

NEUROPULS

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Document Validation

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Document Abstract

This report presents the Impact & Risk Assessment of the NEUROPULS Horizon Europe project (Grant Agreement n° 101070238).

This deliverable is part of WP7, which is the main interface between the project and the outside world, academics, and industrials, in addition to impact targets groups.

The impact assessment focuses on identifying and analyzing the potential impacts of the project within a broader context, as well as continuous monitoring how these impacts evolve due to technical progress, increased interest from stakeholders, and changes in the competitive environment. The risk assessment focuses on risk management processes, i.e., identifying, analyzing, prioritizing, managing, and controlling risks that could affect the project's execution and objectives.

In this initial version, we are exhibiting a first impact assessment in the different areas (technological, economic, scientific and societal). The methodology we have followed is based on a qualitative assessment, exposing the different elements favouring each impact, going beyond the internal environment of the project. Indeed, NEUROPULS technological layers were put in perspective considering the context of emerging neuromorphic computing, HW based security and silicon photonics, to reach the European sovereignty. From economic perspective, we have assessed the impact on the European market expansion, linked to the areas cited above, but also to enabling crucial sectors such as AI, edge computing, IoT and cybersecurity. A specific focus has been done on the creation of a robust and innovative silicon photonics value chain in Europe, considered as a strategic outcome, for which NEUROPULS would have a strong value creation, in the context of a fragmented global landscape, and a demand that appears attractive and promising. Regarding scientific impact, we have pointed out the advancement in fundamental knowledge quantified by a number of patents which have been filed within NEUROPULS, linked to strategic areas. Open science practices, used and promoted within the project have been mentioned, as a key aspect to create a scientific impact, in compliance with Horizon Europe approach. Scientific collaborations & research synergies, creating a vibrant ecosystem has been identified as a potential path to maximize the impact on the European research network in silicon photonics and neuromorphic computing technology. Finally, societal impacts have been outlined, although being less direct than other impacts: reducing energy consumption and environmental impact, creating a more secure and resilient society and facilitating a wider adoption of AI and new technologies.

The second section is dedicated to risk assessment process, in line with the generic guidelines provided in ISO 31000. This methodology has been explained, through the different steps of the process: risk identification, analysis & evaluation, response planning and implementation, and risk monitoring & reporting.

The outcome of this process has resulted into a risk assessment table, detailing 9 principal risks and 10 unexpected ones.

This table constitutes the main tool to manage the risk assessment during the project lifetime: it should be updated and reported to the relevant parties, on a 3-month basis. The final version, corresponding to the reporting period (M1-M21) has been highlighted, from which we have extracted relevant information to rank the different risks, and determine the priority level that should be given to each one and mitigation measures if it occurs.

Plotting a risk assessment chart, we were able to map the risks to 3 qualitative levels of impact: “low”, “medium” & “high”, as combination of risk probability & risk severity.



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This methodology was efficient to have a global overview of NEUROPULS risk assessment and degree of confidence that we can have on the project. Consequently, we highlighted the risks evaluated as “high”, in order to better anticipate them, and provide the highest priority to the mitigation measures associated to them.

Finally, we identified the risks that have materialized during the reporting period and discussed the appropriate mitigation strategy. Risk linked to fabrication delay, being highly impactful for the realization of the project, led us to claim one year amendment, and use a higher priority for the runs done by CEA-LETI. Similarly, risk related to Personnel change has materialized, for which we chose to shift the risk to other parties, by involving other collaborators within the partner’s organization, or other stakeholders. This mitigation strategy seems to be the most appropriate and would strengthen agile collaboration within the consortium.

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Impact

1. Technological impact

1.1 Innovation for neuromorphic computing

Semiconductors are among the most important enabling technologies of the twenty-first century. The **global semiconductor "arms race"** has been driven by the pursuit of ever-smaller feature sizes on silicon wafers. As more transistors are integrated onto a single chip, processing power and energy efficiency increase. This increase in power and efficiency lowers the cost of computation and allows modern AI models to be trained and operated more accurately, quickly, and cost-effectively—a factor that has become especially critical with the rise of generative AI.

Supercomputers, built from these advanced semiconductor technologies, have played a pivotal role in pushing the boundaries of scientific research and AI development by providing immense computational power. However, they are **rapidly approaching the exascale era, in which requirements regarding latency, bandwidth, and energy consumption are becoming challenging for digital electronics**, due to the physical constraints of further progress in Moore’s law and Dennard scaling. Thus, **the computing community is increasingly looking at novel technologies and computer architectures to enable continued performance improvements.**

Neuromorphic computing, based on brain-inspired computational principles, is one such approach capable of addressing this issue by radically changing the methods of processing information. While traditional computing operates with binary values, neuromorphic computing imitates the biological brain by leveraging temporal events (spikes) as input and output, thus allowing higher energy efficiency and low-resource processing of data (Figure 1).

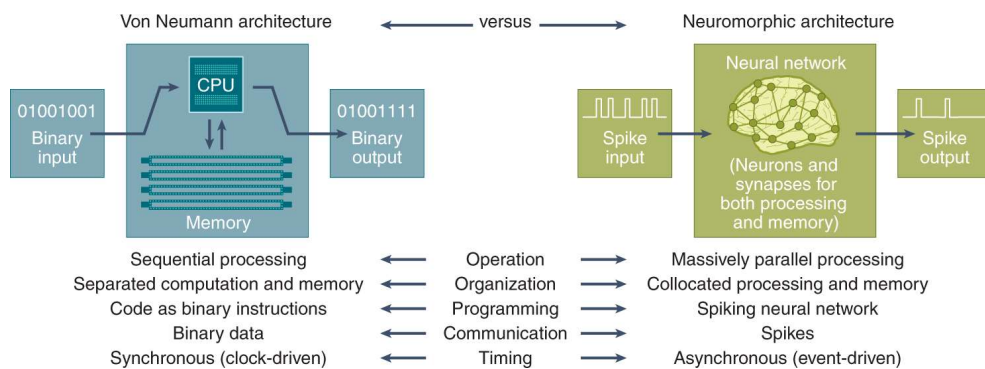


Figure 1 Von Neumann’s architecture versus Neuromorphic architecture ¹

¹ <https://www.nature.com/articles/s43588-021-00184-y/figures/1>

In the field of neuromorphic engineering, research has been carried out on the design of both hardware and software neuro-inspired computing methods, aiming to emulate both the biological structure and the biological function of human brain. Many physical realizations of neuromorphic hardware are under development or are already available for use to the research community.

Both industry and academia have taken an interest in neuromorphic systems: in industry, some examples include IBM's TrueNorth² and Intel's Loihi³, and there are also a variety of startups, including DYNAPs⁴, and academia-led research projects such as BrainScales-2⁵. These large-scale neuromorphic computers are silicon-based and implemented using conventional Complementary Metal Oxide Semiconductor technology (CMOS).

As we approach the limits of what current CMOS technology can achieve in terms of power consumption, cost, and performance, the neuromorphic research community has been exploring **new materials for neuromorphic novel implementations**. These include Phase-Change Materials (PCM), ferroelectrics, non-filamentary materials, and topological insulators⁶. Additionally, **technologies such as silicon photonics and quantum computing are being investigated to complement and, in some cases, eventually replace traditional CMOS, depending on the specific applications and challenges being addressed.**

The NEUROPULS project will allow to further foster the development of neuromorphic computing by advancing research into emerging materials like phase-change materials; silicon photonics; and hardware security to enable delivering high-performance and secure computing at ultra-low power operation, especially in the context of edge applications. The use of PCMs as non-volatile memory elements means that information can be retained without continuous power supply, significantly reducing overall power consumption. When combined with active III-V materials, which facilitate efficient light-matter interaction and optical gain, the resulting systems will be far more energy-efficient, **making them ideal for edge computing applications where power resources are limited**. Meanwhile, its focus on CMOS compatibility ensures that these innovations can be easily integrated into existing manufacturing processes, lowering costs and enhancing scalability. In this way, the research contributes to solving the conundrum of exponential growth in energy consumption while developing both economically viable and sustainable technologies. Besides, as the potential of neuromorphic technology has been only partially explored so far, NEUROPULS is likely to have an impact on its market take-up in a range of existing and new application areas.

1.2 Advancement in Silicon Photonics

Silicon photonics is an emerging and very promising technology that integrates optical components and circuits into chip-scale systems, most commonly in mature CMOS platforms. The fact that it builds directly

² <https://open-neuromorphic.org/blog/truenorth-deep-dive-ibm-neuromorphic-chip-design/>

³ <https://www.intel.fr/content/www/fr/fr/research/neuromorphic-computing.html>

⁴ <https://rockpool.ai/devices/DynapSE/dynapse-overview.html>

⁵ <https://www.frontiersin.org/journals/neuroscience/articles/10.3389/fnins.2022.795876/full>

⁶ Bai Sun, Tao Guo, Guangdong Zhou, Shubham Ranjan, Yixuan Jiao, Lan Wei, Y. Norman Zhou, Yimin A. Wu, "Synaptic devices based neuromorphic computing applications in artificial intelligence," *Materials Today Physics*, Volume 18, 2021, 100393, ISSN 2542-5293, <https://doi.org/10.1016/j.mtphys.2021.100393>.

on the extreme maturity of the silicon-based electronics technology enables robust scale up for volume production from cost and yield perspective.

Photonic devices use light (photons) instead of electrons to represent, transmit, and process data, and thus, **provide fast and high-capacity interconnections among distributed processors as well as to perform calculations inside them more efficiently.** Photonic systems can achieve high degree of parallelism using the inherent fan-out and WDM (Wavelength Division Multiplexing) techniques. They can transmit data at a high rate and at low energy level independently of distance without Joule heating or need for induction coupling, which alleviates the communication energy overheads of electronic systems. However, to benefit from this promising technology at scale, some crucial challenges must be solved, including the development of CMOS-foundry-compatible devices, circuits, integration, and packaging tailored for neuromorphic computing.

NEUROPULS is set to make a significant impact on the development and widespread adoption of silicon photonics by establishing a foundation for overcoming aforementioned challenges through a range of innovations detailed below. Additionally, given the multidisciplinary nature of the project, each innovation can also contribute to the development of new applications in its respective field on a broader scale.

- **The development of low loss PCMs and related fabrication process.** PCMs hold great promise for multifunctional device development, including applications in non-volatile memory, optical data storage, photonics, energy harvesting, biomedical technology, neuromorphic computing, thermal management, and flexible electronics⁷. Thus, in a broader perspective, **NEUROPULS would contribute to enhancing current state-of-the-art and bringing new applications of this technology.**
- **The monolithic integration of advanced technologies, such as integrated photonics, along with emerging materials like PCMs and III-V materials, within a unified platform.** Integrated III-V sources allow for better system compactness, on-chip gain and the capability of realizing high-speed optical spiking neurons, thus removing the need for optical signal amplification in multiple-layer architectures. Meanwhile, PCMs are emerging material presenting unique properties such as fast response time, robust non-volatility, integration onto silicon waveguides and possibility of non-volatile reconfigurability⁸, which is essential for holding a specific neural network configuration in a lossless manner⁹. Thus, the integration of PCMs and III-V materials will enable the creation of highly efficient neuromorphic accelerators that will perform practical AI-focused tasks with much lower power consumption and higher efficiency compared to traditional digital processors and the current

⁷ Patinharekandy, P., Kandammathe, V. S., Teng, J., Ko, J. H., Yoo, Y. J., Jeong, H.-H., Lee, Y., Zhang, S., Cao, T., Popescu, C.-C., Mills, B., Gu, T., Fang, Z., Chen, R., Tong, H., Wang, Y., He, Q., Lu, Y., Liu, Z., Yu, H., Mandal, A., Cui, Y., Ansari, A. S., Bhingardive, V., Kang, M., Lai, C. K., Merklein, M., Müller, M. J., Song, Y. M., Tian, Z., Hu, J., Losurdo, M., Majumdar, A., Miao, X., Chen, X., Gholipour, B., Richardson, K. A., Eggleton, B. J., Wuttig, M., & Singh, R. (2023). *Roadmap for phase change materials in photonics and beyond*. *iScience*, 26(10), 107946. ISSN 2589-0042. <https://doi.org/10.1016/j.isci.2023.107946>

⁸ Most of the work with PCMs in photonic neuromorphic computing has focused on integrating PCMs with silicon in non-scalable and costly approaches using academic laboratory environments that cannot guarantee a high yield and access to functionalities such as monolithic on-chip detectors or doping presence for fully high-speed reconfigurable photonics.

⁹ Compared to electronic approaches based on PCMs that suffer from slow response time (order of hundreds of ns to μ s) and large energy consumption due to the Joule heating mechanism, photonic approaches allow sub-ns response time and a very efficient mechanism for optical energy absorption and consequent heat conversion and temperature raise in PCM technology.

state-of-the-art silicon photonics (see Table 1). This will allow for the development of spiking neural networks (SNNs) based architectures that operate at high speeds with low latency¹⁰ and opens the doors for on-chip training by leveraging emergent plasticity approaches that would lead to significant performance improvements in applications requiring real-time processing, such as robotics, autonomous systems, and advanced AI.

