New Horizons

Securing Europe's strategic autonomy through Photonics

Multi-annual Strategic Research and Innovation Agenda of the Horizon Europe Photonics Partnership

PHOTONICS[21]

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Preface

Preface

Our world has changed irrevocably post COVID-19. How we work, how we communicate, how we travel. The current geopolitical crises and the war in Ukraine, have further changed our perspectives.

There are now new priorities and challenges, at European Union level, at national level, in many cases at regional level, and I have no doubt believe, in our personal lives, as we adapt to this new world.

In parallel, this new Multiannual Strategic Research and Innovation Agenda (SRIA) comes at a singular moment in the history of our European Union. It comes at a time when there is now full recognition that our European Union needs to take its destiny in its own hands to achieve strategic autonomy, to compete in this increasingly multipolar world. To quote the European Commission, it comes “at a make or break moment for the European Union’s long term competitiveness”.[1]

The two overriding priorities, now, of the European Union for economic competitiveness are to achieve Strategic Autonomy in key sectors of the European economy and, to continue strengthening EU strategic supply chains and reduce trade dependencies.

I am pleased to state that the Board of the Photonics Partnership and I, fully believe that the European Photonics community has both the capacity and capability, along with the motivation, to contribute to these two interlinked challenges.

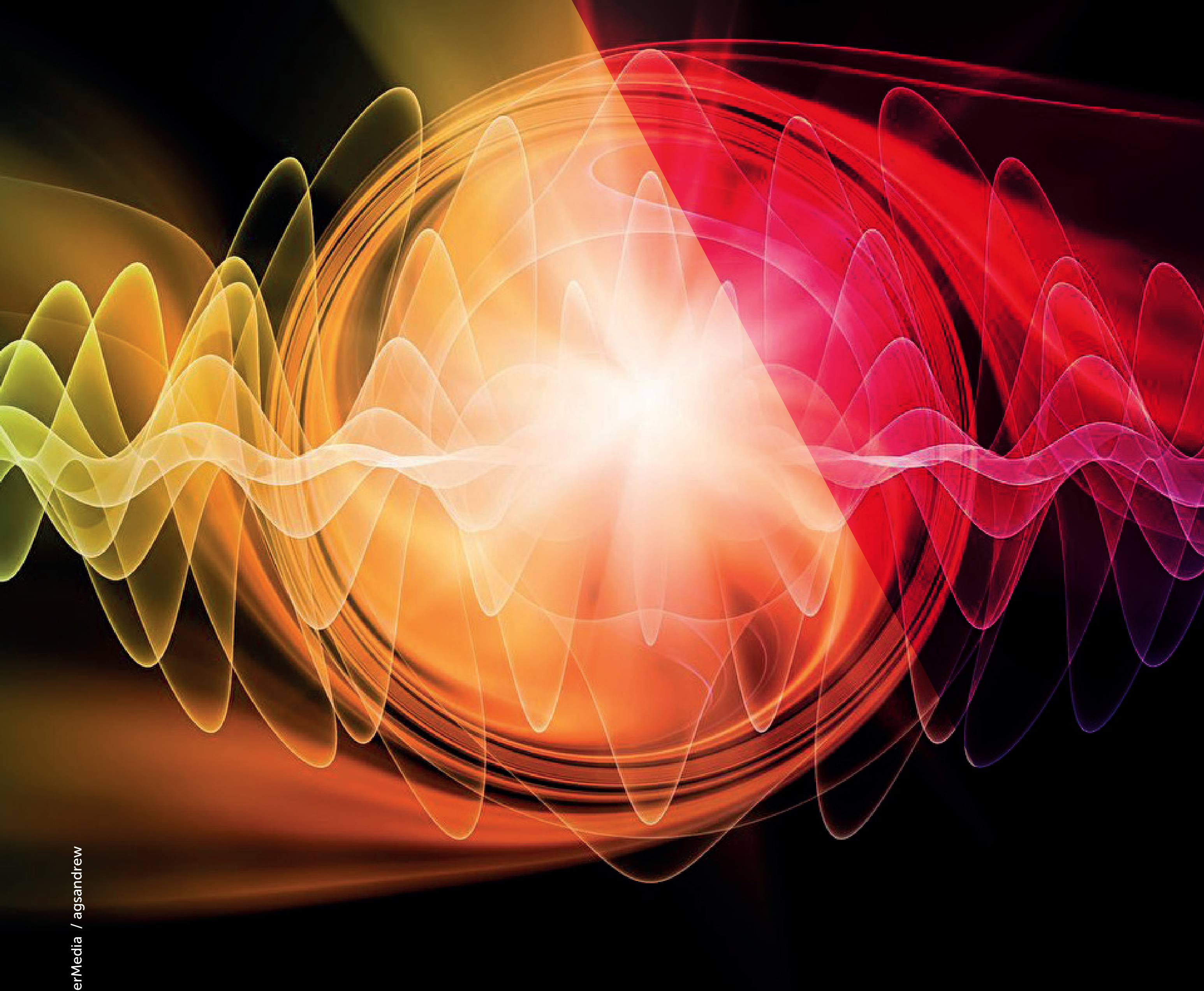
This Multiannual Strategic Research and Innovation Agenda (SRIA) is therefore uniquely shaped by the above context. The first two chapters highlight the critical role of Photonics for achieving strategic autonomy in key EU economic sectors and for strengthening the resilience of key EU strategic value chains. Whilst, in Chapter 3, a blueprint for the way forward for the EU Photonics community with ambitious research and development programmes over the 2025-2030 timeline, responding to these EU challenges, provides the strong foundation necessary for the community to position for the future. I hope you find this SRIA both inspirational and above all useful to align our thinking and actions.

It only remains for me to take this opportunity to thank all the members and colleagues of the Photonics Partnership, for their tireless and innovative work in shaping the future of European industry and society. I also wish to thank the European Commission for their full support of the Photonics Partnership and their encouragement to complete this Multiannual Strategic Research and Innovation Agenda process and implementation.

Photonics21 President Dr Lutz Aschke
on behalf of the Photonics Partnership

[1] COM(2023) 168 final “Long-term competitiveness of the EU: looking beyond 2030”, Brussels, 16.3.2023

Executive summary



"The time is now to work differently, at a make or break moment for the European Union's long term competitiveness"[2] *– European Commission*

"European strategic autonomy is goal #1 for our generation"[3] *– President of the European Council, Charles Michel*

"We have entered a global race in which the mastery of technologies is central. It is largely thanks to disruptive technologies that Europe will be able to embark fully on its twin green and digital transition, while guaranteeing its resilience and [strategic] autonomy"[4] *– EU Commissioner Thierry Breton*

"In a shifting geopolitical environment, the EU needs to continue strengthening its supply chains and reduce trade dependencies".[1]

The above EU leadership position statements provide the background context, the urgency and the focus for the preparation of this latest Multi-annual Strategic Research and Innovation Agenda (SRIA) of the Photonics Public-Private Partnership for the period 2025–2030.

Photonics has a privileged status within the EU as one of six key enabling technologies[5] and as one of only 11 co-programmed partnerships formed by the new von der Leyen Commission in 2021.[6] With this status comes a new responsibility to work differently, to focus and develop the future disruptive Photonics technologies that Europe needs to guarantee its strategic autonomy, and, to contribute to strengthening EU strategic value chains. The reader will observe that the European Photonics community have fully assumed these challenges in this new SRIA roadmap.

Chapter 1 underlines the fact that Photonics is a key technology for achieving European strategic autonomy. This is reflected in the new EU industrial strategy[7], where it is stated "The EU will support the development of key enabling technologies including photonics that are strategically important for Europe's future". It is equally reiterated again by EU leadership, for example, in reference to the Metaverse, where EU Commissioner Breton explicitly highlighted Photonics stating that "Our ability to shape the metaverse will depend on our ability to master and develop cutting-edge technologies in Europe such as Photonics.[8] Last, but not least, this is equally the view of Europe's scientific leadership, as 3 Nobel Laureates stated to the European Commission "there can be no European digital sovereignty, no secure European digital infrastructure or no secure European quantum communications without a European photonics capability and capacity".[9] In short, Photonics is essential to achieve EU strategic autonomy in existing and future emerging economic sectors.

The dramatic impact of the COVID crisis on supply of critical goods led to calls for Europe to address the long-term vulnerabilities of its industrial ecosystems and related supply chains, their (lack of) sovereignty and strong dependence on external input providers. EU industry Commissioner Breton requested Europe to recover supply chains[10] – and the French Minister of the Economy and Finance, Bruno Le Maire – called for European governments to rethink their approach to supply chains to assure "sovereign" and "independent" supplies.[11]

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[2] COM(2023) 168 final "Long-term competitiveness of the EU: looking beyond 2030", Brussels, 16.3.2023

[3] Charles Michel, [@eucopresident], 8 September 2020, European strategic autonomy is goal #1 for our generation. #EUBEF20 [TWEEET], Twitter.

[4] The "Geopolitics of Technology", Commissioner Thierry Breton, Commissioner for the Internal Market, Jul 27, 2021, LinkedIn.

[5] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/key-enabling-technologies_en

[6] In June 2021, the Commission and EU industry committed to invest €22 billion over the period 2021-2027 in eleven new European Partnerships to deliver solutions to major societal challenges. The Partnerships receive €8 billion directly from Horizon Europe, the EU research and innovation programme over the 7 year period. The European Partnership for Photonics was one of the 11 funded.

[7] European Commission, COM (2020) 102 final, "A new industrial strategy for Europe".

[8] Europe's plan to thrive in the metaverse: People, technologies & infrastructure, Thierry Breton, European commissioner for Internal market, September 14, 2022, LinkedIn.

[9] Letter from three Nobel Laureates, Gérard Mourou, Stefan Hell and Theodor Hänsch to European Commissioners Gabriel and Oettinger stating "Photonics is simply essential for powering the European digital economy", published on 28 October 2020 at https://www.photonics21.org/2020/nobel-laureates-warn-jobs-economic-growth-and-lifesaving-healthcare-at-risk-due-to-proposed-ec-sci

[10] Speech of Commissioner Breton at the European Parliament – Committee on Industry, Research and Energy, 24/4/2020.

[11] European industrial sovereignty. Minister Bruno Le Maire's speech – International press conference. 2 April 2020.

The subsequent global disruptions since 2021, due to geopolitical trade tensions and the war in Ukraine, have only compounded the challenges to EU supply chains. As a result, strengthening the resilience and sustainability of European supply chains is now a key pillar of the European Union's drive towards open strategic autonomy[12] triggering a wider awareness of the need to analyse and address strategic dependencies, both technological and industrial, and address them through tailored, facts-based and proportionate policy measures.

Whilst the European Commission has performed detailed dependency reviews of the electronics (chips) sector and a number of others (batteries, photovoltaics, etc.) **it has yet to do so for the Photonics sector**. Chapter 2 of this new SRIA therefore addresses the importance of advanced Photonics technologies across several strategic EU value chains and industrial ecosystems. It is a first contribution to this important future analysis. In doing so, the Photonics Partnership wishes to ensure that Photonics does not become Europe's deep technology "nail" in its strategic autonomy ambitions.[13]

Strategic Value Chains in which Photonics plays a key role:

- High performance computing and quantum computing,
- Augmented and virtual reality for a European metaverse,
- Digital infrastructure,
- Industry 5.0 and manufacturing,
- Automotive and mobility,
- Space and Defence,
- Renewable energies,
- Health and,
- Agriculture and Food.

The Photonics Partnership has therefore identified nine initial strategic value chains (SVCs) within which Photonics technologies, components and solutions play a simply crucial role.

The pervasive nature of advanced Photonics technologies and components are detailed in four of these SVCs; High performance computing and Quantum computing, Augmented and virtual reality – for a European metaverse, Space and Defence, and Agriculture and Food. In addition, short snapshots of the role and importance of Photonics are presented for the remaining five SVCs.

The required advanced Photonics technologies research and development roadmaps over the 2025–2030 timeframe, to support EU ambitions for strategic autonomy and resilient supply chains, are discussed in detail in Chapter 3.

