles (Commercial Vehicles), accounting for 16% of the total Chinese car registrations in 2018, remains stable and strong with a 5% annual growth in 2018.

Finally, the fundamental drivers of the Chinese potential growth are still here:

- In every country that has reach a level of GDP / inhabitant similar to the current Chinese level, a transition has started towards "Western" equipment rates (close to 50%).
- China is still very far from a 50% equipment rate, generating sufficient potential to fuel the growth of the Chinese market by 2040-2050.
- China's forecasted growth over the next five years remains above 5% per year.

As shown in the bar charts below, by 2030, China is clearly the country with the highest automotive growth potential: Chinese will account for 17% of the global population by 2030, China's equipment rate is only at 12% and China's GDP per capita is 8 069 $, enough to afford one car per adult and to tend to a 70% equipment rate on the long run. 700 Million cars are needed today to equip every Chinese adult with a car. By comparison, the global car stock in 2015 was of 1 282 Million cars (Passenger cars and Light Commercial Cars only).

Taking into account these structural elements (projected population growth by 2050, equipment rates by 2050 and GDP growth by 2023), the diagram below present a forecast of the evolution of Passenger cars sales in million units by 2050. This graph enlightens the remaining growth potential of China. It is based on the conservative hypothesis of an equipment rate of 39% in China in 2050, corresponding to the average level observed in Europe (including Russia, Turkey and Eastern countries) in 2014.

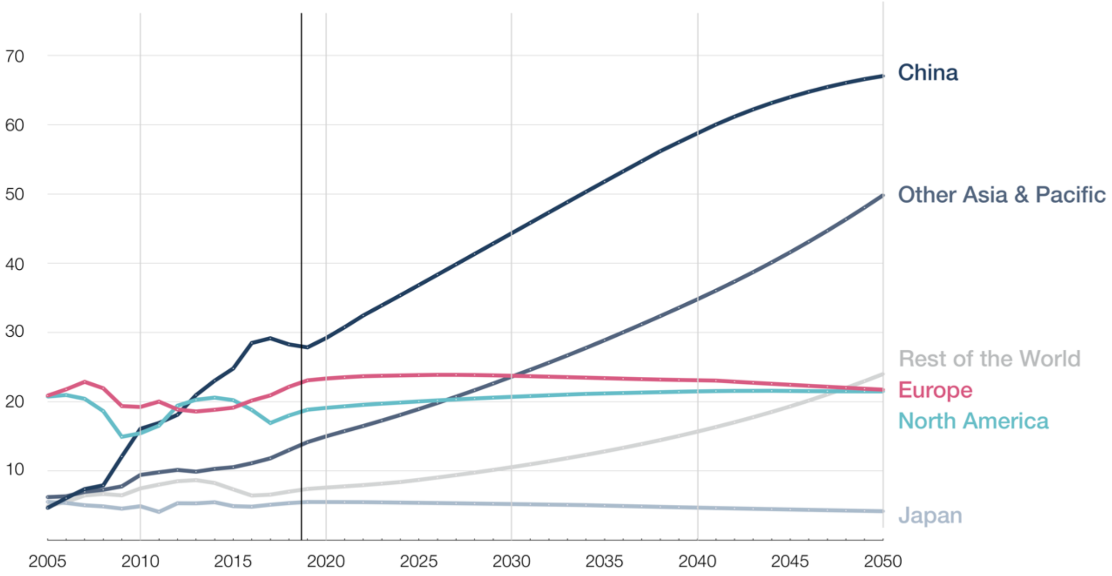


Sources: DECISION Etudes & Conseil, World Bank, International Organization of Motor Vehicle Manufacturers, United Nations: Department of Economic and Social Affairs - Population Division (2018), Eurostat

Remarks: Automotive are defined in those figures as (Light Commercial Vehicles + Passenger Cars). Heavy trucks, buses and coaches are excluded.

High-Income Economy: Countries with a GNI per capita of $12,476 or more according to the World Bank

Forecasts sales of Passenger Cars (M units) – based on structural factors



Source: DECISION Etudes & Conseil

The two main points of uncertainty in the short-medium term are therefore:

- The impact of anti-diesel and anti-gas measures at the World scale and in especially in China;
- The evolution of the US-China trade war and its impact on the Chinese growth.

The table below provides details on our hypothesis on the main components of the world automotive electronics growth, with consolidated figures for 2017 and 2018. The year 2019 is mainly impacted by the rise of anti-pollution emission measures in China. The year 2020 will also suffer from the set-up of the new anti-pollution emission in Europe and other markets. Yet, the lack of confidence and the wait-and-see attitude of the Chinese consumers could hardly last for more than two years. A recover is anticipated for 2021 and a rebound effect during the 2022-2023 period. Automotive Tier 1 suppliers are being affected with a latency due to stock management.

Forecasts of the main components of automotive electronics growth

Scope	Definiton	Source	2016	2017	2018	2019 (est.)	2020 (est.)	2021 (est.)	2022 (est.)	2023 (est.)
Automotive	Sales growth (in unit)	IOMVM	4,7 %	1,9 %	-0,6 %	-1,4 %	-1,4 %	0,7 %	3,3 %	3,5 %
Automotive TOP 100 Tier 1 suppliers	Sales growth (in $)	Automotive news		8,3 %	3,5 %	1,2 %	-2,0 %	0,0 %	2,5 %	5,0 %
Automotive electronics TOP 30 Tier 1 suppliers	Automotive sales growth (in €)	DECISION Etudes & Conseil		6,2 %	5,0 %	3,2 %	2,1 %	1,3 %	5,5 %	6,5 %
	Automotive electronics sales growth (in €)			9,7 %	8,6 %	6,1 %	4,3 %	3,1 %	9,0 %	10,0 %

Source: DECISION Études & Conseil

The automotive electronics market is not suffering from this short-term downturn at the same level than other automotive segments as it is driven by four main trends detailed in the chapter “Emerging automotive markets”, below:

- The digitalization of the automotive value chain;
- The rise of ADAS in automotive electronics hardware;
- The continuing rise of infotainment applications in automotive electronics hardware;
- The rise of automotive embedded software.

C. Aerospace - Defense - Security

Like the automotive industry, the aerospace and defense industries are made up of a complex supply chain ranging from parts and components to general supplies and commodities, electronic systems, and complete assemblies (aircraft, ships, etc.). Historically, this industry developed in Europe, in the USA, in Japan and in the USSR. Both technology and production have remained strongly concentrated in these areas (except in Japan), despite a developing industry in emerging countries such as China, India, Brazil or Israel. The sequels of World War II and American military leadership during the Cold War led to a dominant position of American industry worldwide. Today, this dominance is challenged by Europe, as shown by the success of Airbus in civil aviation and by the emerging powers like China in the defense sector.

Over the past years, the success of the European Airbus Commercial Aircraft, Airbus Helicopters (ex. Eurocopter) and Arianespace on civil markets consolidated Europe as the worldwide number one or two suppliers of civil platforms. Over the past 30 years, Airbus managed to raise as the undisputed rival of Boeing transforming the market from a monopoly situation into a duopoly. With only 42 deliveries and 13% of market share in 1985, the European-based maker managed to catch up and to overtake its historic competitor Boeing and now claims more than 50% of the market. Like Airbus, its subsidiary Airbus Helicopters has achieved the same success by being for several years now, the worldwide leader in the civil helicopters market segment.

On the defense side, the industry is heavily fueled by the growth of US military expenditure. The wars in Iraq and Afghanistan have reinforced the North American territory as the leading production region of defense equipment but with the withdrawal of its troops on these theaters of operation, the USA lowered their military expenses. Furthermore, the economic crisis of 2008 led to budgetary cuts in defense spending in all western countries. Therefore, like the US, Europe faced a sluggish domestic defense market, which led to a fierce competition between the US and Europe to promote their defense equipment and win export markets. Besides the quality of its products, the European defense industry will have to show flexibility in this competition: product adaptation and technology transfer are its specific advantages.

Regarding the Security industry, the structure of the value chain production is not as regionally concentrated as for the Aerospace and Defense one.

Aerospace and defense electronic systems are designed close to their final assembly location, i.e., Europe and the USA. In 2012, Europe represented 23% of world production (including security electronics). Combined with North America, the two regions accounted for two-thirds of total world production in 2012, a share that diminished slightly to 63% in 2018 due to decreasing budgets in the military segment whereas other countries like China and India have fast-growing markets and are engaged in dynamic policies to build larger local industries.

In 2018, the world market/production for electronic aerospace, defense and security systems reached 194 billion Euros, of which 38 billion Euro for aerospace systems, 71 billion Euro for defense systems, and 85 billion Euro for security systems. Civil systems for marine and land transport applications are included under the “industrial & robotic electronics” value chain.

With an average annual rate of 5.3% for the 2018-2023 period, growth in world demand for aerospace, defense and security electronic systems is more dynamic than the previous period 2012 to 2017 (+4.2%) and should perform better than the electronics industry globally. Defense and security segments will indeed grow faster over the 2018-2023 period than over the 2012-2017 period. Defense electronics production should go up significantly over the next five years (+5.0% compared to a mere 2.9% from 2012 to 2017), due to increasing investment in military budgets worldwide. Security electronics on its side should experience an average annual growth of 5.8% worldwide till 2022 compared to 4.8% over the 2012-2017 period. Aerospace electronics will grow at 4.9 % per year on average from 2018 to 2023 (compared to 5.3% from 2012 to 2017).

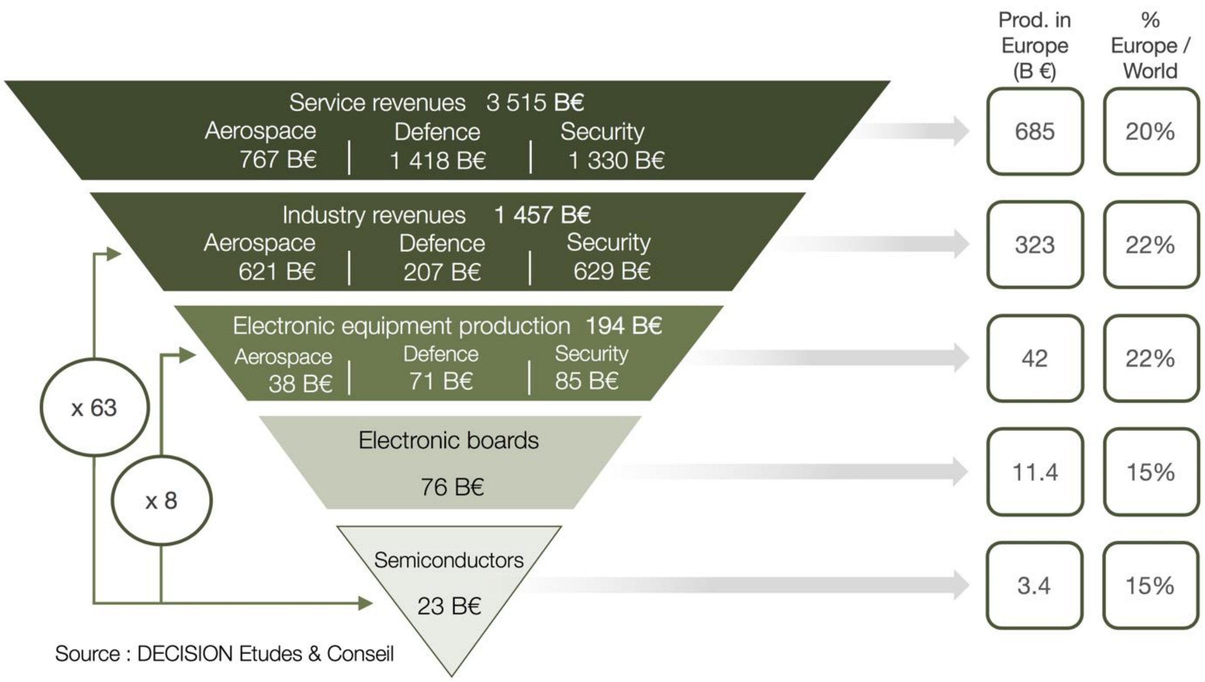
With 4.4% of expected growth from 2018 to 2023 (compared to 2.9% between 2012 and 2017), the prospects for European electronics production are rather favorable. This is because the European military industry should benefit from increasing defense budget dedicated to the procurement of equipment from European countries after many years of budgetary cuts in the major defense-spending countries. Besides, excellent prospects in civil aeronautics driven by a continuing growth of the electronics content in civil aircraft with the arrival of a “more-electric” new generation of aircraft as well as continuing satisfactory aircraft delivery levels pulled by fast-growing demand in world air passenger traffic, especially in Asia and the Middle East will drive civil airborne electronics equipment production in Europe.