Key performance indicators (KPIs)	State-of-the-Art	Project
Optical PCM with low loss and large contrast ratio amorphous vs crystalline phases (FOM= $\Delta n/\Delta k$)	GSST with FOM = 5 at 1550 nm (MIT ²⁴)	> 10
Node number for photonic SNN-based accelerators	4 (OXFORD ²⁵)	64
Energy consumption per MAC in autonomous driving Turing discrete GPU (use-case with lowest E/MAC) – only computation consumption	6 pJ (NVIDIA ²⁶)	< 0.06 pJ
NN compute density (in electronics or photonics)	18 TMAC/s/mm ² (UCSB ²⁷)	100 TMAC/s/mm ²
Bit entropy for fully on-chip photonic PUFs (entropy per raw (postprocessed) response bit)	<i>No existing fully on-chip photonic PUFs</i>	> 50% (> 95%)

Table 1 : Expected KPI of the NEUROPULS project¹¹

- **The development of RISC-V compliant interfaces** that will play a crucial role for **the adoption of silicon photonics in mainstream computing**. RISC-V is an open-source reduced instruction set architecture (ISA) that is gaining popularity for its flexibility and support from a broad community. Compliance with RISC-V ensures that these new accelerators can be easily integrated into existing systems, allowing for smooth programmability and widespread use. **The compatibility with RISC-V also means that advanced neuromorphic systems can be more easily adopted by various industries**, including those focused on AI, IoT, and embedded systems. **This enhances the market potential for silicon photonics in neuromorphic computing technologies and accelerates their integration into practical, real-world applications.**
- **The research on co-design, process integration, and advanced packaging of silicon photonics.** As it is shown by Integrated Photonic Systems Roadmap-International (IPSR-I)¹², there have been extensive research endeavours from large-volume CMOS foundries and IDSMs to build integrated silicon photonics ecosystems towards advanced chip stacking and packaging technologies. Advanced chip packaging has also become an area of intense interest among all major chipmakers¹³ as they seek to develop more powerful chips for applications such as AI. **NEUROPULS will contribute to this endeavour by developing a suitable packaging strategy to facilitate maximal system**

¹⁰ Although spiking laser sources are needed for SNNs, they have been generally employed off-chip, due to the low yield of the III-V/Si process, impairing the full scalability, reliability, and benchmarking of the photonic NNs.

¹¹ European Commission. (2021). *HORIZON-CL4-2021-DIGITAL-EMERGING-01: Digital and emerging technologies for competitiveness and fit for the green deal*. Proposal number: 101070238, Proposal acronym: NEUROPULS.

¹² <https://photonicsmanufacturing.org/roadmap-structure-overview>

¹³ Near Margalit, Chao Xiang, Steven M. Bowers, Alexis Bjorlin, Robert Blum, John E. Bowers; *Perspective on the future of silicon photonics and electronics*. Appl. Phys. Lett. 31 May 2021; 118 (22): 220501. <https://doi.org/10.1063/5.0050117>

performance and impact of the PIC-based accelerator, while satisfying the targeted constraints in terms of power consumption and latency.

- **The development of open-access simulation platforms for the modelling and the evaluation of next generation neuromorphic accelerators based on silicon photonics.** NEUROPULS framework will be vital in exploring different scenarios to optimise computing electronic-photonics platforms, extract relevant metrics, and predict performance of prototypes. On a broader scale, it will also impact a future standardization of such platforms. According to Yole Intelligence, there are still diverse approaches to the basic design of silicon photonics. There is currently no broadly adopted standardization for silicon photonics' basic components and processes ¹⁴.

1.3 Advancement in hardware-based security at silicon-level

The 2023 World Economic Forum's Global Risks Report¹⁵, published in January, put **cybersecurity in the current and future top 10 risks globally**. Gartner analysts predict that over the next two years, 45% of global organizations will be impacted in some way by a supply chain attack, while Microsoft estimates the cost of cybercrime to be projected to hit an annual \$10.5 trillion by 2025¹⁶. Currently, there has been rising concern on future cyberthreats in the light of:

- Further advancements in artificial intelligence (AI): **Adversaries are increasingly leveraging AI to enhance and refine their attacks.** Generative AI enhances the capabilities of threat actors to create new variants of existing ransomware as well as allowing deployment of automated attacks, potentially leading to a surge in the volume of attacks they can carry out. The World Economic Forum (WEF) anticipates a growing use of AI by malicious actors in the future, highlighting the need for even stronger cybersecurity measures.
- **The increasing adoption of mobile and IoT devices, along with the rollout of 5G technology.** 5G is expected to drive the large-scale adoption of connected devices, enabling advanced applications such as driverless cars and smart cities. However, if the deployment is not properly managed, IoT devices—which already have a poor track record in cybersecurity—will become even more vulnerable to attacks. This, combined with the integration of AI, poses a significant cyberthreat¹⁷.

Hardware-based security plays a crucial role in addressing these challenges by securing data, maintaining device integrity, and ensuring that systems start and operate as intended. Additionally, the growing use of AI in sensitive and potentially harmful applications underscores **the need for robust semiconductor security**. This has led to a shift towards enhancing the security and traceability of semiconductors. **However, integrating advanced security features into semiconductor products inevitably drives up costs.**

¹⁴ Yole, Optical Computing report, 2024

¹⁵ https://www3.weforum.org/docs/WEF_Global_Risks_Report_2023.pdf

¹⁶ <https://www.forbes.com/councils/forbestechcouncil/2023/02/22/105-trillion-reasons-why-we-need-a-united-response-to-cyber-risk/>

¹⁷ <https://www.weforum.org/agenda/2024/02/3-trends-ransomware-2024/>

Governments and industries worldwide are currently weighing the necessary trade-offs, costs, and benefits of implementing regulations on semiconductor security¹⁸.

NEUROPULS' innovative integration approach of photonic physical unclonable functions (PUFs) into silicon photonics platforms, represents a significant step towards the development of secure, scalable solutions for edge computing applications and Internet of things (IoT). Deploying computing systems at the edge requires robust security layers to ensure essential services and functionalities, such as data confidentiality, integrity, and accelerator authentication between edge nodes and servers. Common strategies rely on cryptographic protocols, often storing secret keys in non-volatile memory (NVM), such as in the widely adopted AES (Advanced Encryption Standard) protocol. However, the possibility of accessing memory sectors through hardware and software vulnerabilities presents a significant risk, prompting the need for novel security technologies. Among the solutions currently under investigation, hardware primitives like PUFs offer a promising alternative to mitigate memory-based security attacks. PUFs enable real-time key generation without the need for permanent key storage, significantly reducing the attack surface associated with traditional memory. However, despite their potential, electronic-based PUF solutions are vulnerable to cybersecurity attacks, such as modelling and side-channel attacks. These limitations hinder their widespread deployment in edge systems¹⁹. Photonic PUFs are seen as a viable solution to this issue and able to finally bring about the technology for implementing secure, highly complex, yet fast and stable Strong PUFs in silicon (Figure 2). This approach offers superior resistance to attacks compared to traditional electronic PUFs, providing enhanced security through the unique properties of light-based systems. Compared to electronic PUFs, photonic PUFs offer a much richer physics and dynamics to exploit and can allow to achieve highly complex mixing of signals aside their analog propagation, in particular if non-linear phenomena are exploited. These aspects are key to their superior performance against ML attacks which can predict the behaviour of standard implementations of electronic PUFs e.g., XOR arbiter, with better than 99% accuracy²⁰. **However, the use of photonic solutions is often limited due to bulky equipment and/or lack scalability²¹.**

¹⁸ <https://www.weforum.org/agenda/2024/01/balance-regulating-semiconductors-global-security-technological-progress/>

¹⁹ Fabio Pavanello, Ian O'Connor, Ulrich Rührmair, Amy C Foster, Dimitris Syvridis. *Recent Advances in Photonic Physical Unclonable Functions*. 2021 26th IEEE European Test Symposium (ETS), May 2021, BRUGES, Belgium. ffl0.1109/ETS50041.2021.9465434ff. fflhal-03336585

²⁰ C. Zhou, K. K. Parhi, and C. H. Kim, *Secure and Reliable XOR Arbiter PUF Design: An Experimental Study based on 1 Trillion Challenge Response Pair Measurements*, in Proc. - Des. Autom. Conf., vol. Part 12828. Institute of Electrical and Electronics Engineers Inc., jun 2017

²¹ B.T. Bosworth et al. *Unclonable photonic keys hardened against machine learning attacks*, App. Phys. Lett. Phot., vol. 5, 010803, 2020, doi: 10.1063/1.5100178

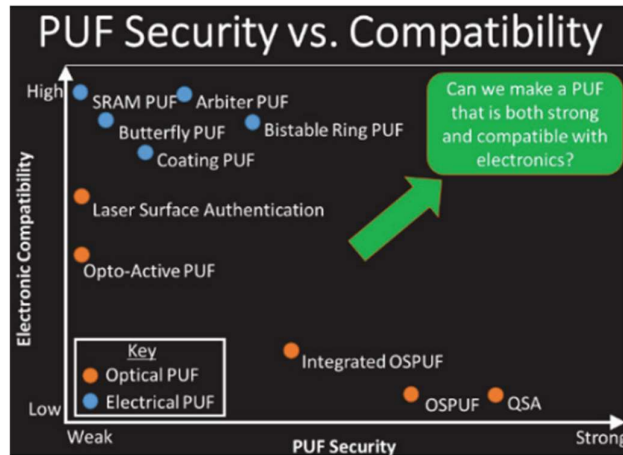


Figure 2: Qualitative perspective on relative strength and practicality of electronic and optical PUFs²²

The NEUROPULS project further advances the development and adoption of photonic PUFs by developing and experimentally realizing photonic PUFs in its enhanced CMOS-compatible silicon photonics platform. Specifically, the developed security layers will communicate by means of security protocols and HW/SW interfaces to a RISC-V processor and will be able to address key security features of the Photonic Neural Networks (PNNs) such as confidentiality, integrity, and authentication and non-repudiation of its outputs. These are essential features in cybersecurity systems and, more in general, systems addressing edge applications. **This would allow to further bring this technology from the laboratory to the market utilizing it for the first time to secure the operation of PNNs.**

Besides, the use of photonic PUFs in silicon photonics enables further increase in cost-efficiency gained from leveraging a common photonic architecture for multiple functionalities, such as PUFs and other silicon photonic components, i.e. sharing resources like the photonic light source helps reduce complexity and manufacturing costs. The investigated photonics PUFs can be also implemented in traditional CMOS platforms, which would however imply higher costs.

1.4 Fostering European Technological Sovereignty

The EU’s digital strategy aims to make the digital transformation work for people and businesses, while helping to achieve its target of a climate-neutral Europe by 2050. Its aim is to make this period **Europe’s “Digital Decade”** by putting its strategic focus on strengthening the EU digital sovereignty and set standards, rather than following those of others – with a clear focus on data, technology, and infrastructure. Given the current landscape and **the potential that photonics has to enhance innovation in several industries** (digital, automotive, health, etc), it has been **recognized as one of Europe’s key enabling technologies (KETs)** for

²² Fabio Pavanello, Ian O’Connor, Ulrich Rührmair, Amy C Foster, Dimitris Syvridis. *Recent Advances in Photonic Physical Unclonable Functions*. 2021 26th IEEE European Test Symposium (ETS), May 2021, BRUGES, Belgium. f10.1109/ETS50041.2021.9465434ff. f10.1109/ETS50041.2021.9465434ff. f10.1109/ETS50041.2021.9465434ff

the 21st Century. The **EU Chips Act** also highlights the need to address semiconductor shortages and strengthen Europe’s technological leadership, **mobilising more than €43 billion of public and private investments** and setting measures to prepare, anticipate, and swiftly respond to any future supply chain disruption. At the same time, **the need for more efficient and energy-saving semiconductors** has fostered growing global interest in the development of **alternative technologies, such as silicon photonics**. This trend is particularly noticeable in the US and China²³²⁴.

Some of the EU research pilot line projects conducted under the Photonics partnership on scaling up PIC production in Europe are presented in Figure 3.



Figure 3: EU Pilot line projects concerning photonics²⁵

Besides, Photonics Partnership triggered a variety of PIC activities in Horizon 2020 and Horizon Europe, including about 35 PIC projects that have been/are currently funded (last 5 years), with the total budget of about € 190 million²⁶.

In this regard, **NEUROPULS is well aligned with the European sovereignty strategy and contributes to the strengthening of common technological ground in the EU, regarding not only semiconductors and silicon photonics but also other strategic digital areas as cybersecurity, AI and GenAI, edge computing and green IT**. The project's pioneering results and proofs of concept aim to drive industrial adoption and commercialization of these technologies across various sectors. By developing specialized European processors, architectures, and computational engines, NEUROPULS seeks to reduce reliance on non-European

²³ <https://www.photonics21.org/2024/experts-urge-cu-to-increase-investment-in-photonics-or-risk-falling-behind-china>

²⁴ <https://www.csis.org/analysis/controlling-light-silicon-photonics-emerging-front-us-china-tech-competition>

²⁵ https://www.photonics21.org/download/ppp-services/photonics-downloads/Keynote_Pierre_Chastanet_European_Commssion_final.pdf?m=1717577833&

²⁶ https://www.photonics21.org/download/ppp-services/photonics-downloads/Keynote_Pierre_Chastanet_European_Commssion_final.pdf?m=1717577833&

providers, address the limitations of current CMOS-based platforms, improve energy efficiency (performance per watt) for edge applications, and enhance security over critical technology infrastructure.

More precisely, the NEUROPULS project will directly or indirectly influence **various strategic areas of technological development in the EU** such as (see Figure 4):

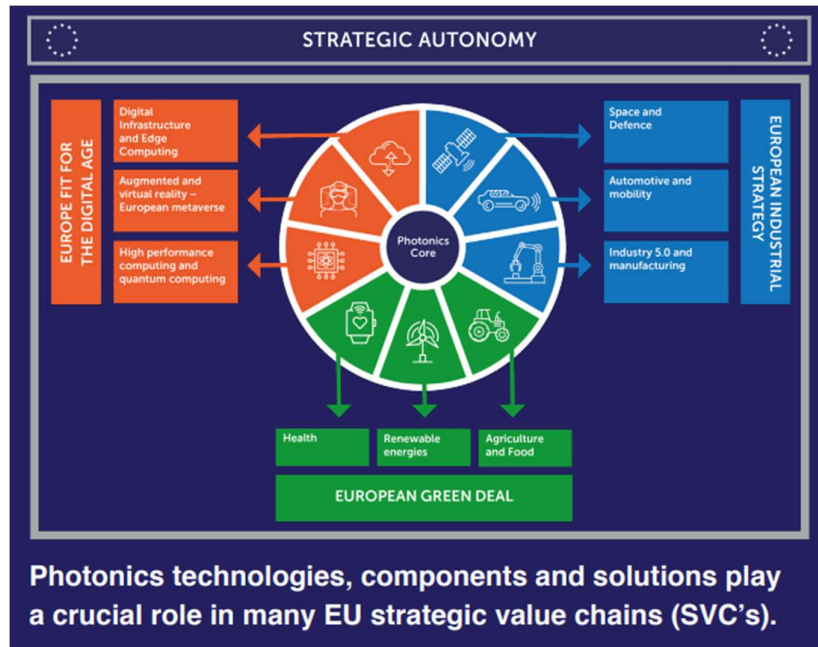


Figure 4: Strategic areas of technological development in the EU related to photonics. ²⁷

- **European Green Deal²⁸**: NEUROPULS addresses the EU's call for ultra-low-power, secure processors for edge computing (RIA)²⁹, as part of the broader initiative on Digital and Emerging Technologies for Competitiveness and Fit for the Green Deal. **By driving innovation in photonic information processing, NEUROPULS is expected to have a transformative impact on the development of HPC and AI, significantly reducing power consumption and enhancing sustainability in these fields.**
- **Digital Infrastructure and edge computing**: NEUROPULS accelerator aims to enable energy-efficient and secure processing at the edge, while addressing energy consumption issues in edge devices. In this way, **NEUROPULS contributes to EU's goal of enhancing digital infrastructure while minimizing the carbon footprint of connected systems.** This initiative is particularly pertinent

²⁷ Photonics Industry Supply Chain Survey 2023. Photonics21, April 2023

²⁸ https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

²⁹ <https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl4-2021-digital-emerging-01-01>

given the expected increase in the number of edge computing devices, projected to rise from 2.7 billion to 7.8 billion between 2020 and 2030³⁰.