With commensurate EU support relative to the huge strategic autonomy challenges, the European Photonics community can absolutely deliver. Chapter 1 of this SRIA highlights the world leading position of EU Photonics. The European Union leads both the USA and China in advanced Photonics technologies in a recent ranking[14] of performance in key technologies for competitiveness. The EU is also leading the USA, China and South Korea in terms of worldwide patent applications in advanced photonics technologies.[15] The EU also continues to excel in world-class photonics science, again demonstrated in 2022, when two Europeans were awarded the Nobel Prize for "experiments with entangled photons, pioneering quantum information science"[16] clearing the way for new photonics technologies based upon quantum information which are of strategic importance to EU security and defence. Finally, this European photonics ecosystem comprises over 5000 SMEs and a number of large companies, directly employ a talent pool of over 400,000 skilled people within the EU.

In short, Photonics technologies are simply indispensable for EU strategic autonomy and resilient strategic value chains. This SRIA demonstrates both the ambition, capability and capacity of the European Photonics community to develop innovative photonics technologies and products to support EU strategic autonomy ambitions.

[12] European Commission Strategic Foresight Report, which highlights resilience as a new compass for all EU policies under the Commission's transition-led agenda and as a result of the coronavirus pandemic.

[13] When President Biden signed the order for a review of US supply chains, he invoked an old proverb: *"For want of a nail, the shoe was lost. For want of a shoe, the horse was lost."… "And on, and on, until the kingdom was lost"*. Source: Building Resilient Supply Chains, Revitalizing American Manufacturing, And Fostering Broad-Based Growth June 2021. A Report by The White House

[14] European Commission SWD (2021) 352 final. Source Advanced Technologies for Industry project. Direct methodology available at https://ati.ec.europa.eu

[15] European Commission SWD (2021) 352 final. Source Advanced Technologies for Industry project. Based on EPO Worldwide Patent Statistical Database (PATSTAT, 2017)

[16] The Royal Swedish Academy of Sciences awarded the Nobel Prize in Physics 2022 to Alain Aspect, Institut d'Optique Graduate School – Université Paris- Saclay, France and Anton Zeilinger, University of Vienna, Austria, "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science."

Introduction

"The emerging global order is increasingly multipolar and contested. While we cannot be certain as to what the future holds, it is up to us to work towards the most favourable scenario to preserve and enhance the EU's capacity and freedom to act, based on a clear understanding of megatrends, uncertainties and opportunities. This is [the essence of] ... the EU's open strategic autonomy on the path towards 2050[17]."

1.1 Photonics is a key technology for achieving European strategic autonomy

The President of the European Council, Charles Michel is explicit "We know that strategic autonomy, which not very long ago was perhaps a matter for theoretical debate, has now become a very real issue at the heart of European affairs"[18], "European strategic autonomy is goal #1 for our generation"[19].

The 2022 EU Strategic Compass[20] has made clear the link between technological capability and EU strategic autonomy, noting, "[Europe's] competitors are not shying away from using emerging and disruptive technologies to take strategic advantage. Increasingly, the lack of sovereign control over essential technological assets and infrastructures undermines autonomous national decision-making in security and foreign policy". Technological prowess is a necessary precondition for a European strategic autonomy.

The 2020 Industrial Strategy underlined the urgent EU need to improve its open strategic autonomy in key areas[5]. Reinforcing this message, EU Commissioner Thierry Breton has stated "We have entered a global race in which the mastery of technologies is central. It is largely thanks to disruptive technologies that Europe will be able to embark fully on its twin green and digital transition, while guaranteeing its resilience and [strategic] autonomy"[21].

The Informal meeting of the Heads of State or Government, Versailles Declaration in March 2022 renewed the EU's "commitment to strengthening EU technological sovereignty[22]."

It is accepted across EU institutions and Member States that "the EU will fail to advance towards strategic autonomy if it is not at the forefront of technological innovation"[23].

One may ask, how does this intense EU focus on strategic autonomy impact the European Photonics community and

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[17] European Union Strategic Foresight Report 2021, Secretariat General, European Commission, Brussels, Belgium, https://ec.europa.eu/info/strategy/strategic-planning/strategic-foresight_en
[18] Report by President Charles Michel to the European Parliament plenary session, January 18th, 2023, Consilium (europa.eu)
[19] Charles Michel, [@eucopresident], 8 September 2020, European strategic autonomy is goal #1 for our generation. #EUBEF20 [TWEEET], Twitter.
[20] https://data.consilium.europa.eu/doc/document/ST-7371-2022-INIT/en/pdf
[21] The "Geopolitics of Technology", Commissioner Thierry Breton, Commissioner for the Internal Market, Jul 27, 2021, LinkedIn.
[22] Informal meeting of the Heads of State or Government, Versailles Declaration 10 and 11 March 2022, https://www.consilium.europa.eu/media/54773/20220311-versailles-declaration-en.pdf
[23] Strategic autonomy for European choices: The key to Europe's shaping power, EPC discussion paper, Giovanni Grevi, 19 July 2019.

its roadmap going forward? In fact, Photonics has a privileged status within the EU as one of six key enabling technologies[24] and also as one of only 11 co-programmed partnerships formed by the new Commission administration in 2021[25]. With this status comes therefore a new responsibility to contribute towards European strategic autonomy, which, as the reader will observe, is fully assumed in this new SRIA roadmap.

Moreover, Photonics is not only recognised within the European Commission and EU Member States as a "key enabling technology", but one with the potential to underpin a stronger more resilient European economy. This is reflected in many European Commission communications and statements including one from the 2020 new industrial strategy for Europe, stating "The EU will support the development of key enabling technologies including photonics that are strategically important for Europe's future".[26]

This is equally the view of Europe's scientific leadership, as 3 Nobel Laureats stated to the European Commisison "there can be no European digital sovereignty, no secure European digital infrastructure or no secure European quantum communications without a European photonics capability and capacity"[27]. In short, Photonics is essential to achieve EU strategic autonomy in existing and future emerging economic sectors.

One recent example of the increasingly critical importance of photonics technologies is in the emerging digital economic of the future Metaverse, which – as stated in the 2022 European Commission President von der Leyen's State of the Union letter of intent[28] – is "one of the pressing EU challenges ahead of us". In his follow-up, EU Commissioner Breton explicitly highlighted Photonics stating that "Our ability to shape the metaverse will depend on our ability to master and develop cutting-edge technologies in Europe such as Photonics .... or new materials".[29]

To reduce its technological vulnerabilities and asymmetric dependencies[30] the EU has decided to invest in [amongst others] photonics deep-tech capabilities.

The importance of Photonics for technological sovereignty, in support of open European Autonomy, has been reflected explicitly in all relevant European Commission research programmes call for proposals (see box below).

A first example is the call to "**Secure Technological Sovereignty for Europe by maintaining leadership in Quantum Photonic Integrated Circuit** technologies" within Horizon Europe programme, Cluster 4: Digital, Industry and Space (deadline 29 March 2023). The call has as **expected outcome "Supporting a European open strategic autonomy** in key technologies and related manufacturing value chains".

A second example is the call on Digital And Emerging Technologies For Competitiveness And Fit For The Green Deal (Horizon Europe) which states "As the digitalisation of all sectors accelerates, most industries depend on early access to digital components. Dependence on these technologies represents a clear threat to Europe's autonomy.... **Europe needs to develop the essential ... photonic components ... and set out a credible pathway to contributing to an open strategic autonomy in digital technologies**".

A final example is the KDT-JU-2022-1-IA-Focus-Topic on **Industrial supply chain for silicon photonics**. "Bringing this technology to industrial scale is a challenge but there is urgency and it befits **the objective of the KDT JU to reinforce the Union's strategic autonomy**".

[24] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/key-enabling-technologies_en
[25] In June 2021, the Commission and EU industry committed to invest €22 billion over the period 2021-2027 in 11 new European Partnerships to deliver solutions to major societal challenges. The Partnerships will receive €8 billion directly from Horizon Europe, the EU research and innovation programme over the 7 year period. The European Partnership for Photonics was one of the 11 funded.
[26] European Commission, COM (2020) 102 final, "A new industrial strategic for Europe".
[27] Letter from three Nobel Laureates, Gérard Mourou, Stefan Hell and Theodor Hänsch to European Commissioners Gabriel and Oettinger stating "Photonics is simply essential for powering the European digital economy", published on 28 October 2020 at https://www.photonics21.org/2020/nobel-laureates-warn-jobs-economic-growth-and-lifesaving-healthcare-at-risk-due-to-proposed-ec-sci
[28] https://state-of-the-union.ec.europa.eu/system/files/2022-09/SOTEU_2022_Letter_of_Intent_EN_0.pdf
[29] Europe's plan to thrive in the metaverse: People, technologies & infrastructure, Thierry Breton, European commissioner for Internal market, September 14, 2022, LinkedIn.
[30] The Geopolitics of Technology: How The EU Can Become A Global Player, Julian Ringhof and José Ignacio Torreblanca, May 2022, https://ecfr.eu/

A turning point was the COVID-19 pandemic which tested the resilience of advanced economies worldwide with severe disruptions in supply chains and production due to a range of demand and supply side issues, aggravated by the geopolitical climate. The crisis highlighted that whilst the EU gains resilience from world markets being open and, being integrated in global value chains, disruptions in these global value chains can affect specific essential products and inputs that are particularly critical for the EU economy[31]. In this context, the European Council invited the Commission to "identify strategic dependencies, particularly in the most sensitive industrial ecosystems ...., and to propose measures to reduce these".

The recent 2022 EU Strategic Compass[20] reflects this learning that the "EU must reduce technological and industrial dependencies. Achieving technological sovereignty in some critical technology areas, mitigating strategic dependencies in others, and reducing the vulnerability of our value chains are critical if we are to meet the challenges of a more dangerous world and be more resilient."

As will be shown in Chapter 2, photonics components and technologies are in fact a critical element in several of the EU's already identified strategic value chains and will also be critical in newly emerging sectors, such as the Metaverse. These strategic EU value chains include: High performance computing and quantum computing, Augmented and virtual reality – for a European metaverse, Digital infrastructure, Industry 5.0 and manufacturing, Automotive and mobility, Space and Defence, Renewable energies, Health and, Agriculture and Food. Across these sectors, the growth of the EU Photonics industry is three (3) times the growth of EU GDP and almost five (5) times that of the whole EU industry.

In addition, many of the critical Photonics components and technologies for future EU space and defence applications will increasingly originate in the civilian domain. One example of this dual-use nature of critical photonics technology is solar Photovoltaic (PV) technologies, that will not only be a crucial energy source in the context of the green transition objectives, but in addition, will also have important applications in the area of EU space and defence solutions.

In all these examples a sovereign EU photonics materials and technology capability will be necessary if the EU is to increase its resilience to external factors affecting the EU's structural dependency on imports[32].

This enormous technological potential for Photonics technologies to support European Union digital sovereignty and strategic autonomy ambitions is underpinned by a world-class European capability and capacity in Photonics scientific research, world leading photonics technology development, within a vibrant European-wide Photonics ecosystem, supported by appropriate regional, national and European public authorities and industry association[33].

1.2 Europe is a world-leader in Photonics research, development and application

The European Photonics ecosystem and landscape is recognised to be a world in photonics science, technology and innovation.

World-class photonics science: Europe continues to excel in world-class photonics science. This was again demonstrated in 2022, when two Europeans were awarded the Nobel Prize for "experiments with entangled photons, pioneering quantum information science"[34]. The EU Nobel Laureates were Alain Aspect (Institut d'Optique, Université Paris-Saclay, Paris, France; École Polytechnique, Palaiseau, France) and Anton Zeilinger (University of Vienna, Vienna, Austria; Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna, Austria). Their results have cleared the way for new photonics technologies based upon quantum information which are of strategic importance to EU security and defence.

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[31] COMMISSION STAFF WORKING DOCUMENT, Strategic dependencies and capacities, Accompanying the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery.