The security sector is composed of:

- Physical security products (police, customs and fire brigades' vehicles, coastal surveillance boats, customs aircraft, helicopters, etc.);
- Electronic security products (CCTV cameras, fire alarms, intrusion alarms, surveillance radars, detection equipment, etc.);
- Cybersecurity software and services (that is electronic software);
- Private security services (Guarding, CCTV, investigation, etc.).

The electronic security sector is composed of electronic security products (hardware) and cybersecurity software and services. Security is currently one of the global industries that generates the highest growth. This high growth is driven by the growth of cybersecurity and the growth of the security electronic products.

World Aerospace – Defense – Security value chain in 2018 (B €)



D. Health & Care

Healthcare electronics are a very particular market, largely dominated by health organisations (hospitals, clinics, social security and insurance) who are the customers, the operators, and who often finance patient expenses.

Over the past decade, Health & Care has been one of the fastest growing electronic segments (7% per year over the 2010-2017 period), and this trend should continue during the coming decade (5.4% per year over the 2018-2023 period). Yet, Health & Care is a rather small electronics market with only 97 B € in 2018 (with 4.8% of the global electronic systems production, Health & Care is the 7th market in terms of size just above home appliances):

- The "professional" subsegment (90% of the total) is driven by better health facilities in Asia, Latin America, and Africa;

- The “consumer” subsegment (10% today, very fast growing) is driven by the IoT and connected wearables, and the coming e-health.

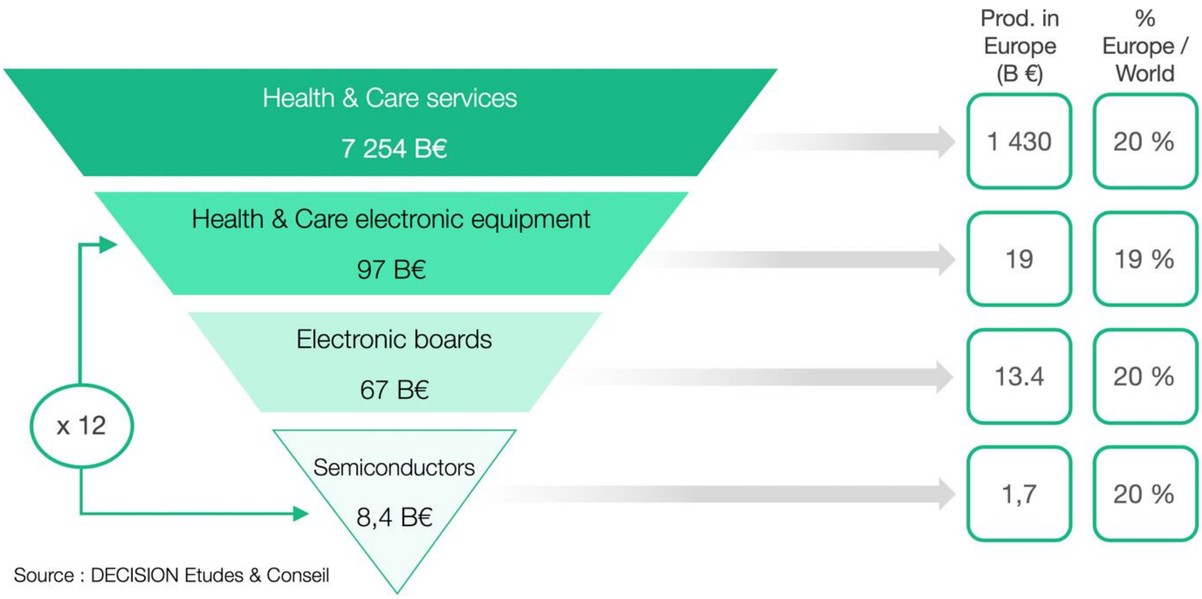
The USA dominates this segment with 40-45% of global production, and leading global companies (Medtronic, GE Healthcare).

Europe is the third producing region in terms of electronic equipment dedicate to Health & Care with 20% of the world production in 2018 (just above China, also holding 20% of the world production shares). Europe has indeed led global companies (Philips and Siemens) well established in the institutional markets. In Europe, healthcare electronics production was 19 B € in 2018, accounting for 40 000 – 45 000 employees. Finally, electronic equipment dedicated to Health & Care represented 6,5% of the European production value of electronic equipment in 2018.

Yet, the Chinese healthcare industry is growing very much faster.

Japan holds significant positions, but mostly on its domestic market, and less in the rest of the world.

World Health & Care value chain in 2018 (B €)



E. Telecommunications

In 2018, the worldwide production of telecommunication equipment encompassing both phones (smartphones and other phones) and infrastructure (fixed and mobile) reached an output of 402.6 billion euros. With global growth of zero percent compared to 2017, both phones and infrastructure production evolved at the same flat pace over the past year.

i. Telecommunication infrastructure

With a global output of 170.7 billion euros in 2018, telecommunication and network equipment production remained steady compared to 2017. However, if carrier network equipment (mobile and fixed networks) representing 67% of the infrastructure equipment with 114.3 billion euros of value in 2018, this subsegment decreased by 3.6% over the previous year, suffering from harsh competition on prices and of delayed project to deploy 5G base stations. Both main Chinese manufacturers, Huawei and ZTE particularly suffered in terms of revenues (with respective decreases of 3.5% and 12.6%) whereas the European Nokia and Ericsson resisted a little bit better (-3.1% and -1.6% respectively).

On the contrary, enterprise & private network equipment experienced an increase in production by 8.3% worldwide in value pushed by a solid demand of companies to renew and update their internal communication systems.

Production of communications infrastructure equipment in Europe has more than halved since 2010. The USA has succeeded in more or less maintaining their production, although all “historic” telecommunications equipment manufacturing countries or regions have been dwarfed by the surge of production in Asia and specifically in China.

Among the top ten telecommunications infrastructure suppliers, the Chinese players are leading (Huawei and ZTE), followed by the American players (Cisco and Juniper Networks). European players (Nokia and Eriksson), ranks in third position, significantly above Chinese and Americans. Japanese (NEC Corporation and Fujitsu), and South Korean (Samsung) players are also in good position.

In the Carrier Networks Segment, market leaders are Huawei (#1) followed by the European Nokia (#2) after the acquisition of the equipment manufacturer Alcatel-Lucent in 2016. Ericsson is ranked (#3), before the Japanese NEC (#4) and the Chinese ZTE (#5).

In the Telecoms Software Systems and Services segment, the major suppliers are predominantly US-based with the undisputed market leader Cisco followed by Fujitsu (#2) and Juniper Networks (#3). Ericsson and Huawei are also growing rapidly on this segment.

ii. Phones

Smartphones

After the booming years of 2012, 2013 and 2014 where growths achieved respectively, 40.1%, 36.4% and 30.1% in units to reach 1,264 million smartphones manufactured in 2013, the market then grew at a slower pace. The production peak was reached in 2016/2017 with around 1,490 million devices produced. In 2018 and for the first time, the smartphone market decreased by 4.2% to reach 1,425 million units. In value, however, according to our estimates, the global smartphone production slightly increased (+0.3%) to reach 205.2 billion euros, pushed by higher average selling prices.

2018 was marked by the strong decline of the largest manufacturer Samsung, whose production of the declined by 5.4% year-on-year due to the poor sale performances of its flagship products: The Galaxy S9 and the Galaxy Note 9 which suffered from harsh competition from Chinese brands in the mid-tier and entry-tier segments. On the other hand, Huawei’s smartphone shipments boomed by 31% in 2018 (200 million units) bridging more and more its gap with Samsung. Huawei expands aggressively by investing in branding and distribution in emerging markets of the Middle East, Asia/Pacific and Africa. Xiaomi, the second-largest Chinese smartphone manufacturer, experienced a boom in its sales by 38% in units to reach a production of 127 million units, while other Chinese makers increased or remained flat. On its side, Apple experienced a slight decrease in units (4.2%) in 2018 due to a saturated premium smartphone market, with slowing growth rates and increased competition in Greater China (as well as the slowdown of the Chinese economy in the second half of the year). Apple’s iPhone production is essentially carried out by Taiwanese manufacturer Hon Hai Precision (under is name Foxconn) whose manufacturing facilities are in mainland China.

As a consequence, as all these manufacturers have the large majority of their production sites on their national territory, smartphone production in China went up by 5% in value in 2018.

Over the next five years, we expect the market to remain flat in 2019 and to experience a rebound in 2020 and in 2021 to grow at a higher rate of respectively 2.6% and 1.2% with the arrival of 5G-connected devices.

After having lost its worldwide crown with its leader Nokia around 2011, Europe has seen its production moving out of its frontiers to China and to other Asian countries like Vietnam and Malaysia especially.

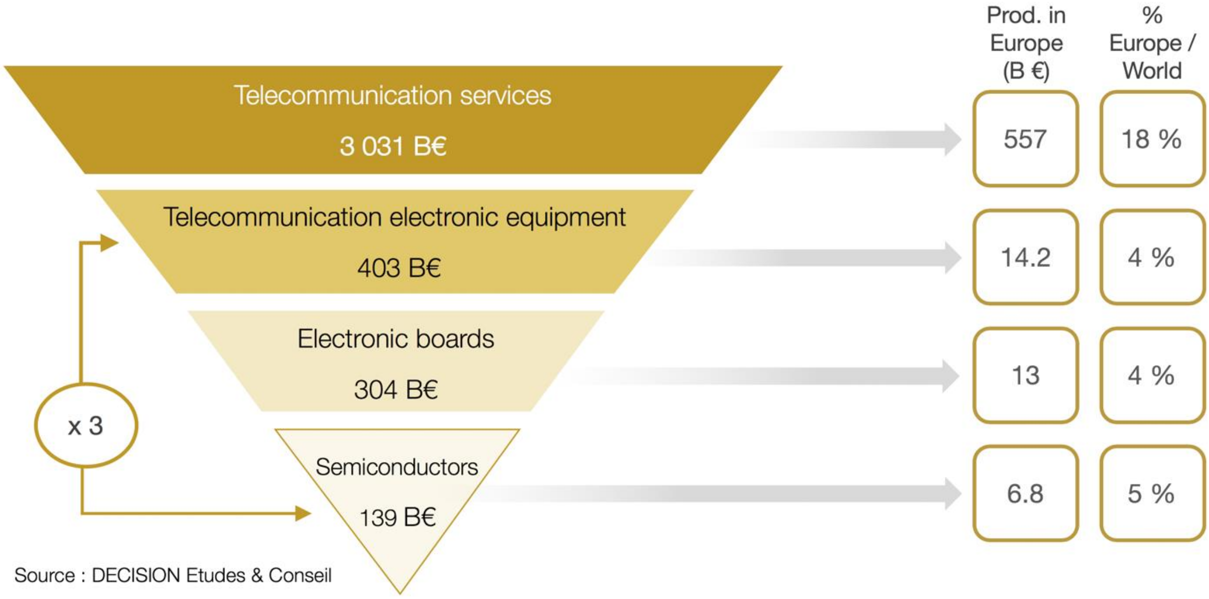
Feature phones

After having been cannibalized by the smartphone sales between 2010 to 2016, the feature phones sales have been growing back since 2017. From 1,000 million devices produced in 2010 to fewer than 400 million phones in 2016, the market collapsed. However, with the return of the Nokia brand, led by HMD Global (Finland), and the rise of some local actors, such as Jio (India), sales were back on track in 2017 and 2018 with growths around 10%. Pushed by a wave of nostalgia but not also HMD Global number 1 worldwide in two years of activity. The top five sellers of feature phones in the world are, in order, iTel (a Hong Kong brand) and HMD Global in first place tie (14% each), Jio Reliance (11%), Samsung (8%) and the Nigerian brand Tecno (6%). In 2017, iTel was already in first place, followed by Samsung and HMD.