- **High performance computing and quantum computing:** Neuromorphic architectures, such as those developed in NEUROPULS, offer an alternative to traditional HPC systems by allowing data processing in a brain-inspired manner, which could be more efficient for specific AI and machine learning tasks. Photonics is poised to play an important role in this rapidly growing field. Leading companies like NVIDIA and Intel are significantly investing in the silicon photonics ecosystem, recognizing its role in supporting large language models (LLMs) and generative AI. By integrating silicon photonics and phase-change materials (PCMs), **NEUROPULS aims to deliver high computational performance with minimal energy use, which is crucial for large-scale HPC applications, e.g., trajectory prediction in autonomous driving.**
- **Augmented and virtual reality:** NEUROPULS' research on silicon photonics and photonics PUFs can significantly advance augmented reality (AR), virtual reality (VR), and the metaverse by **enabling high-speed and secure data transmission**, which is crucial for real-time interactions and high-resolution visuals. Additionally, silicon photonics enhances optical sensors and LIDAR technology for accurate tracking and mapping, while its low power consumption benefits battery-operated devices.
- **European industrial strategy:** NEUROPULS is also aligned with the European industrial strategy, e.g., through its work on photonics Physical Unclonable Functions (PUFs) which falls within the EU's focus on cybersecurity and data protection (GDPR³¹, CRA³², etc.). This technology is especially relevant for critical industry-specific applications in edge computing, in sectors such as:
 - ✓ Automotive: Enhancing anomaly and intrusion detection in vehicle networks to improve safety and security.
 - ✓ Space and Defence: Tackling challenges related to Global Navigation Satellite System (GNSS) radio frequency signals, which are critical for both military and civilian operations.
 - ✓ Industry 5.0: ensuring robust security for sensitive information and enhancing data integrity in manufacturing and critical infrastructure.

2. Economic impact

The economic impact of the NEUROPULS project is poised to be substantial, especially as it aligns with Europe's digital transformation and drives for technological sovereignty. The enabled technological innovations will catalyze growth in crucial sectors such as **AI, edge computing, IoT**, and **cybersecurity**, while also creating new opportunities for European industries.

³⁰

<https://transformainsights.com/news/edge-computing-rapid-growth-iot#:~:text=New%20Transforma%20Insights%20reports%20covering,edge%20capabilities%20in%20IoT%20devices.>

³¹ General Data Protection Regulation

³² European Cyber Resilience Act

2.1 Boost to European market expansion

As shown above, the semiconductors industry is an important pillar of the future of European technological sovereignty and economic prosperity. A variety of measures and incentives have been put in place at the EU level to boost this industry. In the light of increasing demand for more efficient and energy-saving semiconductors, there has been a growing global interest in the development of alternative technologies, such as silicon photonics.

Today, silicon photonics is a small subset of the \$700B silicon IC industry³³. The silicon photonics market (PIC dies) is expected to undergo a significant increase in volumes to cover a **total addressable market (TAM) of \$600M by 2028**, addressing several domains such as datacom, telecom, automotive, health, and environment monitoring with **an expected CAGR of 44% over the 2022-2028 period**³⁴.

Meanwhile, according to the Optical Computing Report published by Yole Group (2024), the **optical computing market is nascent** and most of the initiatives are on the R&D stage, with new optical computing start-ups constantly emerging with diverse approaches. Yole Intelligence anticipates that initial shipments of optical processors will commence in 2027, primarily generating Non-Recurring Engineering (NRE) revenues. Following a period of market acceptance, direct sales of general-purpose systems are expected to begin a few years later. This transition is projected to drive significant growth in the optical processor market, potentially reaching **\$3 billion by 2034, with a CAGR₂₀₂₇₋₂₀₃₄ of 101%** (see **Erreur ! Source du renvoi introuvable.**).

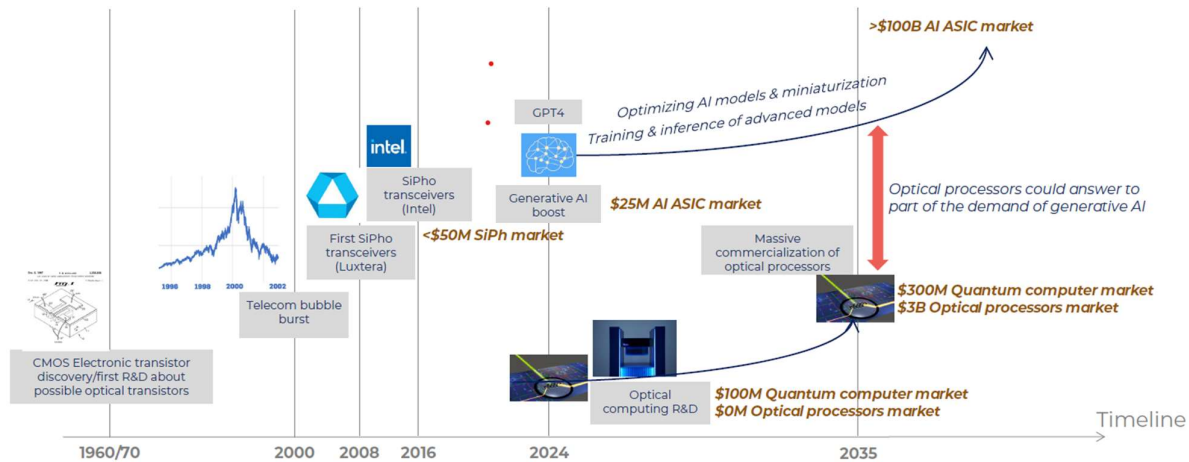


Figure 5: Key moments for the computing field since 1960³⁵

Although this market is still emerging, it holds significant strategic importance and should not be overlooked. Its potential to drive technological innovation and stimulate growth in critical sectors such as AI, edge computing, IoT, cybersecurity, and quantum computing is substantial. According to the aforementioned

³³ https://photonicsmanufacturing.org/sites/default/files/documents/2024_ipsr-i_silicon_photonics_updated_v2.pdf

³⁴ Silicon Photonics 2023. Market and Technology Trends Report. Yole Intelligence, November 2023.

³⁵ Yole, Optical Computing report, 2024

Yole report, **about 1 million (optical computing) units will be delivered in 2034 for AI applications.** Initially, optical processors are expected to have a higher average selling price (ASP) compared to AI ASICs. However, **as production volumes increase and sales to Original Equipment Manufacturers (OEMs) grow, the ASPs of optical processors will gradually decrease.**

In the context of the silicon photonics market, **NEUROPULS is poised to deliver innovations in device design, compactness and reconfigurability, resulting in greater efficiency and cost reduction.** For example, the fabrication cost of a fully packaged chip is anticipated to drop below €100 in large-scale production, whereas current prices for foundry integration platforms range from \$800 to nearly \$10,000 per mm², depending on the complexity of the offering^{36,37}. Moreover, given the modest size of the current silicon photonics market, leveraging existing CMOS fabs with mature processes is economically prudent. This approach will allow to avoid the need for significant capital investment in building dedicated silicon photonics fabrication infrastructure^{38,39}, fostering further market development.

At the same time, the impact of the NEUROPULS project will extend beyond the silicon photonics market. It will also foster the development of other sectors, such as neuromorphic computing, AI, IoT, edge computing, and cybersecurity:

- ✓ In 2023, the **global neuromorphic computing market** was valued at approximately USD 92.45 million. This market is forecasted to expand significantly, reaching **about USD 139.29 million in 2024 and projected to grow to USD 672.06 million by 2028**, reflecting an impressive CAGR of 48.2%. North America led the global market in 2023, holding a dominant share of 32.31%⁴⁰. **NEUROPULS will contribute to the further development of European neuromorphic computing research and community building, paving the way for unexplored research paths and approaches. This is expected to strengthen Europe's position in the market.** Its innovative platform will provide a series of novel building blocks that will find useful applications in next-generation photonic systems for unconventional computing, but also for applications such as quantum computing therefore providing a route for fast prototyping of advanced systems.
- ✓ According to the IDC Worldwide AI and Generative AI Spending Guide, presently, **the global AI market stands at nearly \$235 billion, with projections indicating a rise to over \$631 billion by 2028**, with a CAGR of 29.0%⁴¹; meanwhile **the European AI market is projected to hit \$47.6 billion in 2024**, with a CAGR of 33.7% over 2022-2027⁴². Europe represents around one-fifth of the global AI market⁴³. **One of key drivers for silicon photonics and neuromorphic computing markets lies in solving AI's data bottleneck.** The AI revolution has brought a range of technical challenges in its

³⁶ Yole, Silicon Photonics report, 2023

³⁷ Siew, S. Y., Li, B., Gao, F., Zheng, H. Y., Zhang, W., Guo, P., Xie, S. W., Song, A., Dong, B., Luo, L. W., Li, C., Luo, X., & Lo, G.-Q. (2021). Review of Silicon Photonics Technology and Platform Development. *Journal of Lightwave Technology*, **39**(13), 4374–4389. <https://doi.org/10.1109/JLT.2021.3074605>

³⁸ Rahim, A., Spuesens, T., Baets, R., & Bogaerts, W. (2020). Open-Access Silicon Photonics: Current Status and Emerging Initiatives. *IEEE Journal of Selected Topics in Quantum Electronics*, **26**(5), 1-12. <https://doi.org/10.1109/JSTQE.2020.2977474>

³⁹ https://www.optica-opn.org/home/articles/volume_26/july_august_2015/departments/breaking_the_cost_barrier/

⁴⁰ <https://www.fortunebusinessinsights.com/neuromorphic-computing-market-108240>

⁴¹ <https://www.idc.com/getdoc.jsp?containerId=prUS52530724>

⁴² <https://www.idc.com/getdoc.jsp?containerId=prEUR251966524>

⁴³ <https://www.idc.com/getdoc.jsp?containerId=prEUR251966524>

wake, particularly when it comes to LLMs and other state-of-the-art AI algorithms. These models require vast datasets and computational power for training, which strains current hardware and infrastructure. **NEUROPULS will have a significant impact on solving this conundrum by developing solutions that can enhance data transfer speeds and efficiency, reducing the energy consumption, and enabling faster training and deployment of advanced AI systems.**

- ✓ The rapid growth of the IoT market across various industrial sectors, such as aerospace, automotive, and defence, is expected to drive demand for neuromorphic chips. **Silicon photonics has the potential to significantly enhance AI integration in edge applications, where IoT devices can fully capitalize on energy-efficient machine learning capabilities.** This is due to the superior performance of photonic accelerators, which offer improved data processing speeds and improved energy efficiency thanks to the use of optical signals. These advancements could enable IoT devices to process complex AI tasks locally, reducing reliance on cloud infrastructure and allowing for faster, more efficient and secure operations in real-time applications.

According to the latest release of the Worldwide Internet of Things Spending Guide published by IDC, **European organizations are projected to invest approximately \$260 billion in IoT-related solutions in 2024. IDC predicts that IoT spending growth will gradually pick up momentum in 2024 and beyond with the recovery of the European economy, recording a five-year compound annual growth rate (CAGR) of 11.8% and reaching almost \$368 billion by 2027⁴⁴.** At the global scale, IDC forecasts investments in the IoT ecosystem to surpass \$1 trillion in 2026 with a compound annual growth rate (CAGR) of 10.4% over the 2023-2027 forecast period. All this also explains the growing size of **the addressable market for edge computing**. IDC forecast the worldwide spending of enterprises and service providers on **hardware, software, and services for edge solutions** is estimated to reach \$228 billion in 2024, marking a 14% increase from 2023, and to reach **\$378 Billion in 2028** driven by demand on real-time analytics, automation, and enhanced customer experiences⁴⁵. NEUROPULS' work on developing a novel, low-power, secure accelerator powered by silicon photonics will have a significant impact on the evolution of this market, fostering further innovation and growth.

- ✓ NEUROPULS is also positioned to make **a significant impact on the cybersecurity market**, particularly through its development of photonic Physical Unclonable Functions (PUFs). These PUFs implemented in integrated circuits can be used in applications with high-security requirements, more specifically cryptography, Internet of Things (IoT) devices and privacy protection. **This, in turn, will foster the respective cybersecurity markets growth. Gartner predicts an increase of 15.1% from 2024 in the worldwide end-user spending on information security to reach the total \$212 billion in 2025⁴⁶.** Gartner projects that the **IoT cybersecurity market** will experience significant growth, **potentially reaching billions in value by 2028**. This growth is primarily driven by the increasing

⁴⁴ <https://www.idc.com/getdoc.jsp?containerId=prEUR251780724>

⁴⁵ <https://www.idc.com/getdoc.jsp?containerId=prUS52587424>

⁴⁶ <https://www.securityworldmarket.com/me/News/Business-News/gartner-predicts-a-spike-in-cyber-security-spending-in-20251>

adoption of IoT devices across various sectors and the urgent need for enhanced security measures in connected technologies. Additionally, new regulatory initiatives, such as **the European Commission's Cyber Resilience Act**, are expected to bolster IoT security standards, creating a more robust framework for protecting these devices.