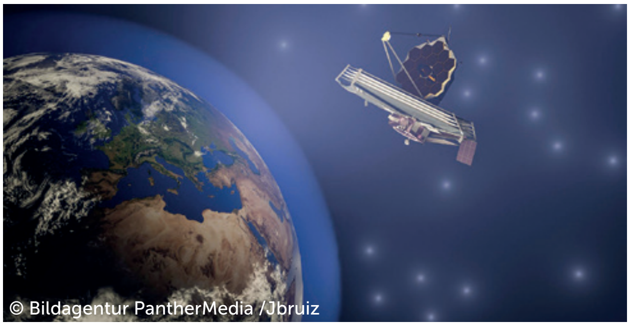
[32] Brussels, 22.2.2022 SWD (2022) 41 final Commission Staff Working Document EU strategic dependencies and capacities: second stage of in-depth reviews.

[33] The European Photonics Industry Consortium, with over 800 members, is now the world's leading industry association that promotes the development of industry working in the field of photonics in Europe. https://epic-assoc.com/the-association/

[34] On the 4 October 2022, the Royal Swedish Academy of Sciences awarded the Nobel Prize in Physics 2022 to Alain Aspect, Institut d'Optique Graduate School – Université Paris- Saclay and École Polytechnique, Palaiseau, France, John F. Clauser, J.F. Clauser & Assoc., Walnut Creek, CA, USA and Anton Zeilinger, University of Vienna, Austria "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science."

This photonics Nobel success builds on the four European Union Nobel Prize winners in Photonics in the past decade alone; scientists Gérard Mourou, Nobel Laureate in Physics 2018; Stefan W. Hell, Nobel Laureate in Chemistry 2014; Serge Haroche Nobel Laureate in Physics in 2012, and Theodor W. Hänsch, Nobel Laureate in Physics 2005; were all awarded the Nobel Prize for their work in the field of Photonics and Photonics enabled sciences.

World-class photonics engineering: The James Webb Space Telescope is the largest and most powerful ever launched into space, designed to solve mysteries in our solar system, look beyond to explore distant galaxies and worlds around other stars, and probe the mysterious structures and origins of our universe.



© Bildagentur PantherMedia /Jbruiz

This James Webb Space Telescope, uses high-precision mirrors manufactured at the Fraunhofer Institute for Applied Optics and Precision Engineering in Jena, Germany. In addition, the world's premier space science observatory contains filter wheel equipment, developed and built at the Max Planck Institute for Astronomy (MPIA) in Heidelberg that turns the Webb Telescope's MIRI camera into a scientific instrument with which astronomers hope to answer some of the most pressing questions in space research. Finally, the Near InfraRed Spectrograph multi-object spectrograph was designed, developed, and integrated on the telescope by a team of more than 70 people at Airbus sites in Germany, as well as Toulouse, France, with support from 17 European subcontractors, reflecting the leading position of European Union photonics engineering.

World leading key photonics technologies: The European Union leads both the USA and China in advanced Photonics technologies in a recent ranking[35] of performance in key technologies for competitiveness. This front-runner position addresses technology generation, start-up creation and skills (see opposite).

The EU is also leading the USA, China and South Korea in terms of worldwide patent applications in advanced photonics technologies[36].

World-class Photonics Research and Innovation Support Ecosystem. The European photonics ecosystem has over 5000 SMEs and a number of large companies. These technology-intensive Photonics companies directly employ over 400,000 people within the EU. This globally leading European Union photonics ecosystem is strongly supported at European and national levels through a number of dedicated programmes.

The primary support instrument at European level is the European Partnership for Photonics[25], with a dedicated research and innovation budget of circa 680 M€; of which, 340 M€ from Horizon Europe and 340 M€ from private partners[37]. The stated objectives of the Partnership include; to secure Europe's technological sovereignty and raise the competitiveness of Europe's economy.

In addition, the European Commission and EU Member States, through the Key Digital Technologies Joint Undertaking[38] funding instrument supports the photonics industry and research community in the area of Silicon based photonics and Photonic Integrated Circuits (PICs)[39].

At National level, Member States, also have dedicated national Photonics funding programmes and support instruments. One recent example being the creation in April 2022 of the Netherlands government €1.1 billion PhotonDelta[40] initiative to create a leading next generation photonic integrated circuits sector.

Leveraging this global front-runner position in photonics science, technology, innovation and eco-system support,

[35] European Commission SWD (2021) 352 final. Source Advanced Technologies for Industry project. Direct methodology available at https://ati.ec.europa.eu/

[36] European Commission SWD (2021) 352 final. Source Advanced Technologies for Industry project. Based on EPO Worldwide Patent Statistical Database (PATSTAT, 2017)

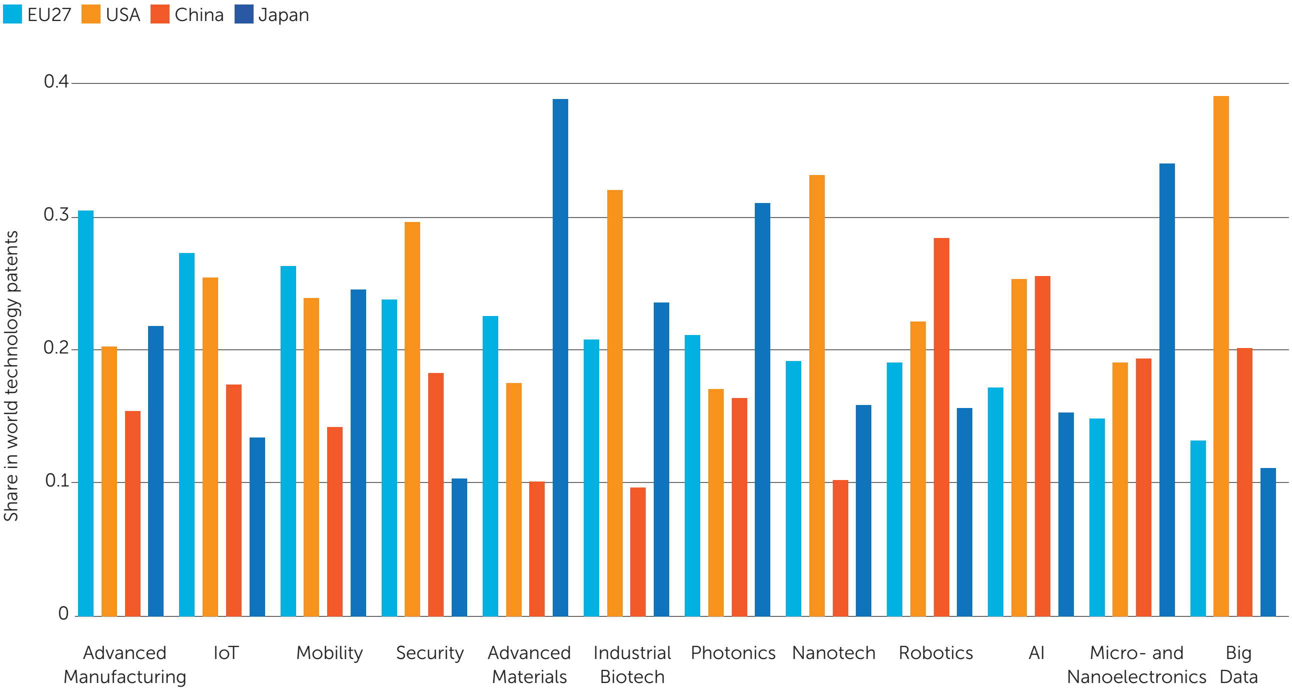
[37] In total, more than 3850 registered personal members, representing more than 1800 affiliations from industry, science, associations and political bodies support the Partnership.

[38] The Key Digital Technologies Joint Undertaking (KDT-JU), the Public-Private Partnership for research, development and innovation in electronic components and systems, funds projects essential for Europe's competitive leadership in the era of the digital economy. KDT JU is the successor to the ECSEL JU programme, supporting its ongoing projects. https://www.kdt-ju.europa.eu

[39] For example; the 2022 KDT-JU Call for proposals on Industrial supply chain for silicon photonics (HORIZON-KDT-JU-2022-1-IA-Focus-Topic-2).

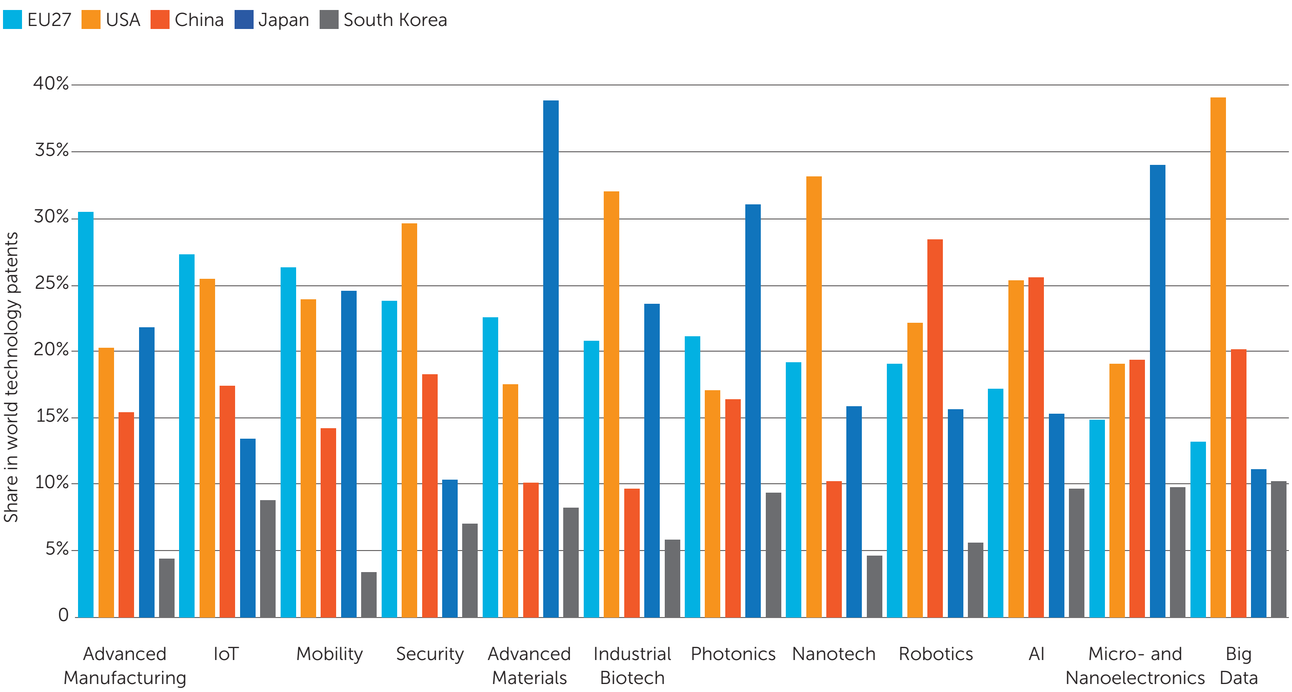
[40] Eindhoven, Netherlands – PhotonDelta, an ecosystem of photonic chip technology organisations, has received €1.1 billion in public and private investment.

Indicator of overall EU performance in key technologies



Source: Advanced Technologies for Industry project

Share in world transnational advanced technology patent applications



Source: Advanced Technologies for Industry project

Europe remains the world's second-largest supplier of Photonics components and systems after China, with a market share of 16%[41] of a global Photonics market currently (2022) at over $800 billion comprising around $105 billion in Photonics components and over $700 billion in Photonics systems[42]. This has translated into an annual employment growth rate of 2.1%, significantly higher than that of employment in European Manufacturing as a whole (approximately 1% CAGR for the EU27).