According to our estimates, the global feature phone market reached 9.6 billion euros in 2018 and should grow at 11.6 billion euros in 2023. The reasons for this growth are three: the return of Nokia, the growth of mobile payments in Africa and the arrival of 4G-compatible terminals, capable of offering first connected.

As smartphones, feature phones are essentially produced in Asia (China and other Asia-Pacific countries), a trend that should not be reversed in the coming years. We forecast production of smartphones to grow at a slower pace in China till 2023 than in Other-Asia-Pacific region thanks to lower production costs.

World Telecommunication value chain in 2018 (B €)



Source : DECISION Etudes & Conseil

F. PC & data processing

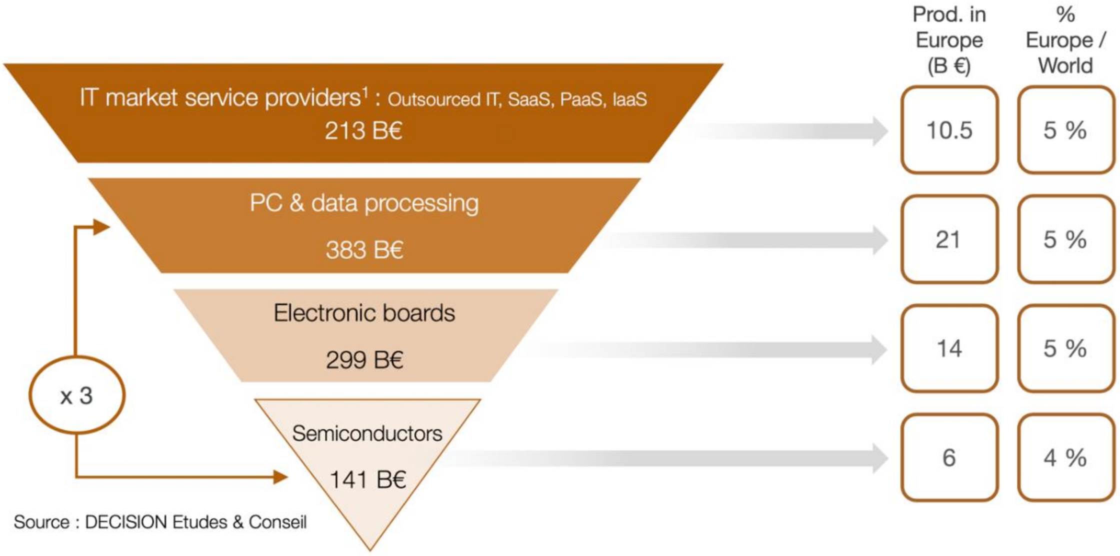
PC & data processing is the third-largest end user segment at the world level, with 18.5% of the world electronic equipment production in 2018.

Yet, with 7.2% of the European electronic equipment production in 2018, PC & data processing only ranks fourth out of eight in Europe (far behind the three first segments).

In spite of a very slight decline, production of Consumer PC in Europe has remained remarkably stable since 2010, when compared to Japan and the USA. Once undisputed master of the computing scene, today the American data processing production has dwindled to roughly the same level as Europe and production in Japan is still severely decreasing.

However, Europe, Japan and the USA combined account for no more than 12% of the consumer PC production in the world. This reflects the near-monopoly positions taken by Asia, and in particular first by Taiwan, and now by China who today accounts for the majority of the world production.

World Consumer PC value chain in 2018 (B €)



[1] The services measured in this diagram only corresponds to the "market services", that is the services produced for sale on the market at a price intended to cover production costs and to provide a profit for the producer. Yet, PC & data processing tools provide a majority of "non market services" once they are sold.

G. Audio & Video

Audio & Video electronics has for a long time become an Asian domain of excellence. Asian countries accounted for nearly 80% of world production in 2018, and Asian companies (South Korean, Chinese and Japanese), have acquired a quasi-monopoly on television production and on other audio and video products, although in these more diverse and innovating fields European companies in particular still hold significant shares of the market.

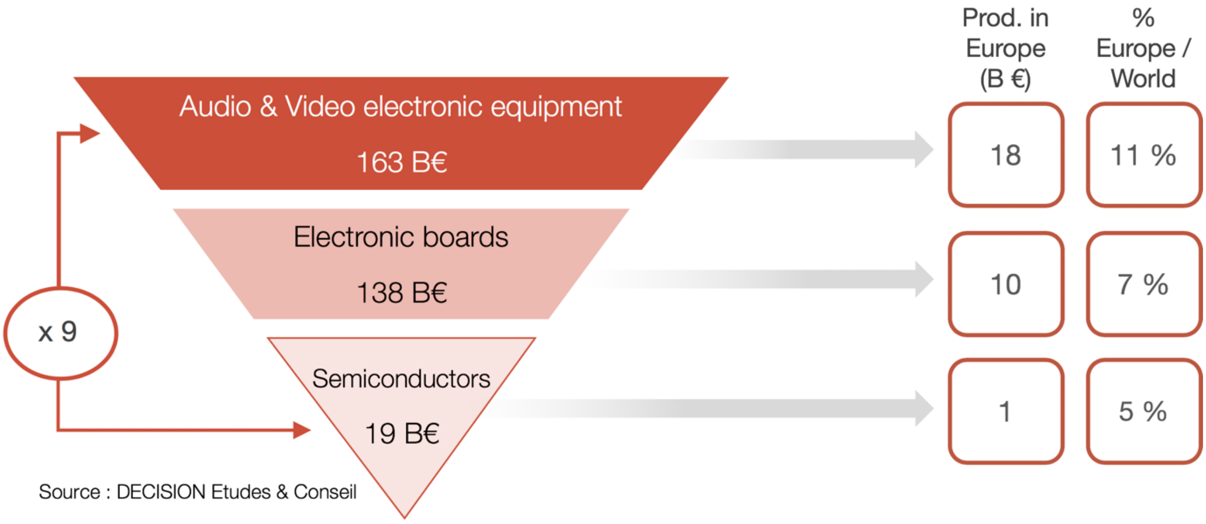
The domination of Asian companies does not mean all their production is in Asia. Some Asian companies (specifically Samsung and LG) who hold large shares of the European market have production facilities in Europe. This is probably why European production of Audio & Video electronics, although it has strongly decreased since 2010, remains relatively strong (more than 10% of the world total), compared to Japan (2%) and the USA (1-2%).

Since the decline of traditional CRT technology in favour of flat-panel TVs, Europe has become a marginal player in the TV industry production. Some Asian TV manufacturers have set up state-of-the-art flat panel modules and assembly facilities in Eastern Europe (Slovakia, Poland, Hungary, Czech Republic, Bulgaria…), to serve the European market.

TV Production Analysis

With nearly 25% of the global production in 2018, Europe continues to represent a large and attractive production region for TV suppliers. However, the European share of the global production has been steadily declining since 2010 (29%) and is expected to decline further until 2023, as Asian consumption develops and captures market share against developed economies. The new 4K TV sets drive the purchasing behaviours in Europe but the market for UHD will develop progressively, in close relation to the price decrease. The TV replacement cycle induced by the switchover to digital terrestrial broadcast started around 2010 and is still going on. In the EU analogue switch-off was in 2012, and throughout most of the world it should be completed after Russia (2018) and Brazil (2023). Consequently, a significant share of the flat-screen TV installed base is still quite recent. A significant "natural" replacement cycle is not expected in Europe before the end of the decade.

World Audio & Video value chain in 2018 (B €)



H. Home Appliances

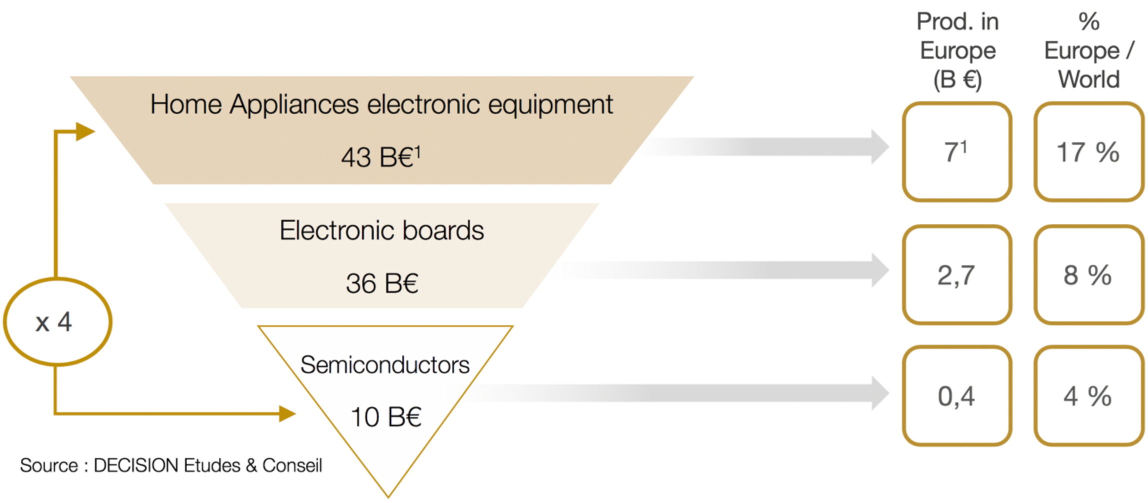
Domestic appliances are the last end-user segment for MNE and other electronic components in terms of production in Europe. European production of domestic appliances was 7 billion euros in 2018, and the industry employs around 45 000 people.

Yet, it is a segment where Europe is strong, with 17% of the global production, and four European companies among the top ten at the worldwide scale. The Europeans Bosch, Electrolux and Miele rank second, third and 10th. The European small appliance specialists SEB, Philips and Dyson rank respectively 9th, 13th and 15th.

Nonetheless the Chinese industry has become the largest in the world, with companies among the world leaders who are developing their own brands after having long sold through OEM under the historic European or other brands. The largest, Haier and Midea.

Domestic appliances do not have a very high semiconductor content (about 5% in average today). This means that in this segment 1 billion euros of semiconductors can leverage nearly 20 billion euros of equipment production, and over 125 000 jobs. And increasingly the functions enabled by the semiconductors in the appliances are what drives the growth of this industry.