The NEUROPULS project will significantly influence industry-specific cybersecurity markets, including **the automotive cyber security market which is projected to grow to \$9.7 billion by 2030⁴⁷** and **defence cybersecurity market**. Currently, the defence industry is experiencing a surge in military **spending on GNSS anti-jamming systems**, driven by increasing number of geopolitical conflicts and a growing reliance on GPS and other navigational and positioning systems. This demand for enhanced security measures is escalating at an unprecedented rate across various platforms, including airborne, naval, ground, and unmanned systems⁴⁸.

- ✓ Last but not least, the NEUROPULS will have an impact on **several markets focused on that are already operating in the optical domain** as in light detection and ranging (LIDAR) devices for autonomous driving, fiber optics for datacom/telecom and fault detection, and potentially microwave photonics for RF signal processing, such as in GNSS anti-jamming systems.

2.2 Creation of a more robust and innovative silicon photonics chain in Europe

As NEUROPULS addresses key aspects of the digital supply chain - **from chip fabrication to software programming** - it will directly or indirectly contribute to strengthen Europe's position in **the silicon photonics value chain**, while fostering a **broader acceptance of the technology, and its adoption by the ecosystem in order to support market uptake**.

Currently, a large part of global silicon photonics industry is focused on optical communication, which is shaped by a diverse array of participants, including major vertically integrated players like Intel, Cisco, Marvell, Broadcom, Nvidia, and IBM; startups such as AyarLabs, OpenLight, Lightmatter, Saliency Labs, iPrionics, and Lightelligence, research institutions like UCSB, Columbia University, Stanford Engineering, CEA Leti, A*Star and MIT; foundries like GlobalFoundries, Tower Semiconductor, Imec, and TSMC, and equipment suppliers like Applied Materials, ASML, and Aixtron (Figure 6). In Europe, the main silicon photonics players include STMicroelectronics, Soitec, GlobalFoundries, Imec, X-FAB, Sicoya, CEA Leti and a variety of academic and research institutions (CNRS, EPFL, etc.). The actors all around the supply chain have been showing growing interest in the silicon photonics technology and have been doing some innovative research in the area.

⁴⁷ McKinsey's "Cybersecurity in automotive: Mastering the challenge" report, March 2020

⁴⁸ <https://www.alliedmarketresearch.com/military-gnss-anti-jamming-systems-market-A13468>

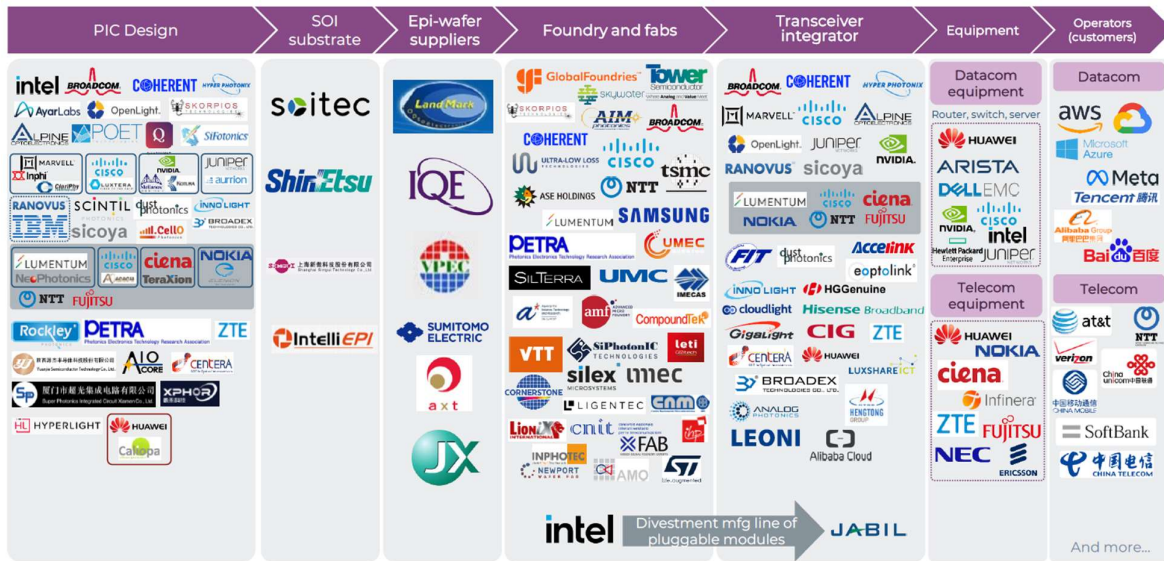


Figure 6 Silicon photonics value chain for optical communication⁴⁹

The optical computing domain, which is still at the very early stage of its development, currently does not have a clearly established value chain. Its market landscape is continuously evolving, characterized by ongoing R&D, strategic alliances, and collaborations. The Figure 7 depicts an ongoing evolution of photonics from communication towards computing, accompanied by the emergence of new market players, working on different types of optical computers, such as analog optical processors, digital optical processors and quantum.

⁴⁹ Silicon Photonics 2023. Market and Technology Trends Report. Yole Intelligence, November 2023.

PHOTONICS, FROM COMMUNICATION TO COMPUTING

An history of 60+ years when photon is becoming smarter and smarter

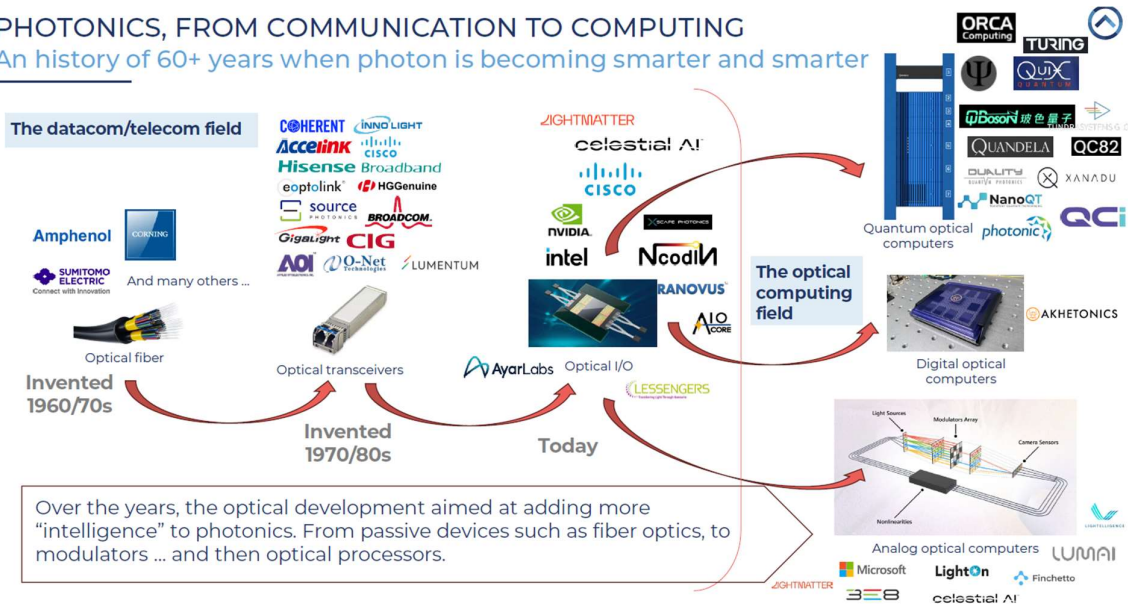


Figure 7 Photonics, from communication to computing⁵⁰

From a broader perspective of the silicon photonics market landscape, photonic integrated circuit (PIC) designers play a crucial role in market development. Intel emerges as a leader, making significant investments in R&D and fostering strategic collaborations. In February 2022, the company acquired Israeli semiconductor solution foundry Tower Semiconductor in a deal worth \$5.4 billion, and in October 2024, unveiled a strategic initiative to sell its pluggable optical transceiver product lines based on silicon photonics technology to Jabil that will take on the manufacturing and deploying of silicon photonics components and modules on behalf of Intel. In 2024, Intel unveiled its own optical compute interconnect (OCI) chiplet⁵¹. The chiplet combines two copackaged systems—a PIC with embedded waveguides, amplifiers and dense wavelength-division multiplexing lasers, and an electronic integrated circuit with control circuitry and drivers. The company has also showed its interest in investing in the EU semiconductor market and photonics silicon market. For example, in 2022, Intel announced its intention to make an initial investment of over EUR 33 billion for R&D and manufacturing in the EU. The investments would span over France, Germany, Ireland, Italy, Poland and Spain. However, recently, Intel has shelved French and Italian chip investments in the R&D center in France has been postponed due to economic and market conditions that had changed significantly since 2022 while "focusing on its active manufacturing projects" in Ireland, Germany and Poland.

⁵⁰ Yole, Optical Computing report, 2024

⁵¹ Silicon Photonics 2023. Market and Technology Trends Report. Yole Intelligence, November 2023. https://www.optica-opn.org/home/articles/volume_35/september_2024/features/photonics_and_ai_industry_perspectives/

Semiconductor foundries, too, are in the game. For example, **GlobalFoundries (GF)**⁵² has been developing its silicon photonics platform, GF Fotonix, as a solution for building AI-focused photonic interconnect solutions; Taiwan Semiconductor Manufacturing Company (**TSMC**) has been working with Broadcom and Nvidia to develop silicon photonics and co-packaged optics (CPO)⁵³. In April 2024, TSMC also unveiled its own silicon photonics roadmap. The potential of integrated photonics was also illustrated by **Nokia**'s recent announcement that it would acquire optical networking and PIC firm **Infinera** for the sum of US\$2.3 billion.

Meanwhile **numerous startups focus on specific applications or novel technologies contributing to significant growth and diversification of the market**. A Silicon Valley-based **Ayar Labs** developed a chiplet (TeraPHY), designed to be integrated in-package with the electronic GPUs or CPUs and engaged in a wide variety of partnerships to propel use cases forward, with firms including the GPU maker NVIDIA, the Swedish telecom firm Ericsson, American companies such as Lockheed, Lumentum, the US Department of Defense, and Intel Corp. for their own silicon photonics solutions for AI. A US start-up, **Lightmatter** has been working on advancing a broader vision of photonics for AI, embracing both optical interconnects for handling AI data and accelerator chips to speed up the actual calculations of computational neural networks. The company's most recent round of fund raising, in December 2023, pushed the firm's total valuation to US\$1.2 billion—putting it firmly in “unicorn” territory⁵⁴. Besides, **the total value of the investments in optical computing in the past five years amounts to \$3,569.13M**. Figure 8 shows this investment by technology and main players.

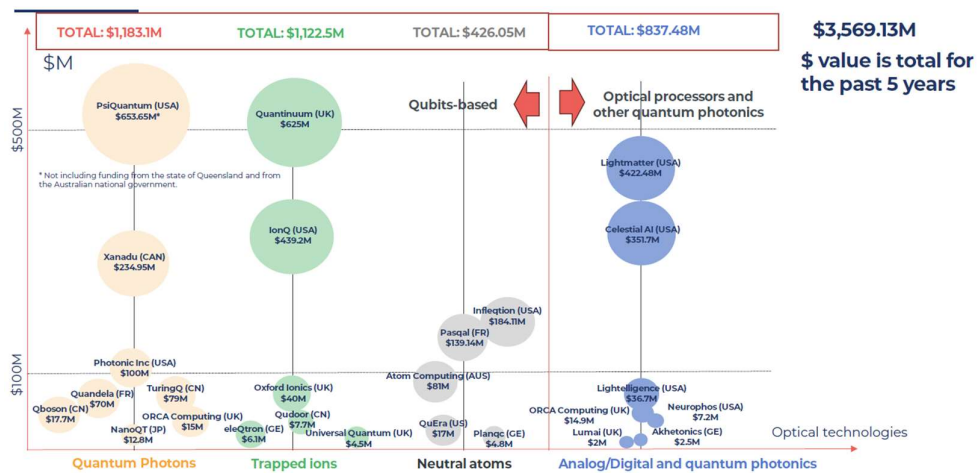


Figure 8: Investments in optical computing⁵⁵

















⁵² GF Fotonix is a 300-mm monolithic silicon technology platform, enabling co-packaged optics and supporting 200 Gbps per wavelength in the C, L and O bands.

⁵³ <https://technode.com/2023/09/12/tsmc-cooperates-with-broadcom-and-nvidia-to-develop-advanced-silicon-photonics-technology-report/>

⁵⁴ https://www.optica-opn.org/home/articles/volume_35/september_2024/features/photonics_and_ai_industry_perspectives/

⁵⁵ Yole, Optical Computing report, 2024

Regarding the **EU startups**, in the past four years, a number of startups working in the area of silicon photonics (PIC design and manufacturing, quantum photonics, photonic processors, etc.) **have emerged and led notable funding rounds, with some of them** listed below (more details in Annex 1).

> \$100,000,000	\$100,000,000 – 10,000,000	< \$10,000,000	< \$1,000,000
 	  	         	

Private ventures play a significant role in developing an innovative network for silicon photonics. For example, **PhotonVentures’** investment strategy leverages **the Dutch PhotonDelta ecosystem** to accelerate European startups and scaleups. In summer 2023, PhotonVentures⁵⁶ has launched a fund aimed at early-stage photonic chip startups and scale-ups, aiming to raise **a total of €100 to €150 million by 2024**. Last year, PhotonDelta secured **€1.1 billion in public and private investment to scale up production, build 200 startups, create new applications for photonic chips and develop infrastructure and talent**⁵⁷.