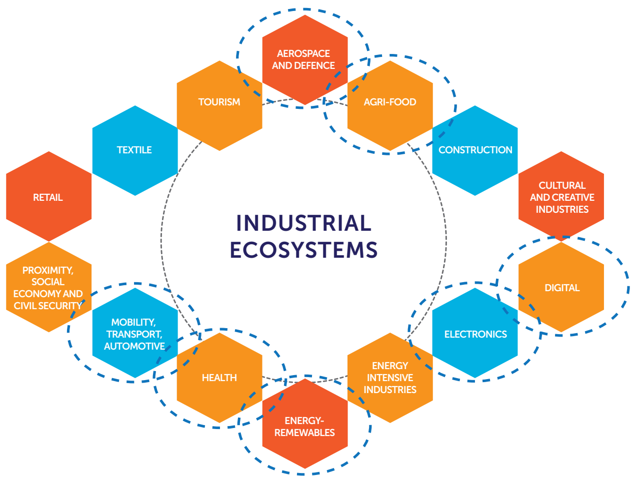
1.3 Objectives of this Photonics21 Multi-annual Strategic Research and Innovation Agenda

This Multi-annual Strategic Research and Innovation Agenda of the Horizon Europe Photonics Partnership, proposes a vision and pathway forward for the European Photonics community. It represents a short to medium-term strategy for the period 2025–2030.

The introductory sections of this Chapter 1 have highlighted the fact that the European Union priority on strategic autonomy will be simply impossible to achieve if the EU is not at the forefront of deep technological innovation in key enabling technologies such as Photonics and Microelectronics. From European Commissioner Breton, the Commission services and the European Investment Bank to Nobel Laureates, it has been stated again and again that Photonics technologies are essential to achieve digital technological sovereignty and thus enable future EU strategic autonomy.

The 2022 EU Strategic Compass emphasised the EU need to reduce technological and industrial dependencies [outside the EU] …. and reduce the vulnerability of EU value chains if the EU is to become more resilient. In Chapter 2, it will be shown that photonics is a strategic enabling technology and critical component across several key EU value chains. In particular, the importance of photonics in four representative strategic value chains are discussed in detail in section 2.2; High performance computing & quantum computing, Augmented & virtual reality for a European metaverse, Space & Defence, and, Agriculture & Food. In addition, in section 2.3, snapshots of the importance of Photonics are presented for five other strategic value chains; Digital infrastructure, Industry 5.0 & Manufacturing, Automotive & Mobility, Renewable energies and Health. It is also highlighted that many of the critical Photonics components and technologies for future EU space and defence applications will originate in one or other of the above civilian value chains, and that Photonics technologies must therefore be supported, across and within as broad a range of sectors and value chains as possible.

Chapter 3 details the major research, innovation and socio-economic challenges for the European Photonics community that must be addressed to support EU ambitions in key strategic sectors of the European economy including: Digital Infrastructure, Manufacturing, Health, Climate Mobility & Energy, Safety, Security, Space & Defence, and Agriculture & Food (see below).



Opportunities or cooperation needs with other Commission initiatives are also described within each of the above sectors in Chapter 3, building on the European Commission identification of the significant potential for the Photonics Partnership to engage with and play a pivotal role in up to 26 other Horizon Europe partnerships, Digital Europe joint undertakings or Commission missions[43].

In parallel to these existing or nascent cooperation initiatives, the Photonics platform through its Executive Board and the Photonics21 secretariat has started a number of collaborations (Focus Groups) in strategic policy areas. These focus groups are listed below under the relevant policy priority:

[41] Photonics Market Data and Industry Report 2020, https://www.flipsnack.com/photonics21/photonics-market-data-and-industry-report-2020/full-view.html
[42] The global Photonics market is expected to break the $1000 billion threshold over the period 2025 to 2027.
[43] Coherence and Synergies of European Partnerships under Horizon Europe, European Commission, DG Research and Innovation, 2020.

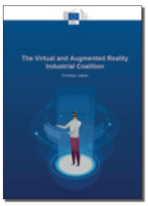
Policy Priority: A Europe fit for the digital age

Focus Group on Quantum Computing/Technologies in collaboration with the Quantum Flagship. The strategy topic is Quantum Photonic Integrated Circuits (started 2021). A first position paper is available.[44]

Focus Group on the Chips Act – addressing the future Chips Joint Undertaking in collaboration with EPoSS[45]. The Strategy topic is Integrated Photonics (started 2022).

Future Focus Groups will address:

High Performance Computing: A Focus Group will be established with the EuroHPC JU.



AR/VR/XR: Metaverse: A Focus Group with the Partnerships AI-Robotics-Big Data/Made in Europe/6G and the VR AR Industrial Coalition. An application to join the VR AR Industrial Coalition[46] has already been made.

Policy Priority: European Green Deal

Photovoltaics: A Focus Group will be established with the Partnership on Photovoltaics

Smart Farming: A Focus Group will be established with the European Partnership for Safe and Sustainable Food Systems and the EU Mission Soil.

Policy Priority: A stronger Europe in the world

Defence Safety and Security: A Focus Group will be established with relevant partnerships.

Finally in Chapter 3, both a roadmap and timetable for research and development activities over the 2025–2030 timeframe is presented for each of the key strategic sectors identified, to acquire the Photonics capacity and capability required to support the EU's strategic autonomy ambitions.

[44] https://www.photonics21.org/download/ppp-services/photonics-downloads/QPIC_position_paper_26-4-22_final_logos.pdf
[45] EPoSS is the European Association leading the development and integration of intelligent and green Smart Systems technologies and solutions for a sustainable society. https://www.smart-systems-integration.org
[56] CNECT-VRARCOALITION@ec.europa.eu

Photonics is a critical deep technology in key European strategic value chains

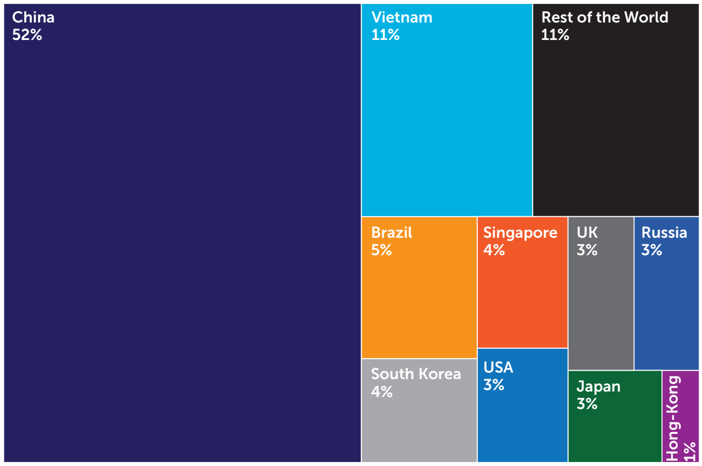
"Trade is at the centre of Europe's economic prosperity and competitiveness. The EU is the world's largest trader of agricultural and manufactured goods and services and ranks first in both inbound and outbound international investments"[47].

2.1

Context

Supply chains are therefore the nervous system of the European economy. Up to 30% of total European value added relies on functioning cross border supply chains, either as a source of input or as a destination for production[48].

In the past three years, global supply chains have been disrupted by a series of events. Firstly, the COVID-19 pandemic which led to the disruption of international supply chains in which an important part of European industry was embedded. This was followed by resurging post-COVID demand shortages which overwhelmed supply chains such as those for the EU automotive sector[49].



Share of EU import value by origin of identified 137 products where the EU is dependent in sensitive ecosystems.
Source: European Commission based on BACI database.

The ongoing strict lockdown measures in some key Asian countries that produced intermediate inputs – further exacerbated supply bottlenecks. This was particularly the case for Europe arising from the concentration of its global trade and supplies in a few regions with over half (52%) of the share of EU import value of the most foreign dependent products originates from China[50].

It is noteworthy that a recent 2022 survey conducted by the Photonics 21 Association[51] and EPIC, which revealed the ongoing vulnerability of the European Photonics supply chain

[47] COM(2021) 66 final. Trade Policy Review – An Open, Sustainable and Assertive Trade Policy.
[48] Accenture Research analysis of OECD TiVA and Oxford Economics Industry Databank
[49] In Germany, car production in the first four months of 2022 was down 32% compared to 2019 as a result of a lack of primary product inputs. VDA Press Release ("Production and market also down in April,"), from 4 May 2022.
[50] "Strategic dependencies and capacities," European Commission (2021) https://op.europa.eu/en/publication-detail/-/publication/8f76a6dd-ae95-11eb-9767-01aa75ed71a1/language-en/format-PDF/source-213710188
[51] Photonics 21 Association, Supply Chain Survey 2022, private communication.

to sudden supply chain shocks arising from geopolitical factors, had a similar conclusion to that of the above dependency study, with 53% of companies stating a dependency on key sources of goods from China.

This initial wave of global and European supply chain disruptions had a considerable and immediate economic impact with losses due to disruptions in the Eurozone estimated at €112.7 billion, or 0.9% of GDP[52]. They also revealed the long-term vulnerabilities of Europe's industrial ecosystems and related supply chains, their (lack of) sovereignty and strong dependence on external input providers. The evident dramatic impact led to calls from EU leaders including Commissioner Breton – to recover supply chains[53] – and the French Minister of the Economy and Finance, Bruno Le Maire – for European governments to rethink their approach to supply chains to assure "sovereign" and "independent" supplies[54].

Similar calls to strengthen strategic supply chains were echoed by the USA and Japan. On February 24, 2021, President Biden signed Executive Order (E.O.) 14017, "America's Supply Chains," in which he directed the U.S. government to undertake a comprehensive review of critical U.S. supply chains to identify risks, address vulnerabilities and develop a strategy to promote resilience[55]. The subsequent passing of the US Chips Act in 2022[56], provided $52 billion dollars in manufacturing grants and research investments for US semiconductor projects. In addition, the establishment of a 25% investment tax credit (ITC) to incentivize semiconductor manufacturing in the U.S. worth another $24 billion dollars[57].

The Japanese government also identified strategic autonomy as a national goal and resilient value chains as a key priority. The Liberal Democratic Party of Japan proposal in December 2020 defined economic security as "ensuring the nation's independence, survival and prosperity in economic terms" and put forward concepts to achieve it, including "securing strategic autonomy" by strengthening the foundations indispensable to maintaining Japan's social and economic activities and avoiding excessive dependence on other countries[58]. This was followed by the Ministry of Economy, Trade and Industry (METI) launching a call for promoting investment in Japan to strengthen supply chains (see box below)[59].

METI Program for Promoting Investment in Japan to Strengthen Supply Chains (2020)

Context: Given the backdrop of the effects of Covid-19, supply chains and their economic activities have been disrupted. These disruptions are primarily a result of the vulnerability of those supply chains caused by the high degree of concentration of production bases/manufacturing plants. Regarding products essential for people's wellbeing, it is crucial to secure a domestic production base to ensure stable supply in case of emergencies. This program aims to strengthen supply chain resilience by supporting businesses in building new plants and introducing new facilities for these products and materials in Japan.

The Ministry of Economy, Trade and Industry (METI) opened a call for applicants for the Program for Promoting Investment in Japan to Strengthen Supply Chains in 2020 that ended with 146 projects selected for an amount of 247.8 billion yen in total.

The projects of these successful applicants target essential goods, parts and materials that are largely produced overseas [to resource production to Japan] and that have a high risk of being impacted by supply chain disruptions. Several METI projects address the Japanese Photonics strategic value chain.

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[52] "From disruption to reinvention – The future of supply chains in Europe", 2022, Accenture.
[53] Speech of Commissioner Breton at the European Parliament – Committee on Industry, Research and Energy, 24/4/2020.
[54] European industrial sovereignty. Minister Bruno Le Maire's speech – International press conference. 2 April 2020.
[55] When President Biden signed the order for a review of US supply chains, he invoked an old proverb: *"For want of a nail, the shoe was lost. For want of a shoe, the horse was lost."… "And on, and on, until the kingdom was lost"*. Source: Building Resilient Supply Chains, Revitalizing American Manufacturing, And Fostering Broad-Based Growth June 2021. A Report by The White House
[56] The Creating Helpful Incentives to Produce Semiconductors and Science Act of 2022 (CHIPS Act), signed into law on August 9, 2022
[57] The CHIPS Act directs $280 billion in spending over the next ten years. The majority—$200 billion—is for scientific R&D and commercialization. Some $52.7 billion is for semiconductor manufacturing, R&D, and workforce development, with another $24 billion worth of tax credits for chip production. There is $3 billion slated for programs aimed at leading-edge technology and wireless supply chains". The CHIPS and Science Act: Here's what's in it, McKinsey & Company, October 4, 2022.
[58] Recommendations Toward Developing Japan's "Economic Security Strategy", December 16, 2020, Strategic Headquarters, Policy Research Council, Liberal Democratic Party of Japan. https://www.jimin.jp/news/policy/201021.html
[59] https://www.jetro.go.jp/

The subsequent global disruptions since 2022, due to geopolitical trade tensions and the war in Ukraine, have only compounded the challenges to EU supply chains with increasing energy prices and inflation, severe disruptions to global markets for critical raw materials[60] and companies across Europe increasingly concerned about the lack of intermediate inputs and critical components.