World Home appliances value chain in 2018 (B €)

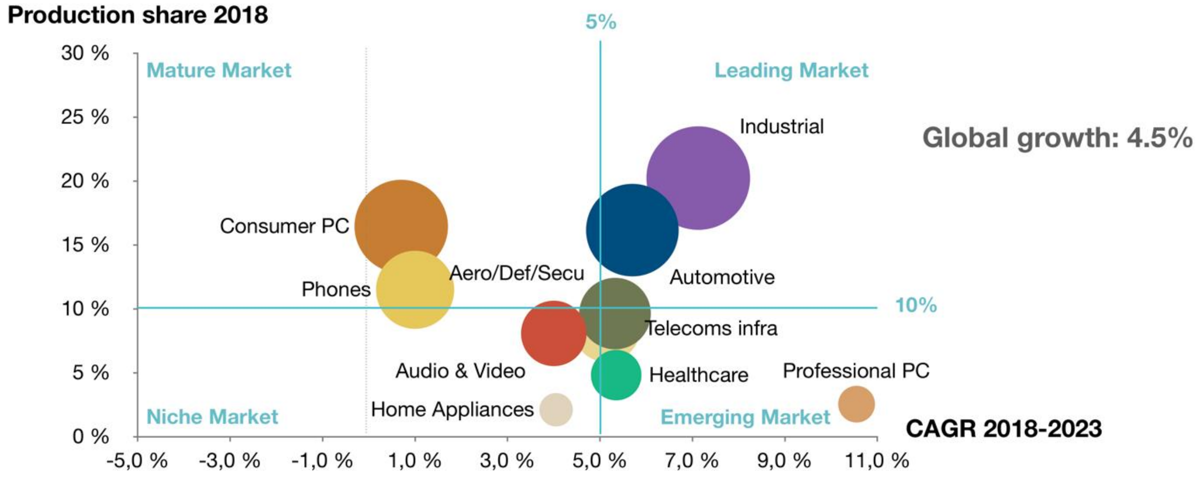


[1] The figures indicated in this diagram as well as the figures considered in the total value of electronic equipments correspond to the share of the value of home appliances precisely corresponding to the electronic sub-systems.

4. Forecasts by segment 2018-2023

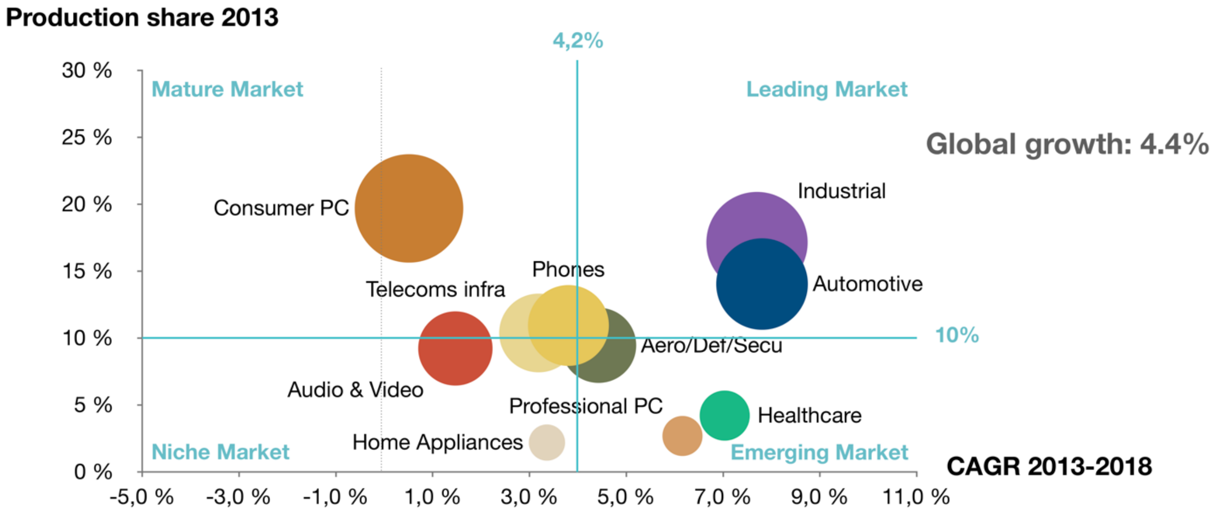
First, the world electronics industry faced a rather challenging year in 2018 with an annual growth of only 3.7%, for three main reasons: The downturn of the automotive market, leading to a slowdown of the automotive electronics' growth from nearly 10% in 2017 to 6.6% in 2018. Second, a conjunctural downturn of the telecommunication infrastructure segment, with a growth of 0% in 2018. Third, a decrease of the -already slow-growth of the phone market, with 0% in 2018. These downturns are considered as mostly short-terms phenomenon (highly linked to US-China trade war), and the expected Compound Annual Growth Rate (CAGR), of the electronics industry is 4.5%/year over the 2018-2023, compared to 4.4%/year for the previous period (2013-2018).

World end-user segment production: Production share in 2018 (B €) & forecast CAGR over the 2018-2023 period



Source: DECISION Etudes & Conseil, (see Methodology)

World end-user segment production: Production share in 2013 (B €) & CAGR over the 2013-2018 period



Source: DECISION Etudes & Conseil, (see Methodology)

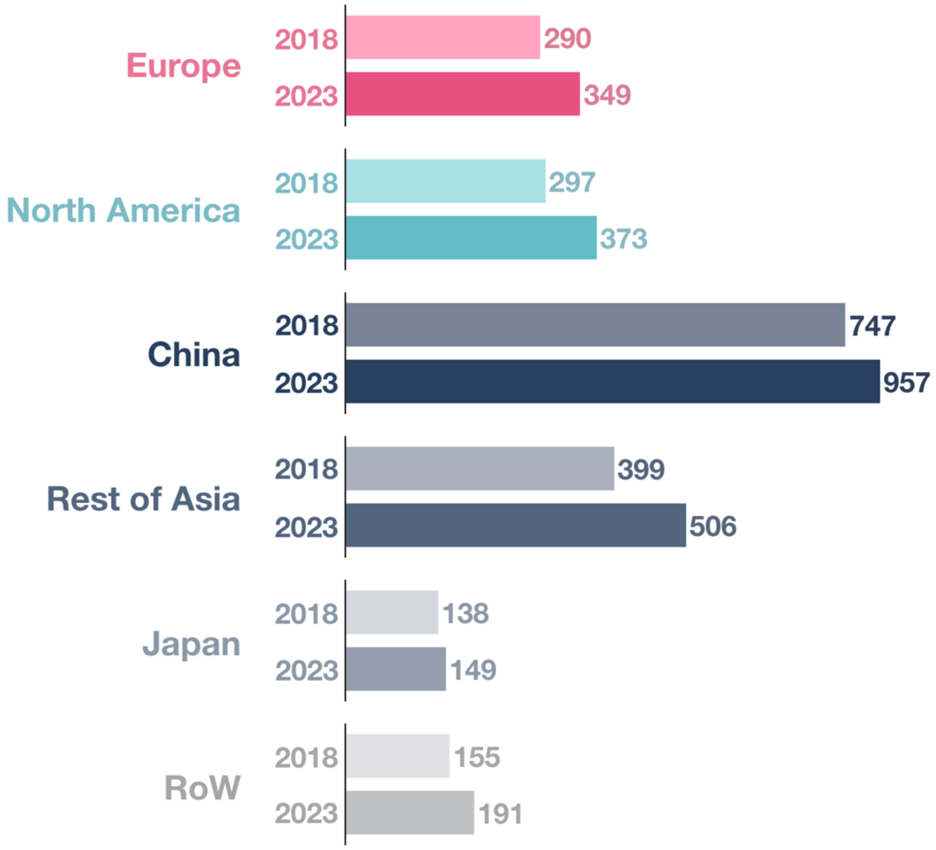
As shown on the two diagrams above, Automotive electronics and Industrial & Robotics electronics should represent respectively 23% and 17% of the world electronics sales in 2023, corresponding to the equivalent of the relative sizes of the PC segment and the telecommunication segment in 2013 (which accounted for respectively 22% and 21% of the world electronics sales).

5. Forecasts by region 2018-2023

Europe, the USA and Japan used to dominate the World Electronics Ecosystem, but today Asia has conquered a lion's share of mass market segments (computers, telephones, consumer audio-video), and is progressing into the more professional segments. In 2018, in terms of total electronic system production, Europe was the 4th region of the World, behind China, other Asia and North America.

Yet, as a consequence of the slow growth of stand-alone electronics and the high growth of embedded electronics, the growth of China and other Asia over the 2018-2023 period (respectively 5.1% and 4.9% per year), will not be so higher than the growth of North America and Europe (respectively 4.7% and 3.8% per year).

World electronic systems production by region (B €): 2018-2023

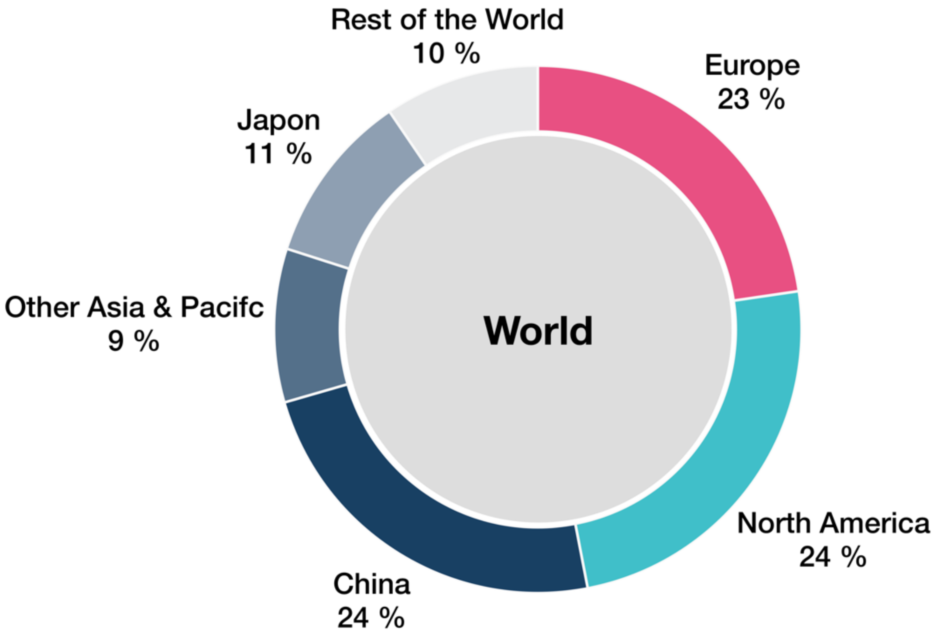


Source: DECISION Études & Conseil, (see Methodology)

The EU share of global production of electronic systems has been declining during the 2010-2018 period. Yet, this trend is expected to end during the 2018-2023 period as the EU is very well positioned on the main end-user electronic segments with the highest potential growth over the 2018-2023 period: Industrial & Robotics electronics, Automotive electronics and Health & Care. Europe represented 14.3% of the world electronic production in 2018 and should represent 13.8% of the world electronic production in 2023 (that is an almost constant share).

Indeed, Europe remains in good position in terms of production of embedded and professional electronics (first region of the world with North America), as shown in the diagram below:

World Production Share in 2018 – Professional and embedded electronics



Source: DECISION Études & Conseil, (see Methodology)

6. Emerging markets 2018-2023

Across the different emerging computing technologies studied in this report (chapter IV), the main emerging market applications that have been the most cited as benefiting from a strong estimated growth and key interactions with the technologies studied are:

1. **IoT and smart systems** (a crossed application spread over almost every end-user electronic application). Smart systems are mainly composed of smart sensors, Wireless Sensor Networks (WSN) and IoT Cloud platforms. Smart sensors have a dedicated chapter in this study;
2. **Emerging automotive markets**: Infotainment and ADAS (Advanced Driving Assistance Systems, leading to autonomous driving);
3. **Data analysis & big data analysis applications** (either remote data analysis in data centers or edge computing);

To a lesser extent, drug and material design (pharmaceutical research), is also highly impacted by many of the emerging technologies studied in this report.

Finally, digital identity is another fast-growing market linked with key sovereignty issues.