Other **strategic collaborations at the European level intended to boost the silicon photonics technology industry scale up by bridging the gap between laboratory and fabrication include:**

⁵⁶ an independent deeptech VC firm that has emerged from PhotonDelta, the pioneering force behind the Dutch integrated photonics ecosystem

⁵⁷ <https://www.eu-startups.com/2023/08/eindhoven-based-photonventures-raises-e60-million-to-invest-in-15-european-photonics-startups/>

- A strategic partnership of Hamamatsu Photonics Europe with Vrije Universiteit Brussel formed in April 2024 to drive photonics innovation⁵⁸. Key areas of collaboration include providing support to companies in photonics feasibility studies, proof-of-concept demonstrations, prototyping, and quality control.
- Photonics4industry Partnership⁵⁹ that aims to strengthen cluster management excellence, create exchange opportunities and build a sustainable pan-European strategic partnership of 5 photonics clusters to accelerate industrial modernization, particularly enhancing the competitiveness of small and medium-sized enterprises (SMEs) members.
- The Integrated Photonic Systems Roadmap-International (IPSR-I), a collaborative program organized by PhotonDelta and the MIT Microphotonics Center (MIT-MphC), aiming to raise €236million, between 2019 and 2026 to provide partners with access to research, knowledge, and business development in the field.

This dynamic once again highlights the attractiveness and potential of silicon photonics for industry, as well as its competitiveness.

NEUROPULS project may lead to the creation of a spin-off or a startup to contribute to developing the silicon photonics value chain in the EU. It can also enable the further take-up of innovation at a global scale through the sale of the project's findings and technology by means of licensing agreements to companies such as AyarLabs, OpenLight, Lightmatter, Saliency Labs, Lightelligence, and others. This will contribute to strengthening the EU positioning in the silicon photonics market. **Besides, some of the members of the consortium have extensive experience with startups, having been helping to launch and scale startups for decades.** For instance, CEA-Leti has successfully transferred silicon photonics technologies to the market, exemplified by its two startups, SteerLight and Scintil Photonics.

The NEUROPULS project should also create the synergies with other European initiatives intended to boost the development and commercialization of silicon photonics such as photonixFAB, an EU €48-million, 3.5-year project, launched in June 2023. The project aims to establish a European photonics device value chain and initial industrial manufacturing capabilities to drive forward photonic product innovation while laying a clear path to high-volume manufacturing. The project is being supported by the Key Digital Technologies Joint Undertaking (KDT JU)⁶⁰, with funding from the EU and the national authorities, and includes key players like Nokia, Nvidia, Ligentec, imec and CEA-Leti. Furthermore, the **PhotonHub Europe**⁶¹, leveraging a budget of about 19 million euros, is aimed to **facilitate the collaborative efforts of startups with partner research institutes across Europe**, providing “test before invest services”⁶².

⁵⁸ <https://www.hamamatsu.com/eu/en/news/press-releases/2024/strategic-partnership-with-vrije-universiteit-brussel-to-drive-photonics-innovation.html>

⁵⁹ <https://photonicsbw.de/projekte/photonics4industry/>

⁶⁰ Le Chips Joint Undertaking (Chips JU) est un partenariat public-privé qui soutient les activités de recherche et d'innovation dans les technologies en matière de **composants et systèmes électroniques**

⁶¹ <https://www.photonhub.eu/applications/digital-infrastructure/>

⁶² <https://www.photonhub.eu/>

Moreover, the test ecosystem in the domain of silicon photonics is currently emerging, and partnerships are being set up (for example, FormFactor collaborates with Keysight and GlobalFoundries to deliver Si photonic testing solutions)⁶³. The lack of testing standards and simulation platforms may hinder the scaling of silicon photonics markets. NEUROPULS aims to address this by providing clear benchmarking guidance for several important use cases in defence and automotive sectors.

Besides, as the optical computing's market is nascent, the maturity of the silicon photonics Process Design Kits (PDKs) owned by R&D fabs and low volume fabs has typically not reached the level of a CMOS IC foundry. They contain libraries of basic building blocks, especially for the MPW-mode of operation. The NEUROPULS project can foster collaboration on the silicon photonics Process Design Kits (PDKs) by sharing its PDK for novel silicon photonics building blocks with existing Electronic Design Automation (EDA) or similar actors under a license to enable the adoption of this technology at scale.

Finally, one of the strengths of NEUROPULS project is its emphasis on the involvement of the end user industries and RTOs (HPE, Algora, BSC) that helps to establish the links with several core industrial segments and ensures expedited market uptake of innovation. NEUROPULS' comprehensive approach should allow to move from the basic research underpinning these different areas with a Technology Readiness Level (TRL) of 2 and 3 to their deployment as fully packaged compact prototypes in relevant application scenarios such as the AI-inspired use-cases identified above leading to an expected TRL of 5. The developed prototypes will allow to potentially scale to large volume manufacturing by ensuring that all the technological steps are carried out with the goal of market take up of NEUROPULS' technology thanks to a high relevance of the investigated 3 use-cases for the industry, namely (i) for **interference detection and filtering in GNSS anti-jamming systems**, (ii) for **trajectory prediction in autonomous driving**, and (iii) for **anomaly detection in edge computing devices and systems**.

All this is proof that the research is of strategic importance and shows an acceleration towards commercialization of silicon photonics and its applications. **The innovations enabled by NEUROPULS on the material, device, hardware and software levels are well positioned to support and intensify the creation of a more robust and innovative silicon photonics chain in Europe.**

2.3 Job Creation and Skills Development

NEUROPULS plays a crucial role in advancing various silicon photonics-related fields, contributing to the creation of high-skilled jobs across Europe, particularly in research and development, engineering, and manufacturing within the photonics and semiconductor industries.

The project's emphasis on **CMOS compatibility** ensures that new technologies leverage existing semiconductor manufacturing processes, therefore minimizing costs and improving scalability. This

⁶³ Silicon Photonics 2023. Market and Technology Trends Report. Yole Intelligence, November 2023.

integration will **generate job opportunities across the technology supply chain**, supporting the widespread commercial deployment of silicon photonics. **A skilled workforce will be critical to the success of this endeavor. However, there is a significant gap:** the current global workforce of technicians and engineers in silicon technology lacks exposure to photonics, while the similarly large photonics workforce is not well-versed in silicon photonics⁶⁴. **This results in a shortage of skilled professionals, such as manufacturing technicians, design and test engineers, technology developers, PDK specialists, and system integration experts.**

In a broader perspective, optics and photonics offer excellent career prospects for graduates and professionals, with opportunities in research and development across industries such as data communications, sensing technologies, medical imaging, renewable energy, and manufacturing. Professionals in these fields are at the forefront of technological advancements, driving global innovation.

Some European institutions are already working to address the skills gap. For instance, the MasterPlus Programme in Optics & Photonics, developed by three Dutch universities in partnership with PhotonDelta and Optics Netherlands, offers specialized training within master's programs to cultivate the necessary workforce. The Photonic Integrated Circuits, Sensors and NETWORKS (PIXNET) Erasmus Mundus Joint master's degree is aimed at training talented students in the design, creation and assessment of innovative integrated devices based on photonic technologies⁶⁵.

Photonics also plays a pivotal role in creating more energy-efficient ICT solutions. Optical networking is expected to be essential in meeting growing ICT demands while reducing energy consumption, paving the way for a sustainable, green, knowledge-based society.

The synergy between NEUROPULS and other research initiatives, enhancing the performance of neuromorphic processors, will foster the development of new AI applications. This growth will drive demand for advanced computing solutions, leading to job creation in technology development, manufacturing, and support services.

Additionally, the photonics industry adds value to **established sectors like telecommunications, healthcare, industry 4.0, automotive, and chemicals** by advancing networking technologies, thereby **bolstering these traditional industries and securing jobs in Europe.**

3. Scientific impact

3.1 Advancement of Fundamental Knowledge

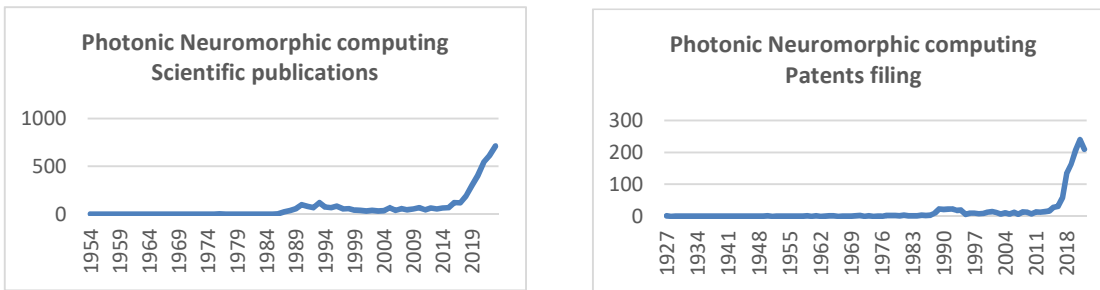
The EU aims to maximize the social and economic value of research and innovation in Europe. Sharing knowledge and improving uptake of research and innovation results by society is a key part of the Commission's proposal to revitalize the European Research Area.

Photonic neuromorphic computing has sparked a wave of new research, and consequently an increasing number of scientific publications. Performing a bibliometric study, we can notice that this number has been

⁶⁴ https://photonicsmanufacturing.org/sites/default/files/documents/2024_ipsr-i_silicon_photonics_updated_v2.pdf

⁶⁵ <https://www.santannapisa.it/it/istanza-master/master-photonic-integrated-circuits-sensors-and-networks>

accelerating since 2017, with a CAGR of +35% between 2017 and 2023. The number of patents has also grown in the same period with a CAGR of +24% (between 2017 and 2022).



Source: Internal analysis, IPMETRIX tool

Figure 9 : R&D indicators for photonic neuromorphic computing technology

NEUROPULS contributes to these general dynamics in the scientific community by advancing fundamental knowledge in photonics and semiconductor physics, particularly in the integration of photonics on silicon platforms. At the same time, NEUROPULS’ interdisciplinary approach will allow to reach a larger network of scientific community, **coming from several research fields such as material science, device physics, photonics, electronics, computer architectures, ML algorithms, software development, and security**. In fact, a strong interaction of material science development and photonic device physics will firstly allow to realize the novel photonic building blocks. From these functional blocks, novel photonic architectures and security primitives will be built and hardware description language interfaces will be developed for PNN driving. This will allow to investigate novel training algorithms as well as novel computing schemes for enhanced efficiency.

The project focus on the system-level development of a parallel simulation platform leveraging PNN models and security layer models would also contribute to enhancing and distributing the **knowledge related to photonic-based PUFs**. Currently, electronic PUF are the main HW security primitive widely accepted by the broad scientific community due to the numerous works present in literature and their native CMOS compatibility. NEUROPULS aims to demonstrate the advantages of photonic PUFs in relevant applied scenarios and in CMOS-compatible platforms. This is intended to **steer the broad R&D community approach towards novel, non-electronic, particularly photonic solutions with a larger degree of strength against e.g., ML attacks**.

Looking at bibliometric indices using IPMETRIX tool, we can see that only 20 organizations have published 1468 documents out of 4825 scientific publications. These organizations include **ACAD CHINESE SCI**, in the first ranking (122 publications), followed by American universities: **University of CALIFORNIA** (118), **PRINCETON university** (109), **MIT** (91), **STANFORD university** (84) and **University of G. WASHINGTON** (81). Many Chinese universities are as well present within this niche group in lower positions (**Beijing, Xidian, Huazhong, Shanghai, Tsinghua...**). In the European ecosystem, we can identify **CNRS**, **university of Aristotle of Thessaloniki (Greece)** and **University of Strathclyde (UK)**, followed by **University of Ghent (Belgium)**.

Therefore, the NEUROPULS’ publishing and patent efforts will contribute to **strengthening the EU positioning in cutting-edge research related to silicon photonics and neuromorphic computing**, which is

currently dominated by publications and patents coming from Chinese and American researchers, and thus also strengthen the general position of the EU in this emerging field, making it more competitive and attractive for investments.

The project has already resulted into a number of patents on these strategic topics, including:

- Patent filed on how to adjust reliably weights with a single heater (**CNRS**)
- Patent filed about methods to achieve faster cooling for PCM-based devices (**CNRS, CEA-LETI**)
- Patent in filing about a chiplet approach to connect different photonic chips with different characteristics (**CNRS, ARGOTECH, CEA**)
- Patent on security protocols for encryption and system identification based on PUFs + software protection solutions to secure the software components interacting with the neuromorphic processor (**UNIV OF VERONA**).

3.2 Contribution to promoting open science practice

The EU promotes an approach to the scientific process that focuses **on spreading knowledge as soon as it is available using digital and collaborative technology**, expert groups, publications, news and events. NEUROPULS contributes to this common endeavor by providing **open access** to its **technical, professional, and scientific publications**. NEUROPULS leverages “gold” and “green” Open Access publishing models to increase public access to scholarly research. During this report period, there have been already about 20 publications⁶⁶ including in publicly available pre-print repositories such as arXiv Zendo, and ResearchGate, as well as in well-respected publishing venues under IEEE and OSA publishing groups.

Meanwhile, the broader awareness of the project and its results is also enhanced through the regular participations in relevant international conferences (more than 20 events up to the date) and events as well as in communicating on the project and challenges it aims to address through newspaper articles and social media posts, e.g., on LinkedIn and X⁶⁷.

Similarly, technical as well as other professional information will be deposited in the **European Open Science Cloud (EOSC)** enabling storage, sharing, processing, analysis, and re-use of research outputs across borders and disciplines. The use of the EOSC and other trusted repositories for sharing data, - e.g., benchmarking on material, device, models, architecture and system levels, - will contribute to a common European effort to:

- **Enhance the transparency and reproducibility of research.** Other scientists can validate and reproduce the research findings, which strengthens scientific integrity and trust in research outcomes.
- **Reduce redundancies and save resources.** Allowing researchers to reuse the existing research data boosts efficiency, as teams can build on each other's work without duplicating efforts.

⁶⁶ The full list is available on the project site: <https://neuropuls.eu/>

⁶⁷ More information on the issue can be found in the Document “Update to the dissemination and communication plan” provided on the project’s site.

- **Foster a culture of openness and collaboration** by making data easily accessible to researchers, policymakers, and the public.