As a result, strengthening the resilience and sustainability of European supply chains is now a key pillar of the European Union's drive towards open strategic autonomy[61] triggering a wider awareness of the need to analyse and address strategic dependencies, both technological and industrial, and address them through tailored, facts-based and proportionate policy measures.

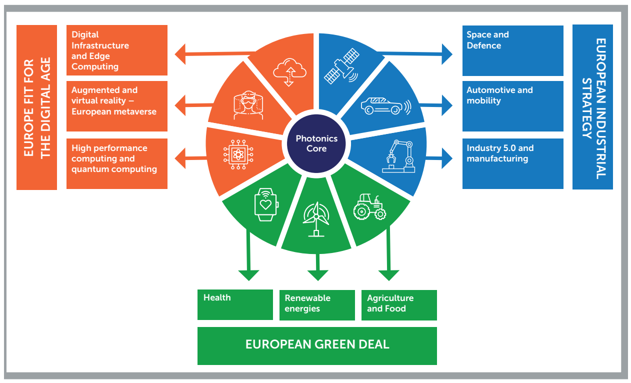
Whilst the European Commission has performed detailed dependency reviews of both the electronics (chips) sector and a number of others (batteries, photovoltaics, etc.) **it has yet to do so for the Photonics sector**. This Chapter 2, which addresses the importance of advanced Photonics technologies across several strategic EU value chains and industrial ecosystems, is a first contribution to this future analysis. In doing so, the Photonics Partnership wishes to ensure that Photonics does not become Europe's "nail" in its strategic autonomy ambitions.[55]

Over the course of the past months, the Photonics Partnership has identified nine initial strategic value chains within which Photonics technologies, components and solutions play a simply crucial role.

These EU strategic value chains (SVC's) are:
- High performance computing and quantum computing,
- Augmented and virtual reality – for a European metaverse,
- Digital infrastructure,
- Industry 5.0 and manufacturing,
- Automotive and mobility,
- Space and Defence,
- Renewable energies,
- Health and,
- Agriculture and Food.

These SVC's will be the focus of a particular attention within the sectorial Partnership working groups as reflected in their future roadmaps for research and development activities over the 2025–2030 timeframe discussed in Chapter 3.

These are shown in the graphic below, linked to the related primary EU policy initiative and growth strategy:
- The European Green Deal[62] is the EU's main new growth strategy to transition the EU economy to a sustainable economic model.
- The "2030 Digital Compass: the European way for the Digital Decade"[63] is the EU's strategy for the digital transformation of Europe by 2030 with a stated ambition to be "digitally sovereign in an open and interconnected world."
- The "New Industrial Strategy for Europe"[64], promoting Europe's competitive sustainability, as well as supporting the Commission's 'geopolitical' ambitions by boosting the EU's open strategic autonomy and ensuring greater resilience.



The following sections detail the critical importance of advanced Photonics technologies and components in four of the above strategic value chains: High performance computing and Quantum computing, Augmented and virtual reality – for a European metaverse, Space and Defence, and Agriculture and Food.

Because of page limitations, short snapshots of the role and importance of Photonics are presented for the remaining five strategic value chains.

[60] OECD, The supply of critical raw materials endangered by Russia's war on Ukraine, 4 August 2022. https://oecd.org/ukraine-hub/en/
[61] European Commission Strategic Foresight Report, which highlights resilience as a new compass for all EU policies under the Commission's transition-led agenda and as a result of the coronavirus pandemic.
[62] COM(2019) 640 final – The European Green Deal
[63] COM(2021) 118 final – 2030 Digital Compass: the European way for the Digital Decade
[64] COM(2020) 102 final A New Industrial Strategy for Europe

Deep Dive on the importance of Photonics in four Strategic Value Chains

HPC combined with Artificial Intelligence and Big Data, will provide unprecedented opportunities for transforming EU businesses, public services and society.

2.2

2.2.1 High Performance Computing and Quantum Computing Strategic Value Chain

High Performance Computing (HPC) refers to computing systems with extremely high computational power that are able to solve hugely complex and demanding problems.[65]

HPC is indispensable today across all EU strategic economic sectors (automotive, manufacturing, space, …) and in the new data driven EU digital economy.

European supercomputing infrastructure therefore represents a strategic resource for the future of EU industry, SMEs and the creation of new jobs. Moreover, HPC combined with Artificial Intelligence and Big Data, will provide unprecedented opportunities for transforming EU businesses, public services and society. One example is cybersecurity.

Access to supercomputing has therefore been long recognised as a mission-critical enabling capability for EU innovation and competitiveness[66]. The importance of HPC for Europe's future prosperity, digital transformation, resilience and strategic autonomy is reflected in the European High Performance Computing Joint Undertaking (EuroHPC JU), a legal and funding entity, created in 2018 and located in Luxembourg, pooling together the resources of the European Union, 32 European countries and three private partners with the ambition of making Europe a world leader in supercomputing[67]. The EuroHPC JU is currently supported by over €7 billion in funding from Horizon Europe, the Digital Europe Programme and the Connecting Europe Facility[68]. To-date, the EuroHPC JU has already procured eight supercomputers, located across Europe with six supercomputers already operational[69].

The EuroHPC JU mission includes "developing a European supercomputing ecosystem, stimulating a technology supply industry from low-power processors to software and middleware, and their integration into supercomputing systems".[70,67]

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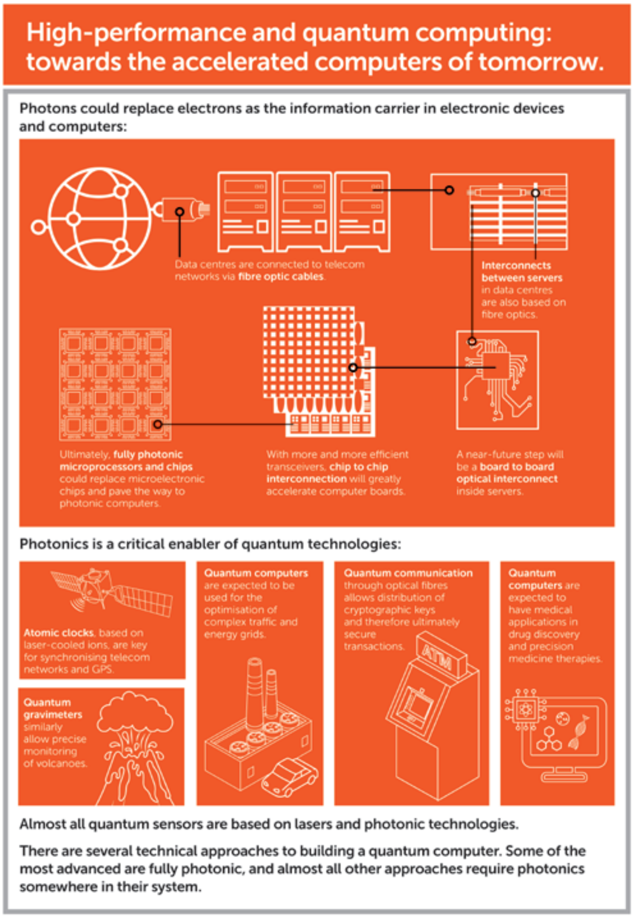
[65] https://digital-strategy.ec.europa.eu/en/policies/high-performance-computing
[66] M. Mazzucato, "Mission-Oriented Research & Innovation in the European Union- A problem-solving approach to fuel innovation- led growth", 2018, European Commission, Directorate-General for Research and Innovation, Brussels.
[67] https://digital-strategy.ec.europa.eu/en/policies/high-performance-computing-joint-undertaking
[68] In July 2021, the Council adopted a new regulation on establishing the new European High Performance Computing JU and repealing Regulation (EU) 2018/1488. It set out an ambitious mission, accompanied by a substantially larger budget of €7 billion for the 2021–2027 period.
[69] LUMI in Finland, LEONARDO in Italy, Vega in Slovenia, MeluXina in Luxembourg, Discoverer in Bulgaria and Karolina in the Czech Republic. Two more supercomputers are also underway: MareNostrum5 in Spain and Deucalion in Portugal, https://eurohpc-ju.europa.eu/
[70] Silicon photonics underpins next-gen HPC and AI, 28 April 2022, https://www.electrooptics.com/analysis-opinion/silicon-photonics-underpins-next-gen-hpc-and-ai



Whilst Photonics is not mentioned explicitly, it is recognised that all HPC systems today already incorporate some Photonics technologies and that in the future, Photonics technologies and solutions will underpin next generation HPC systems.[70,71] In short, a Photonics capability and manufacturing capacity will be critical to achieving a world-leading European HPC strategic autonomy.

For example, silicon Photonics is now seen as essential to overcome the challenges of solving the memory bottleneck for future high-performance computing systems. In particular, optical I/O enables compute, memory, and networking ASICs to communicate with dramatically increased bandwidth, at a lower latency, over longer distances, and at a fraction of the power of existing electrical I/O solutions.

In addition, Photonics technology will also be foundational to enabling emerging heterogeneous compute systems, disaggregated/pooled architectures, and unified memory designs critical to accelerating future datacentre innovation. Because optical interconnects allow off-chip signals to traverse long distances, this will allow the decoupling of a server's elements – processors, memory, accelerators, and storage – enabling flexible and dynamic resource allocation, or composability, to meet the needs of each particular workload.

Finally, the same Photonics technology also has the potential to reduce the amount of energy used in data centres and large computing systems.

The European Union has set a goal to become a world leader in both high-performance computing and quantum computing, with a digital target for 2030... to build state-of-the-art EU quantum computers by 2025.[26]

Recognising this potential impact of Photonics on future HPC systems, the Photonics Partnership has established a Focus Group on Integrated Photonics (commenced 2022 in collaboration with EPoSS) with a view to accelerating future silicon photonics research and development activities within the framework of the future Chips Joint Undertaking.

In parallel, the European Union has set a goal to become a world leader in both high-performance computing and quantum computing, with a digital target for 2030 (within its EU's Digital Decade strategy), to build state-of-the-art EU quantum computers by 2025.[72]

Reflecting this strategy, the EuroHPC JU announced in October 2022, the selection of six sites across the EU to host the first European quantum computers, which will be integrated into EuroHPC supercomputers.[73] This is the first step towards the deployment of a European Quantum Infrastructure, to make the EU a leader in the quantum revolution.

[71] Accelerating the Development of Next-Generation HPC/AI System Architectures with UCIe-Compliant Optical I/O, May 9, 2022, https://www.hpcwire.com/2022/05/09/accelerating-the-development-of-next-generation-hpc-ai-system-architectures-with-ucie-compliant-optical-i-o/
[72] https://digital-strategy.ec.europa.eu/en/policies/quantum

A Photonics technology platform for quantum computing, is the basis for one of the above six successful technology approaches deployed by EuroHPC.[74] In addition, two world leading Photonics based Quantum Computing start-ups are based in the EU; Quandela[75], a start-up based in Paris, France, and Quix Quantum[76], a photonic quantum computing start-up, located in Enschede, the Netherlands.

2.2.2 Augmented and Virtual Reality – for a European metaverse – Strategic Value Chain

The VR/AR industry has rapidly expanded in recent years, both in Europe and globally. At a global level, market forecasts indicate that the industry is expected to boom, having the potential to hit the EUR 766 billion mark in 2025[77] and to add around EUR 1.3 trillion to the global economy by 2030[78].

The European VR/AR industry market size in 2021 was estimated at EUR 9.6 billion, with a 26% growth from the previous year, and its market value is expected to increase between EUR 35 billion and EUR 65 billion by 2025, directly creating employment for up to 860 000 people[79].