A. Emerging automotive markets:

iii. The digitalization of the world automotive value chain

Digital transformation is a global trend that affects every economy and industry: Companies and administrations around the world are digitizing their processes and interconnecting the data networks thus generated.

The digitalization of the automotive value chain leads automakers to progressively reorganize the automotive development around its digital system, but also attracts new entrants on the automotive electronics value chain:

1. First, software developers: Mainly Google and Amazon Web Services, but also Intel, Apple, Google, Baidu, etc. and specialized players such as Mobileye (bought by Intel). Although those companies do not have a great knowledge of the automotive industry, they hold greater knowledge in terms of software development (in particular Automotive Operating Systems). There are interested in the automotive market in the first place through the opportunity to collect automotive-related data and feed their big data applications. Google and Amazon have won around 90% of the European Automotive embedded OS contracts that will last over the next years. Some automakers are actively thriving to compete with these players (in 2017, Renault bought a business unit of Intel in France and accounting 400 engineers specialized in embedded software; Volkswagen has decided to develop its own embedded automotive software to be able to sell the related data to Google and Amazon afterwards);
2. Second, telecommunications companies such as Huawei, Orange or Deutsche Telekom are entering the automotive electronics value chain in line with the development of the connected cars. For instance, as a member of 5GAA, Orange currently works with Deutsche Telekom on the interoperability of automotive connected services, to prevent a border crossing from stopping autonomous functions. This requires very fast download capabilities and therefore the existence of a 5G network;
3. Third, companies specialized in electronic security and / or cybersecurity such as Gemalto (bought by Thales), are entering the automotive electronics value chain to lead automotive’ cybersecurity;
4. Finally, digital transformation also disrupts the automotive services with the entering of new players in the market. Software developers such as Uber, drones’ producers such as Parrot, logistics companies and organization such as Grab or La Poste, companies from the food service industry such as Domino’s Pizza, etc. At the level of services, the main competitors of automakers will be the ones of the fleet management segment (car rental and leasing), in line with the Automotive as a Service trend. For instance, the French leading rail networks management companies (SNCF and RATP), are entering the automotive fleet monitoring management segment with applications such as “car to go” and “Share now”.

The development of embedded computing applications requiring high-processing capabilities also raise the importance of MNE players such as Nvidia, Qualcomm, Intel, etc.

Finally, the automotive digitalization leads new players to develop interactions with the automotive value chain:

- Actors of the smart home (home automation, smartphone applications, etc.);
- Smartphone producers (on smartphone-car communications);
- Actors of the public road: Tolls, road networks, etc. (on Vehicles-to-Infrastructure communication / V2I). For instance, autonomous level 4 on highroads requires Vehicle-to-toll communications.

iv. The rise of automotive embedded software

In automotive electronics, digital transformation leads to a drastic rise of the importance software in the value chain.

In the 1980s, software was very difficult to alter once it was in vehicle production. When they were first developed in the 1980s, electronic control units (ECUs) were housed on chips that were either erasable-programmable read-only memory (EPROM) or masked read-only memory (MROM). EPROMs were slow to program but could be erased and reused, although the process was tedious. MROMs were a better value, because they could be programmed on a large scale, but they couldn’t be updated or rewritten. Wherever software was housed in these early days, this software was very difficult to alter once it was in vehicle production. Most issues were addressed via direct part replacement. Customers were notified of required changes and brought their vehicles into their dealers, where the ECUs (and the software integrated into those ECUs), were physically replaced.

In the late 1990s and early 2000s -along with engine controllers, powertrain controllers and centralized body control modules’ development- ECUs processors started using flash memory and engineers developed several paths for updates to the operating system (OS) and applications, such as on-board diagnostics (OBD) and BDM or JTAG connection ports. During this time, designers were integrating more and more ECUs into car features and rapidly increasing their capabilities, requiring far more memory and processing power than ever before (a modern seat controller, for example, uses pulse counts and a memory switch to store a driver's preferred seat position). To meet the continually increasing demand for new features and the software to support them, the automotive industry created guidelines for three components: common library components, a common OS, and communication and diagnostics standards.

As the applications and the OSs became more sophisticated3, software share in the automotive electronics added value became more and more important. ECUs are now written in higher-level languages (such C or C++), and require more memory and processing power. Furthermore, a car today can have more than 10 million lines of code, compared to about 50,000 in the 1980s. That growth shows no signs of stopping. Software size and complexity will continue to increase as advanced driver assistance systems, autonomous vehicle mapping data and connectivity applications continue to evolve.

Current main challenges for embedded software developers

Shorten updates' time and energy consumption. As computerized as cars have become, the vast majority are powered by a lead-acid battery and internal combustion engine, a power supply system that is simply not optimized for long software updates without additional charging. Very large updates could risk draining the battery, which could erase the module being updated and even deprogram some cars' ECUs, making them inoperable. Yet, because of software integration issues, operating systems, their services and the application logic are often not optimized for software update. As a result, whenever carmakers are to update a module, they are forced to update the entire embedded system. Ideally, each specific component's software could be partitioned, but unfortunately ECUs are not written that way, and even if they were, that could create a different problem because multiple parts and subparts would all need to be individually managed and updated across a distributed system of ECUs. Therefore, the current most common solution used by automakers is to double the storage to allow the car to operate the old system while the new one is being installed. This phenomenon leads to a great increase of memories integrated into cars: The automotive memory IC market is forecast to increase 73% from $ 2.9 billion in 2017 to $5.0 billion in 2021.

Enhance remote update. Diagnostic tools are the primary method for delivering the majority of the ECUs software updates. Yet, several other methods exist, including USB (mostly for updating the "infotainment" systems), and remote methods such as Wi-Fi and cellular systems. Although Wi-Fi and cellular technologies allow for remote updates that are cheaper for automakers and more convenient for passengers, they are currently rarely used for two reasons. First, remote updates need to be designed at the stage of embedded software development and integration because it modifies embedded software architecture. Second, remote update ease cyber-security breaches. Indeed, in today's cars, the infotainment ECUs network (including Wi-Fi and / or cellular interfaces) is most of the time separated from all the other ECUs to prevent a cyber-attack coming from Wi-Fi and / or cellular interfaces to hit powertrain & chassis actuators through their related ECUs.

Market value

In 2018, automotive embedded software (that is software integrated into cars during the production and assembly processes), represented 4% of the average total car production cost and 18% of the average total automotive electronics market including hard & soft, corresponding to a global market of € 72 B. Yet, automotive embedded software global growth is well above the global average automotive electronics growth with a CAGR of more than 10% over the 2018-2023 period. As a consequence, the global automotive embedded software market could equal the global automotive electronics hardware market around 2030.

V. Emerging automotive electronics hardware markets: ADAS & Infotainment

Electronics experienced a slow but steady penetration into vehicle platforms, starting from the generalization of electronic ignition systems in the 1980s.

The **powertrain** is historically one of the main segments of automotive electronics in terms of value, as can be expected since electronic technologies are instrumental in increasing combustion engine performance.

After powertrain, the next big era for the deployment of electronics in the car has been **safety** and **security**. These systems have become key elements of all automobiles through the impact of regulations and consumer demand. Government safety mandates represented a major factor driving the growth of automotive electronics revenue over the period 2000-2010, in the context of public authorities' commitment to reducing casualties on the road. Traditional safety equipment such as airbags, ABS or ESP have already become natural parts of the equipment of most cars. Newer legislated systems including electronic stability control (ESC) and tire pressure monitoring systems (TPMS) have also come into play, both of which require significant electronic content.

Over the 2010-2015 period, the majority of automotive electronics' growth came from infotainment: **information** (integrated GPS, live traffic information, on-board diagnostics, etc.), **comfort** (control & command systems of seats, lights, etc.), and **entertainment** applications (cabin customization, audio system customization, music and video streaming, etc.).

Over the 2015-2030 period, **Advanced Driving Assistance Systems (ADAS)** will be the main driver of automotive electronics. Today, fully autonomous vehicles are brought to the fore by medias as one of the main drivers of automotive electronics within the next decades. Yet, there is no strict frontier between fully autonomous vehicles and non-autonomous vehicles. Advanced Driver Assistance Systems (ADAS) are precisely the continuum of more or less complex electronics subsystems that enable different degrees of autonomous driving. The first steps are already technically mastered by car makers and integrated to high-end, mid-range and even low-end cars. All the regions of the world are concerned as well as all the types of engines (petrol, diesel, hybrid and electric).

The Society of Automotive Engineers (SAE) defines 5 autonomous driving levels:

1. **Level zero – No Automation**. The driver performs all operating tasks. Driving assistance only operates through warning systems.
    - Warning systems: Lane departure detectors & warning systems, Blind spot detectors & warning systems, Fatigue detectors & warning systems, Security distance alerts (objects & events detectors, warning systems), Hands off detection & warning systems, Night vision & associated warning systems
    - Ignition and automatic light switching
1. **Level one – Driver Assistance**. Driver assistance never acts on brakes. Besides, the driver is still fully required for the monitoring of the surrounding environment. The aim of driving assistance is mainly to ease and improve the efficiency of the actions undertaken by the driver.
    - Stability control through steering assistance
    - Cruise control/limiters: Acceleration/deceleration assistance in fixed scenarios
2. **Level two – Partial Automation**. Assistance with steering and / or acceleration functions to allow the driver to disengage from some of his/her tasks. Yet, the driver must always be ready to take control of the vehicle and is still responsible for most safety-critical functions and monitoring of the environment.
    - Lane-keeping correction systems
    - Par assist
    - Adaptive cruise control: Acceleration/deceleration assistance in fixed scenarios
3. **Level three – Conditional Automation**. Complete autonomous driving modes that operate only in specific conditions/scenarios (traffic jam only, highway only, etc.). Some safety-critical functions are undertaken by the car (for instance braking), in fixed scenarios. Human attention to the road is not always required during these fixed scenarios.
    - Automatic emergency braking system
    - Automatic speed adaptation from traffic signs readings
    - Fail operational system
    - Dedicated Short-Range Communications
4. **Level four – High Automation**. Complete autonomous driving, including complete assistance with monitoring of the surrounding environment. All safety-critical functions are undertaken by the car (braking, responding to any events, determining when to change lanes, turn, use signals, etc.). Yet, a driver is still required, the "autonomous driving mode" must be activated by the driver and a few conditions are still required (for instance, the "autonomous driving mode" may not work if the vehicle is off-road).

    - Artificial Intelligence capable of anticipating and responding to any event with a very low failure rate.

5. **Level five – Complete Automation**. Complete autonomous driving in any situation. No need for drivers, gas pedals, brakes, steering wheel, etc.
    - Artificial Intelligence capable of anticipating and responding to any event with a very low failure rate.

Most automakers are currently developing vehicles at level 2. Yet, level 2 ADAS technologies already represents a huge increase in the number of electronic devices and in the degree of complexity of the interactions between these devices.

Besides, first level 3 vehicles are being commercialized since 2017 and will become significant up to 2030. In 2017, Audi launched the world's first series production L3 conditional automation system: the Audi AI traffic jam pilot, which allows the new A8 to drive in slow-moving highway traffic up to 60 km/h without any input from the driver.

Autonomous level 4 and 5 correspond to vehicles that can really be named "autonomous", because no supervision at all is required from the driver who may therefore not be hold responsible for potential accidents.