In addition to this, several partners leverage open-source methods, approaches and tools in their work, **ensuring the continued advancement of open knowledge while fostering awareness of these open technologies and their broader use in the scientific and innovation community**. The tools used during the project include:

- Open-source tools for modelling and simulation of the full system computing with neuromorphic accelerators, in gem5 platform (NKUA)
- Open-source simulation tools for modelling of PCM integrated platform (CNRS)
- Open-source simulation tools for full-stack photonics-based machine learning simulators based on Python (HPE).

All in all, **NEUROPULS’ Open Science strategy will accelerate innovation advancements** through reusable and reproducible results, enable increased quality and efficiency of research and will create more trust in science. It furthermore **facilitates cross-disciplinary research** and inclusion of all relevant, thereby leading to more creativity and greater impacts. **This democratization of science accelerates innovation across Europe and globally.**

3.3 Promote scientific collaborations & research synergies in the area of photonics

NEUROPULS consortium brings together a set of European players, spanning academia, industry, and research organizations each bringing unique expertise to the project, and leverages a dedicated advisory board including companies and research institutes: THALES, HAWAII.TECH, INFINEON TECHNOLOGIES, CYS4, and IMSE-CNM. This strong cooperation **contributes to fostering a vibrant ecosystem to enable the development of a more integrated and capable European research network in silicon photonics, neuromorphic computing technology, and security** (see Figure 10).

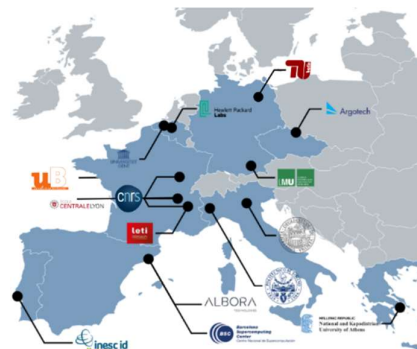


Figure 10 NEUROPULS consortium⁶⁸

⁶⁸ European Commission. (2021). *HORIZON-CL4-2021-DIGITAL-EMERGING-01: Digital and emerging technologies for competitiveness and fit for the green deal*. Proposal number: 101070238, Proposal acronym: NEUROPULS.

The partners are likely to leverage and positively cross-pollinate the NEUROPULS results into their own research ecosystems linked to one or more of the different fundamental technologies characterizing NEUROPULS: photonics, neuromorphic architecture, simulation platforms, advanced security layers. For example, the NEUROPULS project will **boost the already existing synergies at the European level** that exist among some of the partners of NEUROPULS e.g., such as their implication in the European Processor Initiative⁶⁹, in the Human Brain Project⁷⁰, in the “Network of Excellence: Cyber security competence centres for Europe”⁷¹ or in the recently established PHOTONHUB initiative⁷².

Namely, **CEA-LETI** aims to use the results of NEUROPULS for further European projects to upgrade **the exploitation of photonic neuromorphic architectures, into quantum and bio-inspired new paradigms**. PROMETHEUS⁷³ (PROgrammable integrated photonic neuromorphic and quantum networks for High-speed imaging, communications and security applications) is one of the projects under Horizon Europe, aiming to overcome the boundaries between neuromorphic and quantum engineering and merge them to a common disruptive photonic integrated platform.

CNRS also aims to leverage NEUROPULS results for Horizon Europe projects, in which they are currently involved, around **photonics & neuromorphic areas**:

- Neuromorphic computing Enabled by Heavily doped semiconductor Optics, 2023
- III-V semiconductor on silicon nano optical amplifier for signal regeneration and computing, 2023
- Quantum Optical Networks based on Exciton-polaritons, 2023.

Barcelona Supercomputing Center (BSC), an important player in the field of Advanced Computing in Europe (PRACE), is likely to leverage the NEUROPULS results to support **the “Future of Computing” initiatives and Vitamin-V consortium**⁷⁴.

Hewlett Packard Enterprise (HPE) will also utilize the scientific expertise and technology developed within the NEUROPULS project towards further European projects such as GATEPOST (focusing on **development of all-optical digital processors**) and SpikePRO (focusing on **development of electro-optical on-chip spiking neuro-inspired accelerators**). Furthermore, HPE is actively exploring the potential of **silicon photonics-powered neuromorphic technology in customer-focused solutions and knowledge transfer**.

The use of results in further research activities will **maximize the impact of research, enabling the effect of results to be potentially wider than the original focuses**. Encouraging the use of results in further research activities also **fosters the free movement of researchers, scientific knowledge, and innovation**, and encourages a **more competitive European area**.

Besides, NEUROPULS ensures the organization of **specialized doctoral-level student training sessions to contribute sharing and acquiring cutting-edge scientific knowledge**, and complementary skills workshops

⁶⁹ <https://www.european-processor-initiative.eu/>

⁷⁰ <https://www.humanbrainproject.eu/en/d>

⁷¹ <https://cybersec4europe.eu/>

⁷² <https://www.photonhub.eu/partnership/>

⁷³ <https://cordis.europa.eu/project/id/101070195/results>

⁷⁴ <https://www.vitamin-v.eu/>

summer schools, seminars, etc.). This will also **foster student exchanges** and digital training between partners and other interested parties. Training material developed for such schools can be reused to **update engineering curricula at the various academic partners to train future engineers on cutting edge research** endeavours carried out in the field of silicon photonic, neuromorphic computing and cybersecurity.

All in all, a broad European ecosystem, spanning scientific, IoT/edge, industrial community, photonic chip manufacturer and general public are likely to benefit in some extent from the exploitation of the project's results through access to the publication of journal and conference articles, open hardware releases, patents, new content in graduate courses, open PDK for novel building blocks. For existing industrial partners, the project outcomes would provide a technological ground for the development of novel products.

4. Societal impact

4.1 Reducing energy consumption and environmental impact

NEUROPULS focus on developing low-power neuromorphic accelerators can have a **significant impact on reducing the energy consumption of computing systems, which directly contributes to lowering their carbon footprint**. This is especially important as global efforts to combat climate change emphasize reducing the energy demand of emerging technologies.

For instance, datacenters currently account for 1% to 1.5% of global electricity consumption, and this figure is expected to double by 2030 due to the growing energy demands of AI⁷⁵. Google has already seen a 50% rise in emissions since 2019, largely due to AI's energy requirements. In the light of generative AI, the energy consumption has soared even more. To put this into perspective, processing a single ChatGPT query requires 2.9 watt-hours of electricity, compared with 0.3 watt-hours for a Google search, according to the International Energy Agency, while Goldman Sachs Research estimates the overall increase in datacenters power consumption from AI to be on the order of 200 terawatt-hours per year between 2023 and 2030⁷⁶.

Silicon photonics has the potential to significantly reduce energy consumption in both high-performance computing (HPC) and edge computing by leveraging light for data transmission instead of traditional electronic signals⁷⁷. This shift results in much lower energy usage and increased efficiency in datacenters and AI systems, including AI systems on the edge.

The benchmarks carried out during the NEUROPULS work will showcase the viability of its advancements in silicon photonics for accelerating computation in selected real-life use-cases including autonomous driving,

⁷⁵ Le Chips Joint Undertaking (Chips JU) est un partenariat public-privé qui soutient les activités de recherche et d'innovation dans les technologies en matière de **composants et systèmes électroniques**

⁷⁵ <https://www.photonhub.eu/applications/digital-infrastructure/>

⁷⁵ <https://www.photonhub.eu/onhub.eu/>" <https://www.photonhub.eu/articles/AI-poised-to-drive-160-increase-in-power-demand>

⁷⁷ https://www.photonics.com/Articles/Has_Silicon_Photonics_Finally_Found_Its_Killer/a69704

for which development and scaling high energy consumption and latency are the key obstacles⁷⁸. NEUROPULS aims to achieve the energy efficiency gain over two orders of magnitude below the energy consumption of the lowest energy consuming use-case concerning autonomous driving⁷⁹.

Besides, some preliminary studies have showed that photonic chips may achieve a much lesser carbon footprint, - encompassing both operational and embodied carbon (see Figure 11), - than the carbon footprint of CMOS chips (as much as 4 times)⁸⁰.

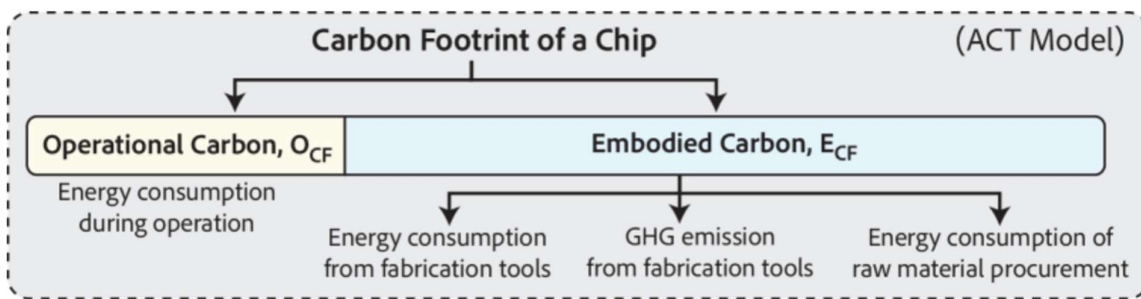


Figure 11: Carbon footprint of a computing chip

4.2 Building a more secure and resilient society

The project’s focus on developing secure neuromorphic computing solutions has significant social implications, contributing to the creation of a more secure and resilient society. By advancing neuromorphic computing technologies with robust security features, the project **addresses critical issues in protecting sensitive data and maintaining trust in digital systems**. This is particularly important for industrial sectors and applications, where data breaches can have severe consequences. For example, in sectors involving critical infrastructure—such as energy grids, water supply systems, and transportation networks—the security enabled by local data processing and neuromorphic computing solutions is vital. A breach in these areas could lead to catastrophic disruptions, safety hazards, or even loss of lives. Similarly, in the financial sector, protecting transaction data from unauthorized access is paramount to prevent fraud, theft, and financial loss. In defence, ensuring the integrity and confidentiality of data is essential to national security and strategic advantage.

NEUROPULS’ findings will provide a platform for **efficient GNSS radio frequency signals jamming detection**. GNSS jammers are a critical threat for applications that are growing dependent on GNSS position, navigation, and time solutions. These sectors include transportation (e.g., aviation, autonomous navigation) and communication (e.g., GNSS timing and synchronization for cellular

⁷⁸ <https://www.edge-ai-vision.com/2021/07/ai-advancements-driving-autonomous-vehicle-ubiquity/>

⁷⁹ For details, see the NEUROPULS proposal.

⁸⁰ Fayza, F., Papa Rao, S., Bunandar, D., Gupta, U., & Joshi, A. (2024). *Photonics for Sustainable Computing*. arXiv:2401.05121v1 [cs.ET]. Boston University, NY CREATES, Lightmatter, Cornell Tech. Retrieved from <https://arxiv.org/abs/2401.05121>

networks). The integration of photonic PUFs in such systems will ensure the integrity of hardware components, making them highly resistant to tampering and machine-learning attacks. This enhanced level of protection is crucial for GNSS systems, as they are often the target of jamming and spoofing attempts.

The NEUROPULS partner, Alhora, already plans to put the technology into practice by envisioning a GNSS jamming monitoring platform based on a dense network of monitoring stations for critical infrastructures (ports, airports, industrial plants, refineries, etc), as NEUROPULS project aims to enable rapid, reliable, and cost-effective detection of intentional/unintentional interferences.

The technology will also help to accelerate the development of safer unmanned vehicles, while being used for **lower-power, high-throughput anomaly/intrusion detection**. This is significant both for edge node network traffic analysis in conventional (wide area) computer networks (WANs), as well as in local in-vehicle networks deployed in the automotive sector.

In a broader context, NEUROPULS can promote the wider and safer adoption of IoT devices and the use of edge computing across various industries and at different scales. By enhancing system and data protection, it contributes to a more secure and resilient digital infrastructure, fostering public trust and improving overall societal safety.

4.3 Improved social conditions through wider adoption of AI and other emerging technologies

By enabling faster and more efficient computing, the NEUROPULS project will have substantial and far-reaching societal impacts, across multiple sectors including:

- **Autonomous Systems, improving real-time decision-making, enhancing vehicle safety and reducing accidents:** autonomous systems powered by advanced neural networks can optimize logistics and transportation, reducing fuel consumption and lowering operational costs⁸¹. **Deloitte** projects that autonomous vehicle technology could save **\$100 billion annually** in logistics and transportation costs globally by improving efficiency and reducing human error.
- **Communication Systems (5G/ 6G technologies):** improving the efficiency and reliability of communication networks in a variety of civil and defence applications, enabling faster data transmission and better handling of information in different environments.

⁸¹ <https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/autonomous-trucks-lead-the-way.html>

- **Defence:** enabling more energy-efficient anomaly detection algorithms that are essential in the context of cyberwar, helping to identify and respond to cyber threats more quickly and accurately.
- **Smart Cities, optimizing urban management:** Neuromorphic computing can enhance smart city applications by enabling energy-efficient real-time sensor data processing for traffic management, energy distribution, and public safety. **Cisco** estimates that smart city technologies could contribute to **\$1.2 trillion in economic benefits** by 2025 through improved operational efficiency and reduced costs in areas such as energy, transportation, and healthcare.
- **Smart Grids, enhancing energy efficiency:** advanced neuromorphic hardware can improve the management of energy resources in smart grids, leading to more efficient energy use and reduced waste. According to The International Energy Agency (IEA), implementing smart grid technologies could result into significant environmental and economic benefits⁸².
- **Healthcare, making it more accessible and affordable**⁸³: more efficient, secure and sustainable neuromorphic computing will foster the development and adoption of AI technologies resulting in advances in medical diagnostics and personal care. For example, AI-driven diagnostic tools, supported by efficient neural networks, can analyze medical imaging data with a high degree of precision. This can lead to earlier detection of diseases such as cancer, potentially improving patient outcomes⁸⁴. The same goes for enabling more sophisticated analysis of patient data, facilitating the development of personalized treatment plans. This can lead to more effective and tailored therapies.