The future importance of VR/AR as a next-generation display platform for deeper human-digital interactions is recognised, not only in the emerging digital economy of the Metaverse, but also in the ongoing digitalisation of European industry (for example, Industry 5.0) and equally, to advance European artistic and cultural spheres. European Commission President von der Leyen's State of the Union letter of intent[80] confirmed the European metaverse as "one of the pressing EU challenges ahead of us".

The European Virtual and Augmented Reality Industrial Consortium in its strategy paper stated "it is paramount to ensure the uptake of VR/AR in Europe"[81]. Moreover, the Consortium strategy paper conclusions emphasised that "a key challenge faced by the VR/AR industry in the EU is the sovereignty of the EU industry". The EU industry is dependent on hardware coming from non-EU countries, both in terms of pieces required to assemble a headset and of headsets itself. Most VR/AR headsets come from the US or Eastern Asia (Japan, South Korea and Taiwan being the most active producers).

[73] These newly acquired quantum computers will be based on purely state-of-the-art European technology and will be located at sites in Czechia, Germany, Spain, France, Italy, and Poland. The total support is €100 million, with 50% coming from the EU and 50% from 17 of the EuroHPC JU participating countries.

[74] The successful consortium is led by GENCI as hosting entity and CEA as hosting site, with the University Politehnica of Bucharest (UPB, Romania), Forschungszentrum Jülich (FZJ, Germany) and Irish Centre for High- End Computing (ICHEC, Ireland) as members. The targeted technology will be a photonic quantum computer that will be installed and coupled with the Joliot Curie supercomputer.

[75] https://www.quandela.com/

[76] https://www.quixquantum.com

[77] Market Research Future (2021), Augmented Reality and Virtual Reality (ARVR) Market Research Report – Global Forecast till 2030, https://www.marketresearchfuture.com/

[78] PwC (2019), Seeing is believing, https://www.pwc.com/seeingisbelieving

[79] Ecorys (2020), The potential of XR for Europe, https://xreuropepotential.com/assets/pdf/ecorys-xr-2021-report.pdf

[80] https://state-of-the-union.ec.europa.eu/system/files/2022-09/SOTEU_2022_Letter_of_Intent_EN_0.pdf

[81] VR/AR Industrial Coalition Strategic paper, Directorate-General for Communications Networks, Content and Technology Audio-visual Industry and Media Support Programmes, June 2022.

EU Commission Breton has stated that "Our ability to shape the metaverse will depend on our ability to master and develop cutting-edge technologies in Europe such as Photonics…."[82].

In fact, Photonics technologies are steadily evolving AR/VR technology to be smaller, lighter, and less power-hungry, as well as more immersive and intuitive for end users. For example, innovative Photonic technologies enabled projectors, displays, waveguides and cameras are steadily improving the performance and power consumption of AR/VR headsets.[83] In the future, what will be needed to sustain and accelerate this growth are even more photonics and photonic engineering; "brighter light sources, more efficient delivery optics, and better eye-tracking…", with ever more applications as shown in the graphic opposite.

Photonics technologies are steadily evolving AR/VR technology to be smaller, lighter, and less power-hungry, as well as more immersive and intuitive for end users.

One example is the design of high-performance AR/VR glasses/headsets. To simultaneously match the exceptional performance of human vision and keep the near-eye display module compact and lightweight imposes unprecedented challenges on optical photonic engineering.[84] Recent progress in holographic optical elements (HOEs) and lithography-enabled devices have enabled innovative ways to tackle these obstacles in AR and VR that are otherwise difficult with traditional optics.

Achieving an EU Strategic Autonomy in the Metaverse thus requires a full Photonics design, development and manufacturing capacity and capability in the European Union with a secured supply chain for key optical materials, components and headsets. In preparation to play its full role in achieving this target, the Photonics Partnership has established a Focus Group with the Partnerships AI-Robotics-Big Data/Made in Europe/6G and the VR AR Industrial Coalition. An application to join the VR AR Industrial Coalition has already been made.[85]

2.2.3 Space and Defence Strategic Value Chains

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The Vice-President of the European Commission, Josep Borrell, opened the 2023 European Space Conference with a warning, "Space has increasingly become a strategic domain for our security and defence. ***Without security in space there will be no security on earth***. … We need powerful, EU-level action to safeguard our security in and through space".[86]

He further underlined that "The geo-political competition we see on Earth is projected into space", following which he informed his audience that "the night before the Russian invasion started (in 2022), the satellite-based telecommunication network, VIASAT, was targeted by a cyber-attack, that managed to bring down entire parts of a big space communications network, used by the Ukrainian military".

Up to 10 % of EU GDP – more than €1100 billion EUR – and critical EU economic sectors (including energy, defence, finance and telecommunications) are estimated to rely partly or entirely on satellite navigation signals, space assets and/or services.[87] This provides a sharp estimation of the magnitude of the financial impact that potential disruption of space services could have.

[82] Europe's plan to thrive in the metaverse: People, technologies & infrastructure, Thierry Breton, European commissioner for Internal market, September 14, 2022, LinkedIn.
[83] Photonics Shapes the Worlds of Augmented and Virtual Reality, https://www.photonics.com/Issues/Photonics_Spectra_August_2021/i1280
[84] https://www.nature.com/articles/s41377-021-00658-8
[85] CNECT-VRARCOALITION@ec.europa.eu
[86] Josep Borrell, High Representative of the European Union for Foreign Affairs and Security Policy/Vice-President of the European Commission, 15th European Space Conference "Securing the Future of Europe in Space" Brussels – 24 & 25 January 2023
[87] European Commission, Impact assessment of a proposal for a regulation establishing the space programme of the Union and the European Union Agency for the Space Programme, Commission Staff Working Document, SWD (2018) 327 final.

The risks of space disruption are varied, from space weather events to man-made events such as military intervention and, increasingly, supply chain disruptions.

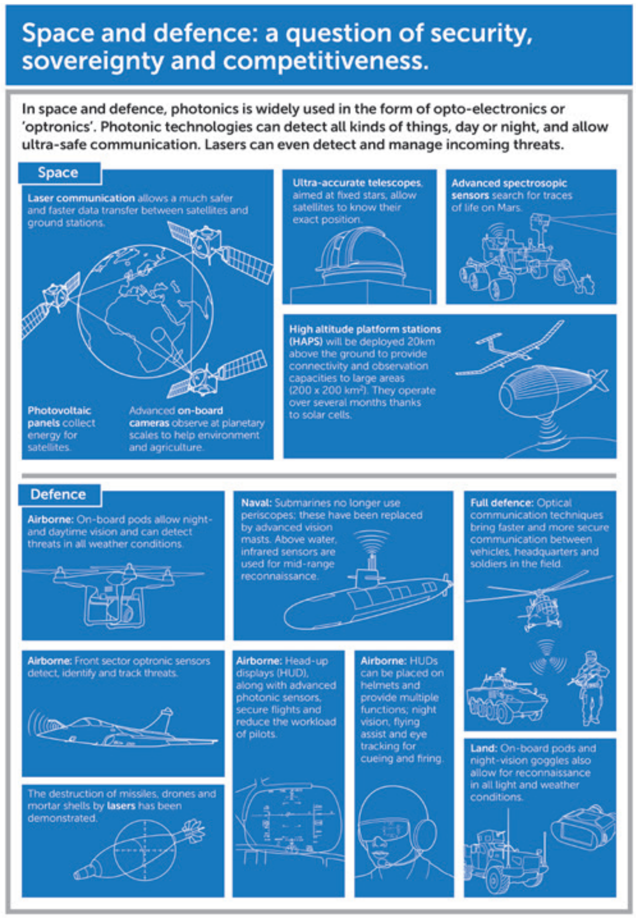
It has been long known that the EU imports a large proportion of its satellites and satellite components for its EU-based manufacturing activities. For a typical ESA satellite in 2016, more than half of the electrical, electronic and electromechanical (EEE) components were procured outside of Europe.[88] Already in 2019, Commissioner Breton had announced, "it is necessary to secure critical [space] supplies and supply chains".[89]

The recent Joint Communication[90] on "An EU Space Strategy for Security and Defence to ensure a stronger and more resilient EU" by the European Commission and the European Union High Representative, provides for a set of actions covering the strand "Resilience and protection of space systems and services in the EU" including to "Enhance the technological sovereignty of the EU by reducing strategic dependencies and ensuring security of supply for space and defence, in close coordination with the European Defence Agency and the European Space Agency".

A Joint Task Force composed of the Commission, ESA and EDA have been working to identify technologies that should either be produced in Europe or diversified through other supply chains and, has identified a number of critical areas that should be addressed over the 2021–2023 period including non-dependence in microelectronics, photonics (optics), materials, and other areas by 2023.

The identification of Photonics as a critical enabling space technology reflects the increasing use of Photonics in the space domain for navigation, telecommunications and remote sensing as shown in the graphic below. Because of advantages related to bandwidth, mass, power consumption, beam size and immunity to electromagnetic interference, photonic subsystems are now being considered in navigation satellite systems, Earth observation satellites, low Earth orbit (LEO) constellations and within telecom satellite payloads.

In addition, satellite on-board systems require continuous power supply for the whole lifetime of the satellite, which is typically provided by solar cells. Ultrahigh efficient solar cells for space application are today only produced outside the EU. In fact, challenges or disruptions in the supply of critical high-performance triple/quadruple junction solar cells could lead to an increase of EU dependency for Galileo and Copernicus satellites as well as for other new EU space assets (e.g. secure communication).



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[88] European Commission, Roadmap for the research and development activities on space critical EEE components for European non-dependence in the framework of the Horizon 2020 – Space: final report, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Publications Office, 2016.

[89] European Commission, "12th Annual Space Conference – Closing Speech Thierry Breton", Brussels, January 22, 2020, https://audiovisual.ec.europa.eu/en/video/I-183295?lg=OR

[90] JOINT COMMUNICATION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL, European Union Space Strategy for Security and Defence, russels, 10.3.2023 JOIN(2023) 9 final

Equally, there is virtually no part of a modern defence system that is not dependent in some way by optics and photonics. Modern defence systems are migrating toward optically based imaging, remote sensing, communications, and weapons. One example, covering both space and defence, is the 2022 U.S. Space Force/military optical intersatellite links (OISL) space communications initiative, considered a foundational technology for future satellites in all orbital regimes, and a solution for connecting its space systems beyond low Earth orbit.

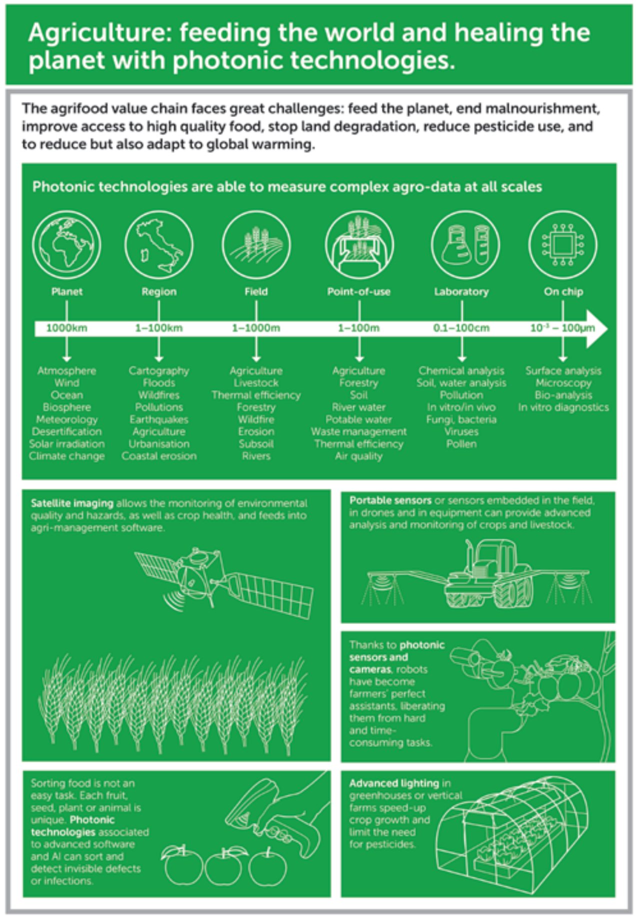
It is the intent therefore of the Photonics Partnership to establish a Focus Group with the future co-programmed European Partnership on Globally Competitive Space Systems (the 'Space Partnership') along with a second Focus Group to be established with the Partnership on Photovoltaics, to ensure its contribution to strategic autonomy in Space and Defence.