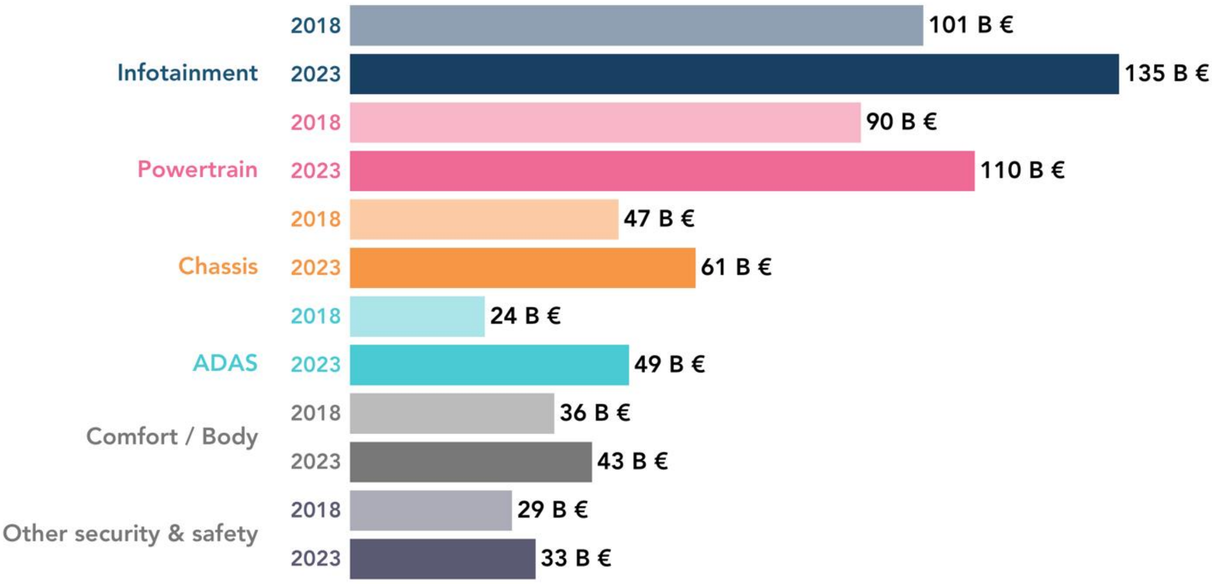
ADAS is the application with the highest potential global leverage effect as it involves a significant number of new electronic control units, actuators and sensors, etc. but also embedded software. Second, ADAS development is not threatened by any potential brake (expect from a systemic global economic crisis caused by war, financial crisis, climate change, etc.), and do not require any infrastructure investment. In other words, a very significant number of electronic ADAS applications are supported by mature self-sufficient[28] technologies with sharply decreasing hardware prices and are not integrated yet into most of the new cars globally produced.

Finally, on the short term, automakers are investing heavily in the development of engine control software and hardware (**Powertrain** and **Chassis)**, to reduce the CO_2 and NOx consumption of both their petrol and diesel vehicles, so that they can continue to market them once all the new European[29] and Chinese regulations will be implemented. As a consequence, electronics dedicated to engine control will grow on the short term (at least up to 2022). Such rise will be associated to the development of the following applications/technologies: mild hybrid (especially 48 V hybrid), injection of urea in diesel cars cylinders, cylinder deactivation systems, continuously variable valve timing, etc. However, the global demand for standard petrol and diesel vehicles should not grow much, in line with the recent pollution emission scandals. The car manufacturers are therefore investing significant amounts to develop engine control systems dedicated to standard petrol and / or diesel vehicles when they know that on the long run, these investments may not be useful.

The bar chart below shows the automotive electronics sub-markets by application in 2018 with forecasted values by 2023. As shown in the diagram below, the two automotive applications that are driving the automotive electronics market are Infotainment and ADAS (Advanced Driving Assistance Systems, leading to autonomous driving). Infotainment will be the first automotive electronics segment by 2023, with € 135 B and a CAGR of 6% over the 2018-2023. Although the ADAS market size is smaller (€ 49 B expected in 2023), it is the automotive electronics segment with the highest growth (a 16% CAGR over the 2018-2023 period). Finally, the significant growth of automotive electronics in chassis should not last long as it comes from the adaptations made by constructors to adapt petrol and diesel motors to meet the more restricting pollution regulations.

[28] Self-sufficient means that ADAS embedded electronics, once integrated into cars, requires no infrastructure investment (in terms of roads, telecommunication networks, etc.), to operate. For instance, the development of electric cars requires the installation of a battery recharging stations network. The development of connected cars is conditioned by the development of 4G, 5G and / or long-range M2M networks… This is not the case for ADAS.

Production values of automotive electronics sub-applications



Source: DECISION Etudes & Conseil

Sub-applications	2018 (B€)	2023 (B€)	CAGR 2018-2023
Infotainment	101	135	6 %
Powertrain	90	110	4 %
Chassis	47	61	5 %
ADAS	24	49	16 %
Comfort / Body	36	43	3 %
Other security & safety	29	33	3 %
TOTAL Automotive electronics	**326**	**430**	**5,7 %**

Methodology note: The data of the graph below are the resultant of a crossed approach: bottom-up and top-down. The top-down approach is the following. First, the TOP 50 automotive electronics tier 1 suppliers have been identified and studied and their activity segmented into the different automotive electronics sub-segments, providing insights on the relative sizes of the different segments. The bottom-up approach has consisted in identifying and listing the different automotive electronics components (listed below), and estimating (thanks to automotive experts), their relative costs. Then, the average electronic value by segment of typical cars (low-cost, mid-range, etc.), has been set up. The confrontation of the top-down and the bottom-up approach (correcting the discrepancies), have led to the graph above.

- **Infotainment** electronics includes screens, instruments, trip computers, navigation systems, head-up displays, car audio, communication systems, etc.

- **Powertrain** electronics includes engine control, transmission ECUs, stop and start systems, electronic throttle control systems / Drive-by-wire systems, battery management systems, regenerative braking systems and sound-generating systems for electric vehicles.

- **Chassis** electronics includes ABS/ESP, other brake systems, 4-wheel drives, active roll controls, hill-start assists, suspension controls and steering assistance systems.

- **ADAS (Advanced Driving Assistance Systems)**, include cameras, ultrasonic sensors, short-range sensors, lane departure detection & warning systems, collision detection & warning systems, driver alert controls / Drowsiness monitors, blind spot detection warnings, hands-off detection, night vision assistance, speed limiters, cruise controls and adaptive cruise controls, lane correction systems, park assist systems, automatic emergency braking systems, automatic speed adaptation from traffic signs readings, fail operational systems, dedicated short-range communications (DSRC), etc. Remark: Figures associated to concepts such as ADAS depend on the definition given to the related concepts. The figures provided in the pie chart correspond to a restricted definition of ADAS. In its broadest definition, ADAS represent a global market of € 39 B in 2018 and € 80 B in 2023;

- **Comfort / Body** includes body control units (seat controls, windows controls, wipers controls, doors controls, tire pressure sensing and warning systems, indoor lighting controls, etc.), heated seats, HVAC, electric chargers, active noise cancellation systems, etc.

- **Other security & safety** electronics includes airbags, keyless entry, alarms, immobilizers, etc.

B. Data analysis / Big data

Data analysis / big data is not an emerging technology. It is rather an emerging field of application that is booming, driven by most of the emerging technologies studied in this report (at different stages of development): machine learning algorithms, HPC, more Moore technologies, photonic interconnects & integrated photonics, but also on the long-run neuromorphic computing, quantum computing, photonic computing and other rebooting computing technologies.

This emerging market is very complex to apprehend for two reasons:

- Solutions are mostly embedded and / or internalized by companies;

- It regroups a great diversity of applications that can either be considered as “data analysis” or not, based on subjective criteria.

Therefore, we do not provide specific market values for the data analysis / big data market.

The EU is very well positioned in terms of pure R&D and know-how in much of the emerging technologies driving the data analysis / big data market. Yet, the European industrial landscape is clearly dominated by the USA in the first place and China to a lesser extent, as one can notice while through the analysis of the 4 markets highly linked with data analysis applications, ranked from the top to the bottom of the value chain:

- Information technology consulting firms (IBM, Accenture, Amazon Web Services, Fujitsu, DXC, TCS, NTT Data, Cognizant, Capgemini, Atos/Bull, Infosys, CGI, etc.), largely dominated by American players, Capgemini, Atos/bull and to a lesser extent Sopra Steria being the most relevant European players;

- Data analysis software & cloud applications. This field covers data analysis applications either through the sale of dedicated software or directly through cloud computing as a service application (sometimes for security information management systems). American players are again dominating this market. A part from the GAFAMI, the USA benefit from a flourishing ecosystem of emerging large companies and mid-sized businesses: VMWare (€6600M sales in 2018), ServiceNow (€2175M sales in 2018), Splunk (€1060B sales in 2018), Palantir technologies (€900M sales in 2018), Tableau software (€775B sales in 2018), but also Dynatrace, New Relic, SolarWinds, AppDynamics, Alteryx, Datadog, Sumo logic, LogRhythm (all these players benefiting from €200-300M sales in 2018 and fast growth). Chinese players are also well represented with the BATX and other rising players. The European players are poorly represented. The main European companies investing in cloud computing are OVH (France), Thales in Cloud for Defense and the main European telecom operators (Deutsch Telekom, Telefonica, Orange, Telecom Italia, Telenor, SFR, etc.);

- Professional software edition (Microsoft, Oracle, SAP, VMWare, Adobe, Salesforce, HCL, Fiserv, Amadeus, Intuit, etc.), largely dominated by American players, SAP and to a lesser extent Amadeus being the most relevant European players;

- Professional PC (servers, data centers). Finally, the professional PC segment (servers, data centers, etc.), which is upstream the data analysis / big data market in the value chain, is also clearly dominated by American players (HPE, Dell, Cray, IBM), and to a lesser extent Asian player (Lenovo, Inspire, etc.). Atos/Bull is the main European player.

C. Digital Identities

vi. Definition & technological evolutions

1. Vocabulary

Digital Identity of persons. Digital identity allows identification and authentication that is the capability to identify a person in a population and to prove that the identity it provides is the right one. Digitization of all activities has a particularly critical impact on identification and authentication. Everyone must to be able to identify himself online to interact with public services like taxes, social security, consult his medical files, retirement files, perform online transactions or remotely access to data from his business.

Digital Identity of objects. With the rapid development of IoT but also additional technologies such as Augmented Reality or Virtual Reality, these two concepts of Identification and Authentication should also apply to the objects in a network and possibly to the "avatars" of a person (e.g., in remote maintenance or remote surgery contexts).

Identities are multiple and contextual:

- Users use different names, pseudonyms or identifiers depending on the context or the services consulted. These identities are verified by various means, for example a couple (identifier – password), an electronic certificate, biometrics features, etc.;

- Not all services need the same level of authentication. An online banking service needs a much higher level of identification and authentication than a subscription to at a municipal swimming pool, or a theater for which a simple badge with a photo is enough. The plurality of digital identities allows people to separate the different aspects of their lives and to provide only the data necessary for each service. It is a question of data security, but it also gives everyone the opportunity to have multiple identities, more or less sensitive and unrelated.

2. Identification & Authentication

The basic technologies involved in Identification are:

- Static Passwords (invented in 196 by F. Cubato);
- Smart-Cards/Hard tokens with PIN code;
- Captcha / software challenges;
- RFID, QR codes;
- Biometric features (Fingerprint, Face recognition, Iris, Palm, Shape of the veins, Signature recognition, GAIT- identification of people by a sequence of walking images, often supported by AI techniques-, Gesture, DNA….);
- One-Time (dynamic) Passwords (OTP);
- Password-less technologies based on Public key cryptography (PKI).