All in all, The NEUROPULS project's advancements in neuromorphic hardware will not only drive technological progress, but also yield substantial societal benefits, highlighting the transformative power of advanced computing technologies in addressing global challenges.

⁸² - <https://www.ibm.com/think/topics/smart-grid>

⁸³ <https://innovationorigins.com/en/integrated-photonics-makes-healthcare-more-accessible-and-affordable/>

⁸⁴ <https://psico-smart.com/en/blogs/blog-integrating-ai-and-machine-learning-in-health-and-wellness-monitoring-systems-165539>

Risk Assessment

5. Risk assessment methodology

As with any research and innovation project, NEUROPULS is associated with risks stemming from its complex, multidisciplinary, and international nature, which may hinder its progress and the achievement of its goals.

The implementation risks have already been defined in the project proposal. Then, the proactive identification of risks and opportunities has been put in place to ensure project success during all stages (milestones) of the project implementation.

Due to NEUROPULS multidisciplinary and cutting-edge nature, it is susceptible to risks of various types, including scientific challenges and non-technical obstacles like regulatory hurdles, staff changes, market viability, as well as unforeseen external factors. To be able to mitigate any potential risk at an early stage and before they have a strong impact on the project, a risk management process has been defined and followed within the project consortium.

The risk management process outlines the activities necessary to identify, analyze, prioritize, manage, and control risks that may impact the project's execution and objectives. The NEUROPULS risk assessment process is based on the generic guidelines provided in ISO 31000, with its main steps presented in Figure 12. In this way, the risk assessment methodology for NEUROPULS will follow a structured, multi-step process to identify, evaluate, and mitigate potential risks, ensuring successful project delivery.

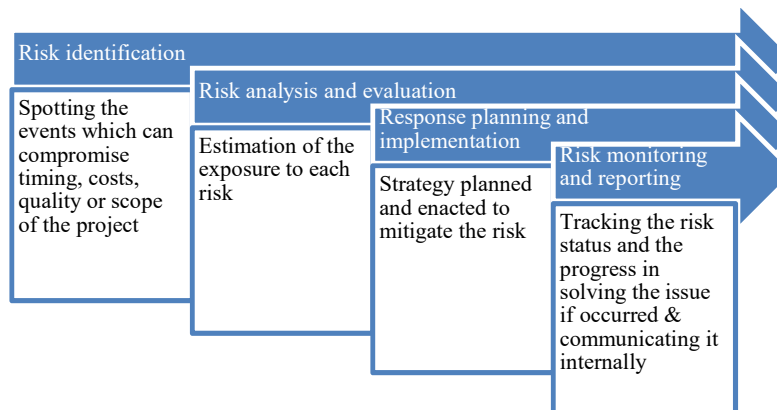


Figure 12 NEUROPULS risk management process⁸⁵

⁸⁵ <https://www.wolterskluwer.com/en/expert-insights/iso-31000-blog-series-a-complete-guide-through-the-risk-management-standard-using>

5.1 Risk identification

Risk identification involves the early detection and documentation of risks that may impact the achievement of the project’s objectives. This process was initially conducted before the project commenced and will continue on a regular basis (quarterly) until its completion, with special attention given during key milestones and reporting periods.

A combination of qualitative and quantitative approaches will be employed to identify risks across technical, environmental, regulatory, and organizational domains, utilizing methods such as workshops, brainstorming sessions, and expert consultations.

To foster the discussions on scenarios that would prevent the achievement of the project objectives from being met, different techniques can be applied such as:

- ✓ taking account of historical data, near misses etc.
- ✓ review of internal and external factors
- ✓ *What if?* scenario analysis. This method considers that what could go wrong is going wrong, and the team needs to find the reasons why it did.
- ✓ Any other brainstorming method including a “whole story framework” which forces to consider the situation from different perspectives in order to think of more risks⁸⁶.

Risks can be identified as foreseen or unforeseen, and if necessary, categorised according to different areas (see Figure 12). While some risks concern the project as a whole, others may be specific to a particular Work Package (WP).

Risk type	Description
R (foreseen)	Identified before the project starts
U (unforeseen)	Identified during the project

Risk category	Description
General	Conflicts, financial issues, etc.
Technical	Technology, performance, data, requirements, etc.
Management	Planning, schedule, communication, etc.
Personnel	Resources, dependency, etc.

Figure 13

⁸⁶ Hnottavange-Telleen, Ken. (2018). *Have we identified all the risks? The Whole Story framework*. Greenhouse Gases: Science and Technology. 8. 10.1002/ghg.1824.

For instance, the risks identified in the context of NEUROPULS project concern:

- ✓ technology, e.g., delays and issues related to fabrication, performance and compatibility / interoperability issues and other unanticipated technological bottlenecks.
- ✓ issues related to personnel (hiring, changes, etc.).
- ✓ general and management issues.

Moreover, it is important to **assess eventual interdependencies** between the identified WP-related risks and document them to consequently analyze how risks identified in one WP could potentially impact other WPs.

Eleven milestones have been identified throughout the project lifecycle and are presented in Figure 14 (MS - milestone; WP – work package; OBJ – objective described in the project proposal).

MS N°	MS name	WP	Date	Means of verification	OBJ
MS1	Functional-level simulation platforms of PNNs	WP5	M18	Availability of platforms for functional-level performance evaluation of NNs	OBJ3
MS2	First silicon photonics Run fabrication finished	WP2	M22	Fabrication report	OBJ1
MS3	Demonstration of on-chip phase transition for PCM patches	WP3	M23	Strong change in optical properties after amorphization/re-crystallization	OBJ1
MS4	Demonstration of high-speed modulated III-V sources	WP3	M23	D2.3	OBJ2
MS5	First-generation photonic accelerator evaluated	WP4	M24	D4.4	OBJ2, OBJ3
MS6	First generation security layers using PUFs evaluated	WP4	M26	D4.5-D4.6	OBJ2
MS7	Use Cases implementation compliant with accelerator	WP6	M36	First working release of all use-cases addressed by the WP	OBJ3
MS8	Simulation platforms for PNNs	WP5	M39	Availability of platforms for performance evaluation of photonic PCM-based NNs	OBJ3
MS9	Second silicon photonics run fabrication finished	WP2	M41	Fabrication report	OBJ1
MS10	Second-generation photonic accelerator evaluated	WP4	M44	D4.4	OBJ2, OBJ3
MS11	Second generation security layers using PUFs evaluated	WP4	M44	D4.5-D4.6	OBJ2

Figure 14: Milestones related to WP identified during the proposal writing. Source: the NEUROPULS proposal.

5.2 Risk analysis and evaluation

Risk analysis assesses the likelihood and impact of identified risks (severity). In the case of the NEUROPULS project, the risk analysis was performed using a risk matrix and a qualitative approach, where each risk’s probability and impact were scored as high, medium, or low. This assessment is used to define the risk level that might be helpful for risk prioritization and management. At this

stage, it is also important to take into account eventual interdependencies and evaluate the consequences of each risk on affected WPs and the project as a whole.

An example of the risk identified, its probability of occurrence and, if occurred, its impact on the project’s research progress is presented in Figure 15.

Risk type	Risk Name	Risk Probability	Risk Impact	WPs impacted	Main milestone impacted	Nature of the risk impact
R1	Fabrication delays	High	Medium	2	MS2, M22	Delay

Figure 15 : Example of a risk identified during proposal writing with a high likelihood of materializing.

To ensure the fluidity and effectiveness of risk management, a **risk assessor/holder** is assigned to each identified risk. Each WP leader also closely monitors the risks identified in their WP and regularly follows up with the owner of each risk.

5.3 Response planning and implementation

NEUROPULS consortium has also worked out a risk response strategy including identifying and planning the mitigation actions required to control the risks, to eliminate the risk and lower the probability that it occurs, and its impact.

These mitigation measures are developed based on each risk’s analysis and evaluation results, considering their potential impact on interconnected WPs. They may involve technical measures, alternative choices for critical materials, or adjustments to project timelines. An example of such a measure is presented in Figure 16.

Risk type	Risk Name	Risk Probability	Risk Impact	WPs impacted	Main milestone impacted	Nature of the risk impact	Mitigation measures
R1	Fabrication delays	High	Medium	2	MS2, M22	Delay	Use higher priority runs by sharing the fabrication

Figure 16 : Example of a risk with its associated mitigation measure.

The responsibility for each mitigation action is then assigned to relevant WP leaders or team members. If relevant, a contingency plan for high-priority risks that could significantly affect multiple WPs can also be established.

5.4 Risk monitoring and reporting

Risk monitoring oversees the implementation of risk response activities, while continuously tracking the project for changes in identified risks or the emergence of new ones. Regular reports provide project stakeholders with summaries of risk management activities and any significant changes in risk status.

The **NEUROPULS project risk register** is maintained and shared with relevant parties to track identified risks, mitigation actions, and risk status over time. It includes information on:

- Identified risks
- Risk analysis results
- Mitigation strategies
- Responsible parties
- Status updates.

This should ensure timely escalation of emerging risks to project stakeholders.

In the NEUROPULS project, risks are continuously monitored through periodic reviews (every three months), with real-time adjustments made to the risk register and related risk management strategy. As for any Horizon Europe project, the project coordinator also continuously monitors and updates the implementation risks in the EU Funding and Tenders Portal.

Given that NEUROPULS is a highly international project, several risk management-related procedures and approaches have been put in place to ensure smooth communication and collaboration with project partners and external stakeholders regarding risk management, such as:

- **Consortium meetings, including monthly review meetings (MRMs), project progress meetings (PPMs) and project general assemblies (PGAs):** The meetings allow, among others, to follow up on the project progress and to discuss the status of existing or emerging risks per WP. Each risk holder can report at these meetings on the development of each risk in terms of its likelihood, impact, status and whether other mitigation actions should be taken. For the sake of efficiency, in meetings involving all the partners in a consortium, namely PGAs and PPMs, only the most prominent risks are presented.
- **Risk managers:** The CEA team helps the project coordinator to ensure that the project's risk management process is respected, and that the most prominent risks are monitored in greater detail.
- **Proactive risk response planning:** NEUROPULS consortium applies a proactive approach to risk management, where each project partner is encouraged to contribute to the risk management plan. It also implies defining clear responsibilities and timelines for risk mitigation strategies (if necessary).
- **Collaborative Risk Management Culture:** The NEUROPULS project aims to foster a culture of collaboration and transparency among participants to facilitate effective risk

communication and coordination. This includes encouraging open dialogue about risks and uncertainties, allowing team members to share insights, concerns, and proposed solutions in an inclusive and supportive environment.

- **Continuous improvement and retour of experience (REX):** The NEUROPULS consortium regularly evaluate the effectiveness of risk management processes and identifies areas for improvement to help the mitigation of future risks and the refining of its risk management approach.

6. Risk assessment current status

6.1 Risk assessment table update

Following the methodology explained above, we counted 9 principal risks and 10 unexpected ones that have been:

- Identified
- Analyzed and evaluated
- Associated to mitigation risks
- Monitored on a 3-month and reported to the relevant parties during the regular team meetings and calls.

The updated risks (principal and unexpected) are detailed in Table 2.

#	Risk Name	Risk Probability	Risk Impact (Severity)	WPs impacted	Main milestone impacted	Nature of the risk impact	State of Play Period M1-M21	State of Play Did you apply risk mitigation measures?	State of Play Did your risk materialize ?	Mitigation measures
R1	Fabrication delays	High	Medium	2	MS2, M22	Delay	1	Yes, resulted in a 1-year extension request	Yes	*Use higher priority runs by sharing the fabrication with high priority industrial projects *1 year extension of project duration
R2	Fabrication issues	Low	Medium	2	MS2, M22	Performance & Delay	1	No	No	Use results from complementary and short-loop runs to build the simulation platform for benchmarking
R3	Laser performance in spiking mode insufficient	Low	Medium	3	MS4, M23	Performance	1	No	No	We are pursuing photonic accelerators that can function both with and without optical spike sources -- Use external spiking sources

										connected via fibres to demonstrator chip
R4	Low performance due to CPU-accelerator communication	High	Medium	4	MS8, M39	Performance	1	No	No	Introduce local memory in the accelerator to decouple data input/output from computation. Reformulate applications to reduce computation/communication imbalance
R5	Delay in obtaining from WP3 a detailed accurate device models for the simulation platform	Medium	High	5	MS8, M39	Delay	1	No	No	Start platform design with a less detailed, parameterized model; increase abstraction. Work with a less detailed, parameterized model, to define the blueprint of the simulation platforms
R6	PUFs are instable	Medium	Medium	4	MS6, M26	Performance	1	No	No	Develop error-correction solutions to increase stability or use them as a public/private key generator if statistical tests are passed
R7	Accelerator cannot scale to fit the use-case networks	Medium	Medium	6	MS7, M36	Performance & Delay	1	No	No	Evaluate the implementation on the use-case by complementing the current approach with a smaller photonic NN
R8	Diverging technological and exploitation goals of the Consortium Members	Low	Medium	7	MS5, M24	Performance & Delay	1	No	No	Follow the basic decision-making procedures defined in the Consortium Agreement; in parallel, provide appropriate discussion forums to Consortium members
R9	Incompatibility between basic gem5 simulation engine and accelerator models	Low	Medium	5	MS1, M18	Performance	1	No	No	Resort on (adapt, extend and integrate) publicly available accelerators models and simulators
U1	NN architecture uncertainty	Low	High	4	MS5, M24	Performance & Delay	1	No	No	Pick most feasible architecture given the constraints of the hardware prototypes designed in WP4

U2	Strong PUFs are vulnerable to machine learning attacks	Medium	Medium	4	MS6, M26	Performance	1	No	No	For authentication via a public medium: identify and leverage more resilient bits of PUF responses to ML attacks; For other use-cases: e.g., based on Physically Obfuscated Keys aka POK, only focus on good statistical properties, but not robustness against ML
U3	Big gap between HW capabilities and use case requirements	Medium	High	6	MS7, M36	Performance	1	No	No	Look for additional alternative use cases/ adopt pre-processing approaches to data
U4	Personnel changes	Medium	Medium	All WPs		Delay	1	Yes	Yes	Reach out to other collaborators within the same entity or other partners that can carry out the tasks proposed in the proposal
U5	Models' computational complexity too high	Medium	Medium	4-5-6	MS8, M39	Performance	1	No	No	Use a higher degree of abstraction in the models by introducing more approximations
U6	Implementation to simulation gap	Medium	Medium	4-5-6	MS7, M36	Performance	1	No	No	Fine-tune the simulator model to match the provided physical information from the implementation.
U7	Lack of standard packaging	Low	Medium	2	MS5, M24	Performance & Delay	1	No	No	Accelerator solutions could leverage custom packaging at the expenses of higher costs for initial exploitation
U8	Lack of commercial platforms	Low	Medium	7		Performance & Delay	1	No	No	Accelerator solutions could leverage custom platforms at the expenses of higher costs for initial exploitation
U9	Personnel hiring	Medium	Low	All WPs		Performance & Delay	1	Yes	Yes	Leverage existing capabilities within each partner
U10	Delay of characterization results of lower levels from the accelerator components	Medium	High	4-5-6	MS1, M18	Delay	1	No	No	Find data from literature to be used in the simulation infrastructure (preliminary simulation results).