2.2.4 Agriculture and Food Strategic Value Chain

"Madrid to push for EU strategic food autonomy", said Spanish Agriculture Minister Luis Plana in a recent interview[91] discussing the future Spanish Presidency of the European Council. He emphasised "The war in Ukraine and the COVID-19 pandemic have forced us to reflect on food geopolitics and have put the concept of strategic autonomy in the value chain on the table".

The 24 February 2022 invasion of Ukraine by Russia has put, food security at the top of the EU political agenda. The 10–11 March Versailles declaration[92] agreed by the EU leaders urged the Commission to present options to address the rising food and input prices and enhance global food security in the light of Russia's war.

Agriculture is a 'crucial security policy' for EU, said EU Agriculture Commissioner Janusz Wojciechowski[93], who placed the sector alongside the likes of energy, at a meeting of EU agriculture ministers on the 21 March 2022.



The Commission presented a package of measures in its communication on "Safeguarding food security & reinforcing the resilience of food systems"[94] on the 23 March, which were promptly supported by the European Council at its meeting on 24–25 March 2022.

In similar fashion, US President Biden in the White House, on November 10, 2022, signed National Security Memorandum-16 (NSM-16)[95] to "Strengthen the security and resilience of United States food and agriculture" emphasising the importance of the Agriculture, food, and related industries to US life, wellness, health, and economy.[96]

[91] Interview, EFEAgro, 19 Jan 2023. (Note: Spain will, for the fifth time, assume the Presidency of the Council of the European Union during the second half of 2023).

[92] The Versailles declaration, 10 and 11 March 2022, https://www.consilium.europa.eu/en/press/press-releases/2022/03/11/the-versailles-declaration-10-11-03-2022/

[93] Meeting of EU agriculture ministers, 21 March 2022, EURACTIV report, 22 Mar 2022

[94] COM(2022) 133 final on Safeguarding food security and reinforcing the resilience of food systems, Brussels, 23.3.2022

[95] https://www.whitehouse.gov/briefing-room/statements-releases/2022/11/10/fact-sheet-biden-harris-administration-releases-national-security-memorandum-to-strengthen-the-security-and-resilience-of-u-s-food-and-agriculture/

[96] Agriculture, food, and related industries contribute about five percent of the United States gross domestic product (GDP), representing over one trillion dollars per year and more than 19 million jobs. The WHITE HOUSE, November 10, 2022, FACT SHEET: Biden-Harris Administration Releases National Security Memorandum to Strengthen the Security and Resilience of U.S. Food and Agriculture.

While food availability is not at stake in the EU, agricultural production will be impacted by the EU's strategic dependences on a number of key inputs. The EU is a considerable net importer of specific products which may be difficult to substitute in the short term, such as sunflower oil and seafood. Moreover, the crisis has exposed the dependency of the EU on a number of key imported inputs such as animal feed and feed additives, as well as on agricultural fertilisers.[97]

By using ever more precise sensors and measuring devices, farmers, food processors and ordinary consumers will be able to monitor and certify the safety, quality, content and even the origin of the food supply chain.

In parallel, "the European Union will be forced to produce more food but with fewer resources as the population grows"[91] again putting pressure on key agricultural inputs. Precision agriculture[98], is now advocated as the preferred EU response to both challenges; those of minimising agricultural inputs – whilst maximising outputs for given conditions. This refers to a farming practice that relies on digital techniques to monitor and optimise farming outcomes. Precision farming has applications in yield monitoring, crop scouting, field mapping, variable rate application (e.g. targeted irrigation, seeding, fertilisation, pesticide use), among others.[99]

Precision agriculture technologies and solutions include geographic information systems, satellite image processing, drones, robotics and sensors. **All** these agri-tech products use or leverage Photonics technologies. In fact, Photonics technologies are present at all stages of an advanced (high intensity) farming value chain from the inputs needed for primary production to packaging and cold storage as well as food processing, distribution and marketing, culminating in the end user (as shown in the infographic opposite).

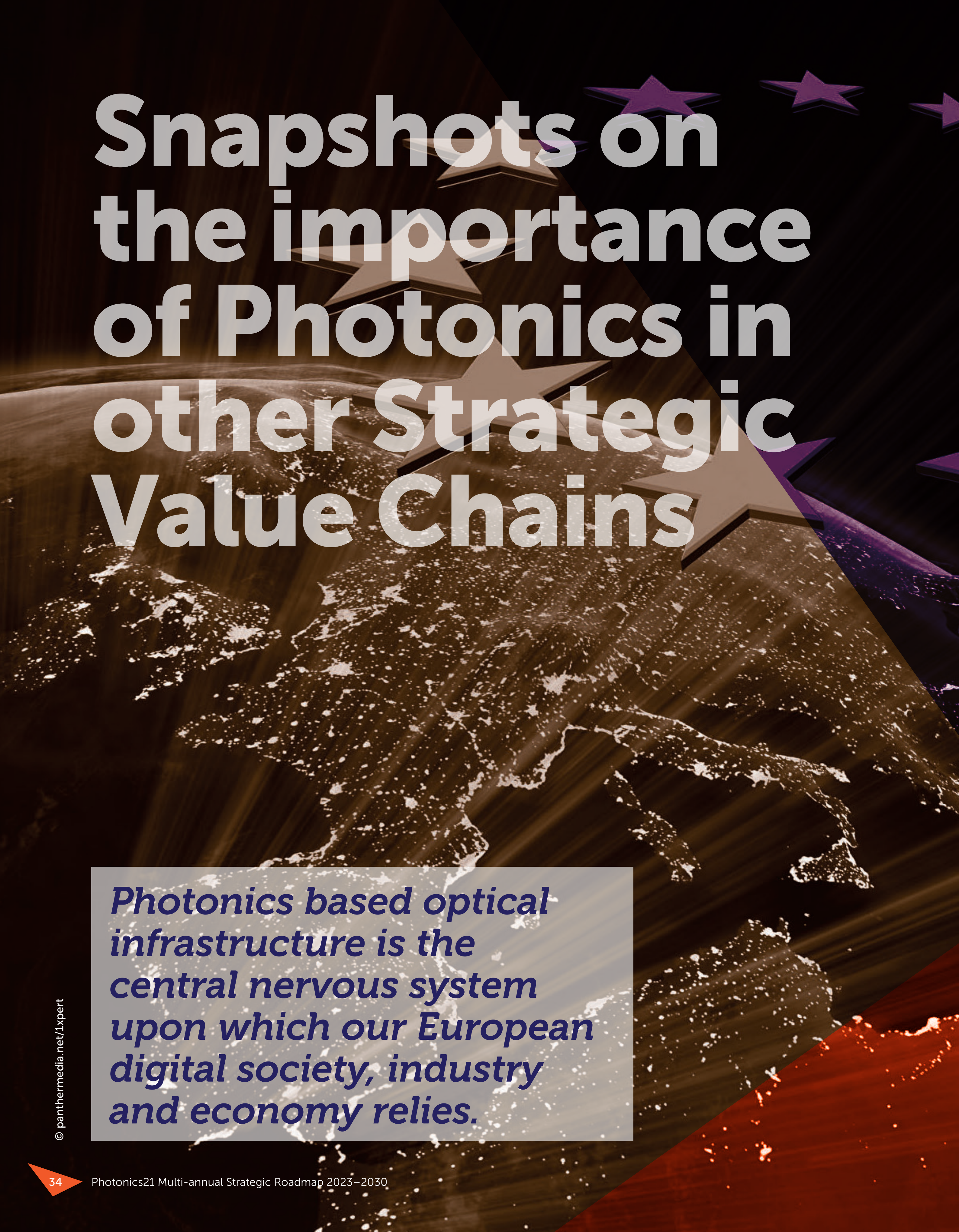
Photonics technologies in high intensity farming can monitor soil health and hydrology, predict protein levels in grain harvests, determine when to pick fruit, map water quality to check the health of fish stocks.

Photonics can therefore help to supply safe, nutritious and affordable food for all and establish a sustainable value chain from farm to fork. By using ever more precise sensors and measuring devices, farmers, food processors and ordinary consumers will be able to monitor and certify the safety, quality, content and even the origin of the food supply chain.

To contribute to the goal of EU strategic food autonomy and food security, the Photonics Partnership will establish a Focus group with the European Partnership for Safe and Sustainable Food Systems and the EU Mission Soil.

[97] Future Shocks 2022: Safeguarding EU and global food security, European Parliament, EPThinkTank, May 20, 2022
[98] Schrijver, R., Poppe, K., Daheim, C. (2016) Precision agriculture and the future of farming in Europe, https://op.europa.eu/en/publication-detail/-/publication/40fe549e-cb49-11e7-a5d5-01aa75ed71a1/language-en and EPRS| European Parliamentary Research Service, Precision Agriculture, https://www.europarl.europa.eu/thinktank/infographics/precisionagriculture/public/index.html
[99] Markets and Markets (2020) Precision Farming Market, https://www.marketsandmarkets.com/Market-Reports/precision-farming-market-1243.html

Snapshots on the importance of Photonics in other Strategic Value Chains



Photonics based optical infrastructure is the central nervous system upon which our European digital society, industry and economy relies.

2.3

2.3.1 Digital Infrastructure Strategic Value Chain

European Commission President Ursula von der Leyen underlined the importance of digital sovereignty in relation to digital infrastructure in her State of the Union speech of 2020. In the same year, Germany, during its EU Presidency, made digital sovereignty one of its priorities for the digital sector. In February 2021, Charles Michel, President of the Council of the European Union, declared: There is 'no strategic autonomy without digital sovereignty'.

In response, the European Commission published its 2021 communication[63] entitled the "2030 Digital Compass: the European way for the Digital Decade" highlighting "the vulnerabilities of our digital space, its increased dependency on critical, often non-EU based, technologies, and .... reliance on a few big tech companies" [often outside the EU]. The Commission stated that "Resilient, secure and trustworthy infrastructures and technologies are indispensable". One of the four cardinal points of the EC Digital Compass is "Secure and performant sustainable digital infrastructures".

Today, it is realised, but rarely stated, that there can be no secure EU digital infrastructure, and hence no strategic digital autonomy without EU Photonics technologies and solutions. Today, Photonics based optical infrastructure is the central nervous system upon which our European digital society, industry and economy relies, transporting data at ultrafast rates in millions of extended fibre-optic networks around the European union to homes and businesses.

In the near future, Photonics technologies will remain a critical building block of Europe's future digital network security via a Photonics enabled quantum communication cyber security capability. In the near future, finally, Photonics technologies will enable secure EU satellite communications and EU Space security.