Over the last 60 years, authentication methods have evolved from Single Factor Authentication (SFA: static password verification stored in encrypted of hashed form), to Multi-Factor Authentication (MFA), most of the time asking for the presentation of "something user knows", and / or "something user is" and / or "something user owns", i.e., combining several of the above-mentioned technologies. Combinations can be the following:

- Hard tokens (mostly used in 2FA with PIN Code plus dynamic OTP);

- Smart cards (mostly combining PIN code and PKI certificate);
- PIN Code + SMS OTP (mostly for Mobile Authentication);
- Phone as token MFA (e.g., PIN Code + Biometry)
- True password less based on Public Key Cryptography and a secure element)

A very critical aspect of authentication is related to its strength versus available attacks–theft, eavesdropping, phishing, side-channel attacks, Meet in the Middle (MiTM), Social Engineering, online guessing, endpoint compromising, etc. Usually, Password and SMS OP are considered as low security. On the contrary, Phone as a Token MFA and Hard Token medium, Smart-Card PKI and True password less is considered very strong. Of course, the cost of implementing these authentication methods is directly in relation (the cheaper being the less secure), etc.

Future technology developments:

- The development of passwordless solutions is already well engaged;
- Most applications are moving towards Multi-Factor Authentication (MFA), sometimes pushed by strong government and international or national agencies recommendations. Banking-Finance-Insurance-Securities (BFIS), PC and Data Processing, Mobile Applications and Government have been -and still are- the fastest markets to introduce MFA solutions. Biometry, as the one of the preferred MFA solutions is therefore also being introduced in almost all domains;
- In the coming decades, the main emerging technology should be the development of *behavioral biometrics* that is biometric applications using AI algorithms to identify people and objects based on their behaviour.

3. <u>Identity and Access Management (IAM)</u>

On the top of Identification and Authentication are Identity and Access Management systems. Such systems refer to all the IT security disciplines, frameworks, and solutions for managing digital identities. While a person (user) has only one physical identity, it may have many different digital identities (sometimes named "credentials") for accessing several accounts representing him. Each account can have different access controls, both per resource and per context. IAM systems are thus a foundational security component to help ensure users have accesses to their needs (no more no less), and that systems, data and applications are inaccessible to unauthorized users.

IAM systems are used to:

- Manage user's digital identities and the roles they are assigned in the IT system(s);
- Define the IT components devices (servers, network component, etc.), data, and other resources protected by IAM;
- Define the appropriate levels of protection and access for sensitive data, systems, resources taking care of their usage context (mobility, geo-localization, etc.);
- Add, remove, change users in the IAM system;
- Add, remove, and amend the user role and access rights in the IAM system.

There are many technologies to simplify password management and other aspects of IAM. A few common types of design principles that are used as part of an IAM system include:

- **Single Sign On (SSO):** An access and login system that allows users to authenticate themselves once then grants them access to all the IT components, data and resources they need without having to log into each of those areas individually, except if the authentication level requested is higher and needs additional credentials;
- **Multi-Factor Authentication (MFA):** Such systems use MFA to authenticate individuals and grant them access to IT components, data and resources;

- **Privileged Access Management:** Such systems typically integrate with the user or employee database and pre-defined roles to establish and provide the access employees need to perform their role;

IDaaS. In the coming decade, the main business model changes should occur through the development of IDaaS. IDaaS refers to Identity and Access Management Services that are offered as part of cloud or Software-as-a-Service (SaaS) subscription-based products. This IAM solution contrasts with traditional solutions that operate entirely on-premises, self-managed and delivered through software or hardware means. These solutions rely heavily on technologies such as Active Directory (AD) and Lightweight Directory Access Protocol (LDAP).

4. A technology-driven market

The digital identify market is driven by many emerging technologies studied in this report.

- **Secure elements.** Secure elements are one of the most popular ways to implement Identification/Authentication. The evolution of secure elements towards eSIM or iSIM is a key enabler for future MFA and IAM IOT-compliant applications.
- **Cryptography.** Most authentication schemes are based on the use of cryptography, generally based on Public Key cryptosystems. In the area of IoT, lightweight cryptography could be an important technology for designing IoT Identification/Authentication systems, as well as the related IAMs.
- **Blockchain.** An important future trend in IAM is to move toward self-sovereignty, i.e. consumer or citizen-centric Digital Identities systems. The perspective is to leave users the possibility to generate their Digital Identities as derivatives from a strong one (at the sense of European eIDAS regulation), issued for example by a Government or a trusted organization. Blockchain technology is a possible option for designing such user-centric systems.
- **Artificial Intelligence.** AI is already used in many biometric technologies such as Voice, Signature or Facial Recognition, GAIT analysis[30] and behavioral analysis. It should also play an increasing role in IAM, as it may offer the potential for intelligent, immediate and fine-grained access control solutions. As a matter of example, the proof of identity at log-on of a user by a predefined MFA scheme (Multi-Factor Authentication), is not ensuring that the same user will be present all the session and do not guarantee that the system continues to believe that it is working only with authorized users. Taking clues from visual images and voices could assist to eliminate this uncertainty. AI systems could constantly monitor users as they move around the network and behavioural factors as well as real-time risk analysis can be used in a combined way.
- **Smart sensors.** With rapid development of IoT, new Identification/Authentication algorithms will need to be embedded in the remote sensing devices and IAM systems will have to be adapted in consequence.

vii. Economic impact, market and main players

A. Economic impact

On the demand side, digital identity is becoming more and more a key element of customer and citizen engagement in the overall digitization process in our modern economies. On the supply side, digital identities become a strategic asset which is mandatory to protect to avoid potentially enormous business losses or massive frauds. Therefore, digital authentication is absolutely critical for all application domains.

Digital Identities solutions are expected to have a critical impact on every electronic application within the coming decade. The only exceptions are the following:

[30] Gait analysis is the systematic study of animal locomotion, more specifically the study of human motion, using the eye and the brain of observers, augmented by instrumentation for measuring body movements, body mechanics, and the activity of the muscles.

- Biometry should have no significant impact in telecommunication infrastructures;
- IAM should have no significant impact on smart home applications and wearable applications.

Identity Access Management (IAM) is mostly critical for B2B and Government applications, as an essential component of the relevant IT infrastructures. Yet, new IAM architectures are expected to emerge with the development of some critical fields of applications in IoT (connected vehicles, smart energy…), pushed by the need to securely interconnect multi-stakeholder ecosystems. AI algorithms will play an increasing role in the design of such new systems.

IoT will be the main driver of growth and will reinforce the primary role of Digital Identities

The Internet of Things (IoT) is the next computing wave that will enable to connect billons of objects generating a deluge of data issued from all sensors controlling the applications (e.g., connected vehicles, energy systems or transportation systems, smart cities, e-health and so on). This phenomenon is already ushering in a wave of disruptive new threats and opportunities.

One of the biggest IoT issues involves managing the ongoing process of securing connected devices and the information they will collect and expose across multiple connection points, many of which are vulnerable to cyber-attacks. There is here an enormous challenge to develop Digital Identities and IAM systems for IoT applications providing a high-level of cyber-security. This is particularly true as digital services to which IoT devices are connected involve often third and outside ecosystems. As a matter of example, a connected car will have to interact with the vehicle's infrastructure, other cars on the road (V2V communications), smart-mobility ecosystems, smart-city information systems and so on. Digital identities are in the kernel of the picture and need to control not only the device but also all the objects/services they are connected to and all the information they share, as well as customer preferences and authorizations.

This will be a very complex problem, as organizations developing large IoT applications will need to interact within several ecosystems, not all under their direct control, especially regarding third party IoT device access and security. These ecosystems will be secure and useful only as long as a secure and consistent control of digital identities, primary access and authorization mechanisms are maintained. Moreover, identity services and security measures need to be embodied to meet both customers' preferences and privacy/security expectations.

B. Associated markets

The three main drivers of growth of digital identities are the following:

- The rise of IoT and the need for IoT identities;
- Regarding specifically the identification & authentication market: the development of biometrics applications and especially behavioral biometrics;
- Regarding specifically the IAM market: the rising number of data and associated identities stored in the cloud.

1. <u>The Identification & authentication market / MFA (Multi-Factor Authentication)</u>

In 2018, this market accounted for ~€30B worldwide and should reach ~€40B in 2023, at a 7-8% CAGR.

Scope & content. The Multifactor authentication market is segmented into solution, product, deployment, and end users. The product segment is sub-segmented into software, hardware, and services. The hardware covers a wide range of hardware tokens, biometrics devices, smart cards, and others. The hardware token is a physical device given to an authorized user of computer services to ease authentication. The hardware token is used in addition to or in place of a password to prove that the customer is genuine. This token acts as an electronic key to access payment services.

Growth drivers.

Two-factor authentication (2FA), is now more and more required for on-line transactions and will remain the dominant MFA segment over the 2019-2025 period, but with increased levels of sophistication. Two-factor authentication provides an additional level of security and intends to make harder for attackers to gain access to a person devices and online accounts. Two-factor authentication is most of the time based on the combination of "what a user knows" (a PIN code) or "what the user is" (e.g., a biometric feature such iris, face, palm, fingerprint,…) or "what a user owns" such as smart cards, smartphone or other tokens able to answer to an on-line challenge (SMS or One Time Password).

Smart card with PIN (but soon integrating biometrics) is currently the most commonly used for two-factor authentication model, largely used in the Banking-Finance-Insurance-Securities sector, attendance systems, online transactions, and access control systems.

Biometry and password less based on PK cryptosystems seem the most promising trend for Mobile Authentication.

Biometrics.

In 2018, biometrics applications (part of the identification & authentication market), accounted for €3-4B worldwide and should reach €7-9B in 2023, at a 15-20% CAGR. In Europe (contrarily to other regions like China, where facial recognition is an extension of the State), the use of biometrics applications will be strictly regulated and will have specifically to obey to the new GDPR directive.

Unsurprisingly, Government applications (with the needs of e-identity documents such as e-ID cards, Schengen permits, e-passports….) and Defense & security applications (Critical Infrastructure protection, access to sensitive sites, etc.) will be the most dynamic applications of biometrics solutions.

2. The IAM market

In 2018, the IAM market accounted for €8-10B worldwide and should reach €15-17B in 2023, at a more than ~13% CAGR.

A. Competitive landscape

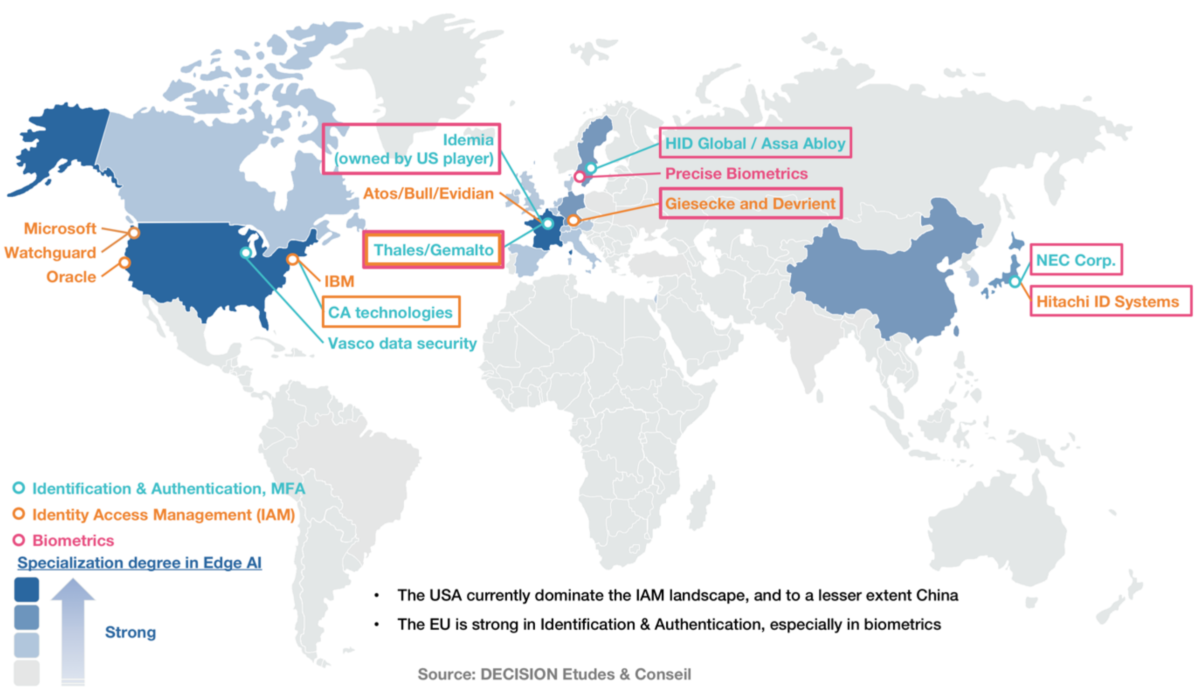
Identification & Authentication. European industrial actors occupy strong positions in the Identification and Authentication area and master key associated technologies such as cryptography and biometrics. The EU has also strong industrial positions in the connected domain of e-secure elements (see the associated chapter in this study). Therefore, in terms of Identification & Authentication, the EU can be considered as on an equal footing with the USA and slightly ahead of Japan.