U11	ASIC – FPGA interface limitations	Medium	Medium	5-6	MS7, M36	Performance & Delay	1	Yes	No	Use off-the-shelf components downgrading the performance requirements
U12	Secure channel PIC <-> EIC	Medium	Medium	4-5-6	MS7, M36	Performance	1	No	No	The PUF result actually used will result from the combination between the Photonic PUF with ASIC PUF

Table 2: Risk Table Update (from project start until M21 (Sept 2024)).

6.2 Risk scoring

First, we have qualitatively assessed the risk impact level (severity) and probability: Low, Medium & High.

We then qualitatively assess the criticality of each risk by combining its severity and probability, as demonstrated in the following formula for the risk score:

$$\text{Risk Score} = \text{Severity (Impact level)} \times \text{Probability}$$

The criticality of a risk is determined using the risk chart, based on the combinations outlined in Table 3, and, consequently, each identified risk is ranked as being “High” or “Medium” or “Low”.

Risk Score	Probability	Severity
High	High	High
	High	Medium
	Medium	High
Medium	Medium	Medium
Low	Low	Low
	Low	Medium
	Medium	Low

Table 3: Risk scoring methodology

Based on that, the risks have been mapped regarding their scoring, qualitatively into a risks assessment chart, as illustrated in Figure 17.

With this mapping, we could determine the priority of the risks on which we should focus effort and resource allocation for applying the mitigation measures.

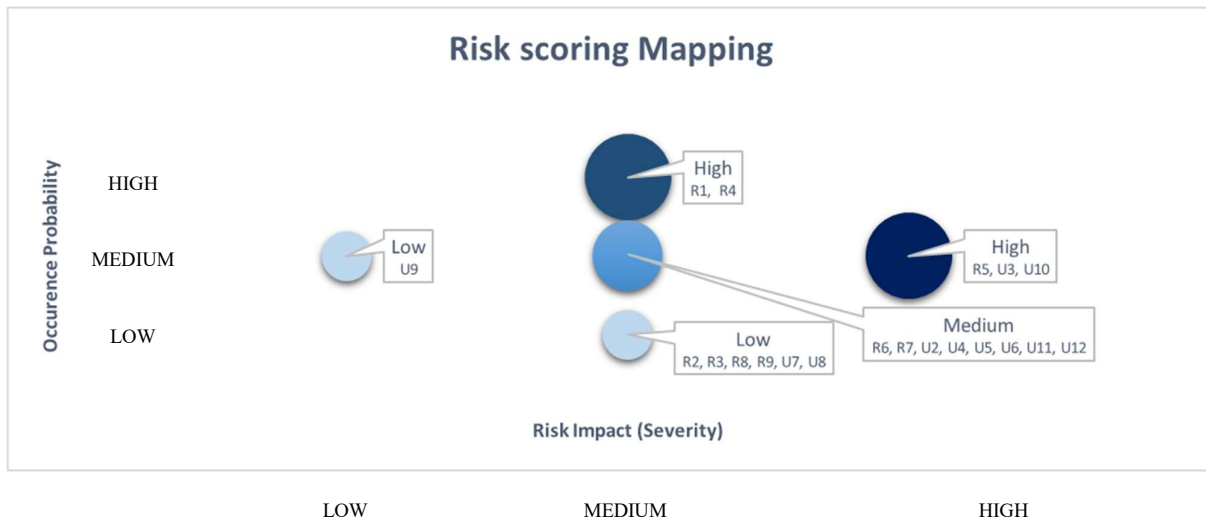


Figure 18: Risk Assessment Chart with reference to Table 2

From the Risk assessment chart, it seems that most of the risks' scores are low or medium. Nevertheless, some risks are high and can generate significant consequences:

- **R1**: Fabrication delays, impacting **WP2**
- **R4**: Low performance due to CPU-accelerator communication impacting **WP4**
- **R5**: Delay in obtaining from WP3 a detailed accurate device models for the simulation platform impacting **WP5**
- **U3**: Big gap between HW capabilities and use case requirements impacting **WP6**
- **U10**: Delay of characterization results of lower levels from the accelerator components impacting **WP 4, 5 & 6**

It is worth mentioning that the impact of these high risks can also be fine-tuned, considering the correlation of the different WPs on which they have a first direct impact.

The interdependency of NEUROPULS workflow makes the first WPs more critical for the global project success (except from WP1 and WP7 which are transversal).

Among the list of these WPs (see Table 3), the WP2 having at end of September 2024, a first milestone MS2 (M22), is being impacted by a “high” risk n materialized. This risk is linked to the fabrication delay at a material level, for the first Silicon photonics run. Given the critical impact on almost all the other WPs, it is important to provide the highest priority for the mitigation measures specified in the risk assessment table updated (see Table 4

WP	WP Title	Leader No	Leader	PM	Start	End
1	Project coordination & management	1	CNRS	40	1	48
2	Chip fabrication, packaging, and material characterization	2	CEA	185	1	42
3	Device design and characterization	1	CNRS	99	1	42
4	Photonic computing architectures and security layers development	3	UGENT	181	1	46
5	System architecture modelling and simulation	9	NKUA	188	1	42
6	Benchmarking of the secure low-power system	4	POLITO	183	1	48
7	Dissemination and exploitation	7	HPE	53	1	48

Table 4: List of WPs present in NEUROPULS. Source: the NEUROPULS proposal.

The other risk that has been materialized is **U4: Personnel changes**, scored as **Medium** from Figure 19. This risk, defined in a transversal perimeter (thus, impacting all WPs), should equally be considered in a serious and effective way by implementing the mitigation measures.

6.3 Risk Mitigation measures

Mitigation measures aim to eliminate the negative impacts of risks on the project, taking into account its objectives, organization, and environment. Consequently, this step in the risk management process is essential for:

- Risk reduction
- Enhancing safety
- Protecting resources
- Ensuring compliance
- Decision Making facilitation
- Cost efficiency
- Enhancing reputation

Nevertheless, the execution of mitigation measures is the result of arbitration, taking into account the ranking of the risk, as explained in section 2.2, and other factors such as time effort, cost, and resources. This arbitration should be done, not only with the impacted stakeholders, but with the whole consortium, and after informing the Project Officer.

In a practical way, it consists of determining the most appropriate mitigation strategy:

- **Risk Avoidance:** Implement measures to bypass the risk entirely. This may involve, in some cases, changing the scope of the project or adopting a new strategy that has not been proposed initially.
- **Risk Reduction:** Implement measures to reduce the likelihood or impact of the risk. This could include implementing safety protocols and taking extra margins (delay, performance, resources).

- Risk Transfer: Shift the risk (with its associated objective) to another party, often through insurance or outsourcing. This means that another entity will bear the cost, if the risk occurs.
- Risk Acceptance: Acknowledge the risk and decide to accept it if the costs of mitigation are higher than the potential impact. This may involve developing contingency plans.

Considering the period until M21, 2 risks have materialized:

- **R1**: Fabrication delays, ranked as **High**
- **U4**: Personnel changes, ranked as **Medium**

After arbitration, the mitigation strategy that has been selected for these 2 risks is different, as their critical level is different:

- **Risk reduction for R1**: using higher priority runs by sharing the fabrication runs with high priority industrial projects and asking for 1 year extension of project duration. This mitigation measure, although being costly and impactful for NEUROPULS milestones, organization, and finance, has been evaluated as necessary: a risk acceptance would be impossible for the realization of the project, a risk transfer would be ineffective as CEA-LETI is the only stakeholder having the skills & means to ensure the fabrication, and an outsourcing would be very difficult (too costly, and not anticipated). Finally, a risk avoidance cannot be considered as bypassing the risk would involve the redefinition of one of the main technological foundations of the project
- **Risk transfer for U4**: shifting the risk to other collaborators in the same entity or other partners to accomplish the missing tasks. The risk transfer has been evaluated as the most appropriate, benefiting from the agile organization of the consortium, and the strong involvement of each partner (internal skill transfer, resources back-up...).

Risk analysis and assessment has resulted, during the reporting period, into two mitigation measures. The first one, the most impactful on NEUROPULS global milestones, organization, and finance consists of one year amendment demand to palliate the fabrication delay (R1).

The second one, consists of shifting the risk to other collaborators in the same partner's entity or to other stakeholders. This mitigation measure, not very impactful, would ensure the execution of missing tasks due to Personnel changes, in addition to enhancing an agile collaboration into the consortium.

Conclusion & Perspectives

At this stage of the project, we have identified the main impacts of NEUROPULS project: technological, economic, scientific and societal. The overall impact is assessed to be substantial and promising, driven essentially by the technological layers and scientific knowledge linked to strategic and emerging areas: neuromorphic computing, HW based security & silicon photonics.

Economic impact has been evaluated as potential, because it is linked to multiple growing markets, forecasted to accelerate in the coming years. Nevertheless, it is important to mention that this impact pathway is strongly linked to the commercial exploitation of NEUROPULS, from one side and to the market uptake from the other side.

Regarding societal impact, it has been assessed over the long term, and could be considered as indirect, because depending on many hypotheses: maturity of the technology, its commercialization, and a large adoption by the industry.

In the next version, we will highlight explicitly the impacts' pathways, by associating them to the most relevant partners, if necessary (ex. Industrial partners to accelerate the technology transfer, and consequently accelerate the economic impact).

In relation to Exploitation activities, a monitoring of the external environment is essential to assess the competitive evolution, and the global landscape, in term of R&D, and industrial dynamics regarding the core technologies that NEUROPULS is enabling. New scenarios would be considered if major disruptions occur in the market or in the R&D landscape. Similarly, stability of NEUROPULS organization, finance & partners' involvement is a key factor to build up the impact's pathways. Coming to the Risk assessment, we have provided, in this first version, the methodology, and tools that will be used during the project lifetime. The Risk Assessment table is the principal tool on which we are centralizing the different data, linked to each identified risk. This tool should be updated on a 3-month basis and reported to the relevant parties. Additionally, we have qualitatively scored the different risks, by privileging strong mitigation strategies to reduce the impacts for the risks evaluated as "high".







During the reporting period, as a mitigation measure, one year amendment has been claimed to palliate the fabrication delay. In spite of being costly in term of organization, milestones, and finance, this mitigation measure has been judged as necessary. In a general way, we highlighted the importance of arbitration to implement mitigation measures, if the associated risk occurs.

This risk assessment process will be continued with respect to the methodological guidelines we specified. New unexpected risks could appear, linked to the operational advancement of NEUROPULS.

In order to be effective, this process requires a high degree of commitment and rigor, and smooth and agile communication with the consortium's partners. Negotiation skills are required during difficult arbitrations, and following the responsibility matrix of stakeholders.

Annex 1

Name	Field/Short description	Money raised
 Finchetto	Finchetto is a start up from Intel Ignite (London) developing light-speed photonic processors that enable faster, more sustainable computing.	£1m grant (SBRI Future Telecoms Challenge)
	Black semiconductor manufactures microchips with integrated electronic-photonic circuits using graphene technology.	254,400,000
	Scintil Photonics is a fabless company that develops silicon photonic integrated circuits	€18,616,587
	The company designs and manufactures lasers and photonic instruments for applications in academia, remote sensing, biophotonics, defence and metrology.	£16,050,000
	Salience Labs is building a hybrid photonic-electronic chip for AI.	\$11,500,000
	Sparrow Quantum is a spin-out company of the University of Copenhagen, developing and commercializing photonic quantum technology components.	\$9,863,210
	Optoscribe uses its innovative laser direct write technology to manufacture 3D glass-based integrated photonic circuits. In 2022, Intel acquired an unknown majority stake.	£8,240,002
	Miraex develops photonic and quantum solutions for next-gen sensing, networking, and computing.	\$6,942,086
	New Origin operates as a photonic chips foundry.	€6,000,000
	QuiX Quantum is an European market leader for quantum computing hardware based on photonics.	€5,500,000
	The lossless optical engine that offers smart switching and processing ensuring seamless AI cluster communication and future-proofing data center infrastructure.	€3,700,000

	<p>ALCYON PHOTONICS is a Spain-based startup working on integrated photonic circuit designs.</p>	<p>€2,449,949</p>
	<p>A German start up working on all-optical XPU, a cross-domain processor for general-purpose, ultra-low power, high-performance computing and AI.</p>	<p>€2,300,000</p>
	<p>CamGraPhIC designs, develops and manufactures next-generation photonic circuits for telecoms and datacoms.</p>	<p>£1,260,000</p>
	<p>CareGlance provides photonic devices for real-time biomedical and industrial applications.</p>	<p>€250,000</p>
	<p>LiGenTec is a B2B deep tech start up, manufacturing Photonic Integrated Circuits.</p>	<p>Total Raised \$8.78M including €3.6M from the EU Horizon 2020 EIC Accelerator program.</p>
	<p>Quantopticon develops software for simulating quantum-photonic devices.</p>	<p>\$100,000</p>
	<p>Photonpath is a manufacturer of integrated photonic devices to obtain, transmit and process information using light.</p>	<p>Not disclosed</p>



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