The EU has strong scientific and industrial R&D skills in the global area of Identification/Authentication.

- The main EU R&D centers are:
    - In France: the INRIA, the CEA List and the INT (Institut National des Télécommunications);
    - In Germany: the FhG (Fraunhofer Institute for Integrated Systems and Device Technology);
    - In Belgium: the UCL (Université Catholique de Louvain), and the KUL (KU Leven University).
- The EU is in particular very strong in Biometry with both domestic and international R&D laboratories. The main EU industrial players have large in-house R&D centers and have recently bought foreign players including R&D centers with key competences. The American 3M (including Cogent Communications) has been bought by the French Gemalto in 2016 and the American L-1 Identity Solutions have been bought by the French Idemia in 2011. Idemia (born from the merger of Morpho and Oberthur Technologies) is owned by the American player Advent International but the management, the headquarter and most of the skilled workers remain in France for now. The German FhG and the French INT are also particularly recognized in biometrics.

Identity Access Management (IAM). The EU's position is weaker in IAM systems, especially versus the American leaders. The EU lacks large companies such as the GAFAMI of BATX, able to create large business ecosystems and service platforms around Digital Identities. In terms of industrial R&D, the EU is a niche player. Yet, the EU has strong scientific skills in classical or No-SQL Data-Base, AI technologies, which will be key for the design of future IoT enabled IAM systems.

World Map - Main industrial players - Digital Identities



B. An opportunity for the EU

1. A necessity to protect the EU sovereignty

While most European State members take serious care of their citizen's digital identities (with most government issuing e-identity documents such as identity cards, social security cards, visas, driving licenses or passports…), they pay relatively few attentions to the potential added value of such documents in the digital economy. Indeed, on the pure business side, the major result of digital identities is in attracting and retaining customers and delivering continuously new services and new value-added. In this respect organizations considering digital identities (and the related IAM) beyond security compliance are in the best position to deliver value to their customers and businesses. This has been well understood in particular by the GAFAM and BATXi.

In the B2C work, the proliferation of digital identities for one single consumer undoubtedly meets a demand from the users but presents several risks that should be considered:

- On the one hand, identities are often provided by different private actors of the Internet, in particular the GAFAMI which aggregate the data on their platforms and value them at their profit. As a consequence, these large actors (mostly American) deprive users control over their character data staff while they colonize little by little the European digital economy;

- On the other hand, if a service or product can be offered by several providers, the user ends up choosing the easiest authentication method offered (often by a GAFAMI) and bypass security each time this can be done), because of better convenience.

This point raises an important issue of EU economic sovereignty. Using a strong digital identity issued by a European trusted organization instead of private ones should allow users to be identified and authenticated with no swallowing of their personal data to large American or Chinese firms in every transaction they perform daily, whether with government or private service suppliers. This facility should, of course, offer on any device owned by the user (computer, tablet, smartphone, etc.) with additional capabilities such a pseudonymization or anonymization.

To slow down the current situation with the swallowing of European user data by the large American and Chinese monopolies, self-sovereignty concepts could be added in IAM systems, offering to individuals and organizations who have one or more credentials to claims relating to those credentials without having to go through an intermediary. Self-sovereignty is a way to give to individuals a full control of their Digital Identities. This has strong technical implications:

- Users must control their identities: they must agree to the use of their Digital Identities, have access to their data and have the right of "digital death". Exposure of claims must be a minimum disclosure principle;
- MFA algorithms must be transparent and context aware (seamless adaptation to security level);
- Digital Identities must be persistent (long-lived);
- Digital Identities should be usable as widely as possible. For instance, information and services about Digital Identities must be cross-border interoperable.

2. Conclusion

Digital Identity is a key a strategic domain for the EU to ensure European sovereignty in existing and future businesses and slow the current colonization of our digital economy by large American and Chinese monopolies.

The domain has to be addressed in a holistic way, including regulation, complete architecture models including IoT aspects, technologies (MFA and IAM), standardization and cross-border interoperability. Customer or citizen trust, security and privacy by design, scalability and transparency will be the key design challenges.

GLOSSARY

AD: Active Directory
ADAS: Advanced Driving Assistance System
AEC: Automotive Electronics Council
AES: Advanced Encryption Standard
AGI: Artificial General Intelligence
AiP: Antenna in Package
ANSSI: Agence Nationale de la Sécurité des Systèmes d'Information
ASIC: Application-Specific Integrated Circuit
BaaS: Blockchain as a Service
BAQIS: Beijing Academy of Quantum Information Sciences
BCM: Bayesian Computing Machine
BFIS: Banking-Finance-Insurance-Securities
BSI: Bundesamt für Sicherheit in der Informationstechnik
CAC: Cyberspace Administration of China
CAGR: Compound Annual Growth Rate
CBRAM: Conductive Bridging RAM
CICIIF: China Integrated Circuit Industry Investment Fund
CMOS: Complementary Metal Oxide Semi-conductor
COPAC: Coherent Optical PArallel Computing
CQCCT: Center for Quantum Computation and Communication Technology
CPS: Cyber-Physical Systems
CPU: Central Processing Unit
CSP: Chip Scale Package
DARPA: Defense Advanced Research Projects Agency
DDoS: Distributed Denial of Service
DLT: Distributed Ledger Technology
DPOS: Delegated proof of stake
DRAM: Dynamic Random-Access Memory
DRL: Deep Reinforcement Learning
DSP: Digital Signal Processors / Distributed Services Platform
DSTL: Defence Science and Technology Laboratory
DWDM: Dense Wavelength Division Multiplexing
EBP: European Blockchain Partnership
ECS: Electronics Components and Systems
ECSEL: Electronics Components and Systems for European Leadership
ED: Embedded Die
EECC: Edge Computing Consortium Europe
EEPROM: Electrically-Erasable Programmable Read-Only Memory
EMI: ElectroMagnetic Interference
EPI: European Processor Initiative

EPROM: Erasable Programmable Read-Only Memory
ETP4HPC: European Technology Platform for High Performance Computing
EUV: Extreme UltraViolet
FC: Flip Chip
FC CSP: Flip-Chip Chip Scale Package
FDSOI: Fully Depleted Silicon On Insulator
FeFETs: Ferroelectric Field-Effect Transistors
FHE: Fully Homomorphic Encryption
FI: Fan In
FO: Fan Out
FPGA: Field-Programmable Gate Array
GAFAMI: Google-Apple-Facebook-Amazon-Microsoft-IBM
GAN cryptography: Generative Adversarial Neural networks Cryptography
GCHQ: Government Communications Headquarters
GDPR: General Data Protection Regulation
GNSS: Global Navigation Satellite System
GPRS: General Packet Radio Service
GPU: Graphics Processing Unit
GSM: Groupe Speciale Mobile
HBM: High Bandwidth Memory
HBP: Human Brain Project
HBS: Hash-Based Signatures
HIPEAC: High Performance and Embedded Architecture and Compilation
HPC: High Performance Computing
HPDA: High Performance Data Analytics
HSM: Hardware Security Module
HV: High Voltage
HW: Hardware
IAM: Identity Access Management
IARPA: Intelligence Advanced Research Projects Activity
ICT: Information and Communication Technologies
IDM: Integrated Device Manufacturer
IC: Integrated Circuit
ICO: Initial Coin Offering
IEEE: Institute of Electrical and Electronics Engineers
IGBT: Insulated Gate Bipolar Transistor
InFO: Integrated Fan Out
IQC: Institute for Quantum Computing
IRDS: International Roadmap for Devices and Systems
ITAR: International Traffic in Arms Regulations
ITC: Information Technology Consulting
ITRS: International Technology Roadmap for Semiconductors
KSI: Keyless Signature Infrastructure
LANL: Los Alamos National Laboratory
LDAP: Lightweight Directory Access Protocol
LGAA: Lateral Gate-All-Around-Device

LDWS: Lane Departure Warning Systems
MCU: MicroController Unit
MEMS: Micro Electro Mechanical System
MESO: Magneto-Electric Spin-Orbit
MFA: Multi-Factor Authentication
MiTM: Meet in the Middle
MNE: Micro and Nano Electronics
MOEMS: Micro-opto-electro-mechanical system
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
MPI: Message Passing Interface
MPU: MicroProcessor Unit
MRAM: Magnetoresistive RAM
mSAP: modified Semi Additive Processes
NAND memory: NOT AND memory
NCSC: National Cyber Security Centre
NEMS: Nano Electro Mechanical Systems
NFC: Near-Field-Communication
NFV: Network Function Virtualisation
NICT: National Institute of Information and Communication Technologies
NIST: National Institute of Standards and Technology
NQIT: Networked Quantum Information Technologies Hub
NRAM: Nanotube RAM
NRI: Nanoelectronics Research Initiative
NTT: Nippon Telegraph and Telephone
NUDT: National University of Defense Technology
NV center: Nitrogen-Vacancy center
NVM: Non-Volatile Memory
ONISQ: Optimization with Noisy Intermediate-Scale Quantum
OpenMP: Open Multi-Processing
OPU: Optical Processing Unit
OS: Operating Systems
OT: Operational Technologies
QCI: Quantum Communications Infrastructure
QKD: Quantum Key Distribution
QRNG: Quantum Random Number Generators
QST: Quantum and Radiological Science and Technology
QuASAR: Quantum-Assisted Sensing and Readout
PBFT: Practical byzantine fault tolerance
PCM: Phase-Change Memory
PCMOS: Probabilistic Complementary Metal Oxide Semi-conductor
PCQC: Paris Center for Quantum Computing
PCRAM: Phase-Change RAM
PGAS: Partitioned Global Address Space
PKC: Public Key Cryptography
PIC: Photonic Integrated Circuit
PiM: Processing-in-Memory

PMIC: Power management integrated circuit
PPAML: Probabilistic Programming for Advancing Machine Learning
PUF: Physically Uncloneable Functions
RAM: Random Access Memory
RDL: Re-Distribution Layer
ReRAM: Resistive RAM
RF: Radio Frequency
RFMEMS: Radio frequency microelectromechanical system
ROM: Read-Only Memory
SaaS: Software as a Service
SBIR: Small Business Innovation Research
SK: Symmetric Key
SIM: Subscriber Identity Module
SIMD: Single Instruction Multiple Data
SiP: System-in-Package
SoC: System on Chip
SRAM: Static RAM
SSD: Solid-State Drives
SW: Software
TBPS: Total Bits Per Second
TSV: Through-Silicon Via
UICC: Universal Integrated Circuit Card
USTC: University of Science & Technologies
WL CSP: Wafer Level Chip Size Package
WLP: Wafer Level Package
WSN: Wireless Sensor Networks

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