2.3.2 Industry 5.0 and Manufacturing Strategic Value Chains

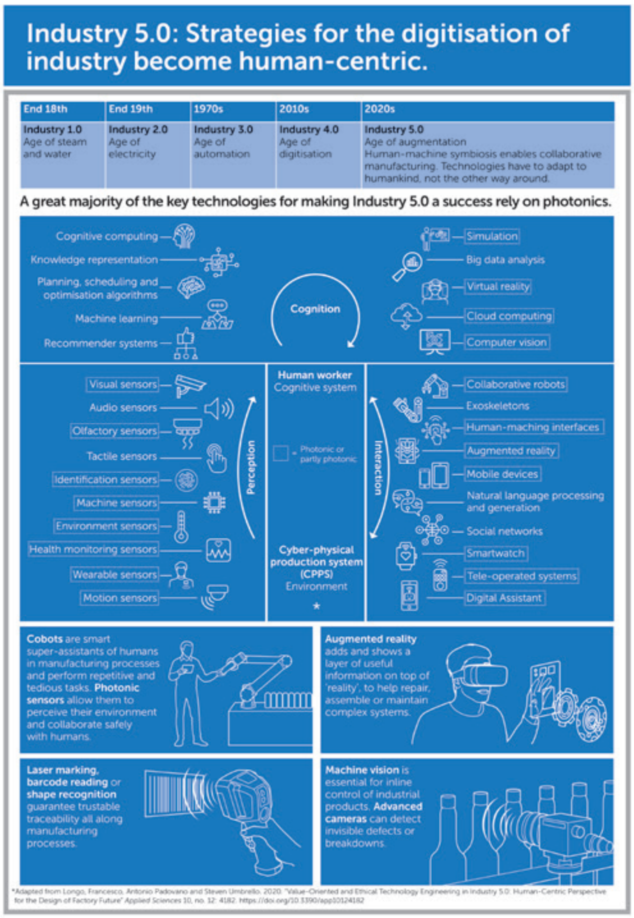
The manufacturing sector is strategic for the European union. Today, over 28.5 million people are employed in manufacturing, in almost 2 million enterprises, of which 99.2% are SMEs[100]. The EU27 has 22% of the world's manufacturing output, yielding a trade surplus in manufactured goods of €421 billion annually. Moreover, manufacturing companies represent 64% of private sector research development expenditure and 49% of innovation expenditure in Europe. Without a strong

[100] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/key-enabling-technologies/advanced-manufacturing_en

manufacturing sector and pull-through of technologies, EU deep-tech research would drop dramatically.

Over the past three years, the major innovation challenge for EU manufacturing has been the digital transformation. Industry 4.0 was the focus, enabled by IoT (the Internet of Things) and supporting technologies. It allowed integrated cyber-physical convergence, digitization, wide-scale automation and accelerated the transition from industrial automation to a full industrial digital transformation.

Photonics was a key enabler for this deployment of Industry 4.0. Photonics sensor systems provided both the sensing and measurement functionalities required to achieve Industry 4.0 in smart industrial environments and the broader manufacturing sector. Photonics enabled optical communications systems provided the security of data transfer required in hostile manufacturing environments.



The EU Industry 5.0 smart factory strategy builds upon the Industry 4.0 approach of deploying IoT technologies in manufacturing facilities. However, the concept of Industry 5.0 is built around three broad pillars; human-centric, resilient and sustainable. 'Industry 5.0' moves past a focus on IoT technology and digital transformation focused growth towards human centric manufacturing processes and, reducing and shifting consumption to new forms of sustainable, circular and regenerative economic value creation.

The EU Industry 5.0 smart factory strategy builds upon the Industry 4.0 approach of deploying IoT technologies in manufacturing facilities.

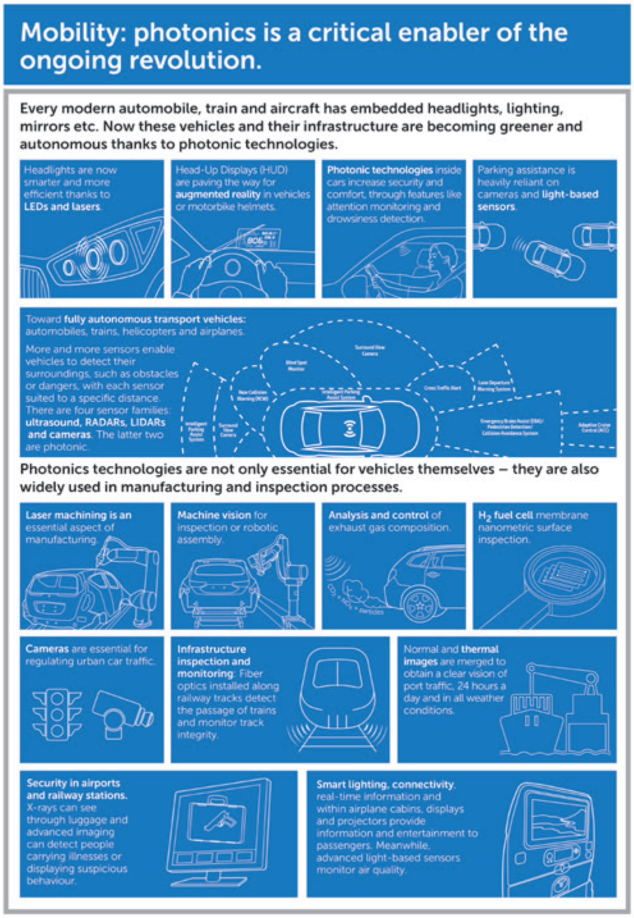
The technologies supporting the concept of Industry 5.0[101]include; human-centric solutions and human-machine-interaction technologies that interconnect and combine the strengths of humans and machines, augmented and virtual reality technologies, cyber safe data transmission, storage, and analysis technologies that are able to handle data and system interoperability, along with technologies for energy efficiency to reduce the increasing ICT footprint.

Photonics technologies will thus play an even more critical role in Industry 5.0 providing the vision for the rapidly increasing number of collaborative robots ('cobots') on the factory floor, providing the data transmission solutions for connectivity, enabling augmented and virtual manufacturing environments and landscapes, and as processes move to be more sustainable and circular, underpinning a new revolution in additive manufacturing to reduce resource consumption and waste. In addition, Photonics will enable augmented, virtual or mixed reality technology solutions, for training with cobots.

2.3.3 Automotive and Mobility Strategic Value Chain

The automotive sector is Europe's key export industry, and accounts for over 8% of EU economic output. It provides direct and indirect employment for around 13 million EU citizens, including around 8.5% of total EU manufacturing employment[102]. Almost 20% of the

[101] "Enabling Technologies for Industry 5.0", Results of a workshop with Europe's technology leaders, European Commission, Directorate-General for Research and Innovation, Unit F5 Industry 5.0, 2020
[102] https://www.acea.auto/figure/manufacturing-jobs-in-eu-automotive-sector/



world's motor vehicles are produced in Europe, with the auto industry accounting for Europe's largest trade surplus by category.

The automotive sector and its whole value chain is therefore a backbone of the European economy. It represents 11.5% of EU manufacturing employment. €374.6 billion in tax revenue for European governments in major markets and a €79.5 billion trade surplus for the EU[102]. Moreover the volume-driven car industry is a key R&D driver, accounting for 28% of the entire EU spending on R&D (€62 billion in 2019).

Photonics is now pervasive within an automotive industry supply chain, transitioning from mere lighting functions to providing cutting-edge technology for imaging, sensing, displaying, and for media communication networks as shown in the infographic.

For example, the demand for Photonic sensors is expected to grow by 21 percent (%) a year as advanced driver-assistance and autonomous-driving systems increasingly require sensors with high precision and resolution.[103]

Mobileye, the autonomous driving subsidiary of Intel, will use photonic integrated circuits (PICs) to power their next generation of lidar sensors and expects to have these deployed by 2025.[104]

2.3.4 Renewable Energies Strategic Value Chains

Year on year, Photonics enabled photovoltaics (PV) makes up a bigger part of the EU's energy mix. By the end of 2020, the EU reached 136 GW of solar PV installed generation capacity. In 2021, the EU output of PV electricity accounted for 5,5% of the EU's gross electricity output. In 2021, the solar PV industry employed around 360,000 jobs, it is expected to create 584,000 jobs by 2025, and around 1.1 million jobs by 2030.[105]

Solar energy is recognised as an important component of an independent EU energy mix and, was presented in the European response plan to the Russian invasion of Ukraine, known as REPowerEU[106], as key in fostering EU's strategic autonomy[107], climate change mitigation efforts and industrial competitiveness.

The Commission adopted in May 2022 the EU solar energy strategy[108] which identified the remaining barriers and challenges in the solar energy sector and supply chains, and outlined initiatives to accelerate the deployment of solar technologies.

Photonics enabled solar energy systems also make a significant contribution to decarbonising the EU building stock, as they can deliver a substantial part of a building's electricity and heat demand, either through solar heat collectors, solar PV (with heat pumps) or a combination of the two, including hybrid PV-thermal technologies.

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[103] https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/the-next-wave-of-innovation-in-photonics
[104] Intel sees bright future for silicon photonics, moving information at light speed in datacenters and beyond, Venture Beat, May 24, 2021
[105] https://energy.ec.europa.eu/topics/renewable-energy/solar-energy_en
[106] REPowerEU: Joint European Action for more affordable, secure and sustainable energy Strasbourg, 8.3.2022 COM(2022) 108 final
[107] https://www.realinstitutoelcano.org/en/activities/workshop-the-contribution-of-solar-pv-to-european-strategic-autonomy/
[108] COM(2022) 221 final, EU Solar Energy Strategy, Brussels, 18.5.2022

In 2019, solar heat accounted for 38 GWth[109], primarily in the form of solar heating systems for domestic hot water in residential homes. Concentrated solar heat technologies can also be used to provide heat for industrial applications and district heating.

Photonics can also be employed in other renewable energy applications including processes that use sunlight and LEDs to turn carbon dioxide and green hydrogen into clean energy products like methane gas and methanol liquid fuel.[110]

Looking to the future, Photonics enabled innovations in pulsed high-power laser-based technologies and nonlinear optical elements, are also advancing the promise of fusion energy, with considerable progress in the development of a new renewable energy source, laser fusion energy. The attainment of fusion ignition and energy gain was demonstrated at the National Ignition Facility (NIF) in the US in December, 2022.[111]

2.3.5 Health Strategic Value Chain

"Europeans clearly need to protect their own health sovereignty". States compete in the health arena, sometimes quite viciously. They seek to capture key technologies and intellectual property, and, particularly in times of emergency, they struggle over scarce resources such as [medical] equipment".[112]

Photonics technologies and solutions are essential for a fully functioning EU health autonomy.

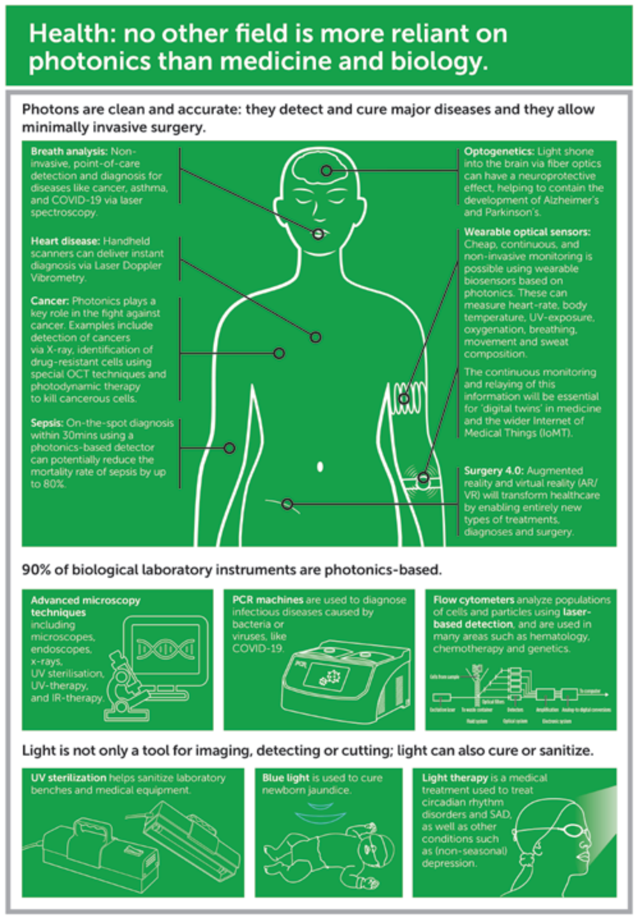
In its 2021 Strategic Foresight Report, the European Commission identified 10 key areas in which the EU should strengthen its open strategic autonomy, including the areas of 'ensuring sustainable and resilient health and food systems'.[113]

The coronavirus crisis showed that supply chains and the innovation potential of the health sector are of strategic importance. In particular, the crisis also demonstrated some serious deficiencies in access to medical equipment.

Photonics technologies and solutions are essential for a fully functioning EU health autonomy. Photonics products are used in critical healthcare applications from diagnostics and therapeutics to medical devices such as surgical guidance tools, patient monitoring and diagnostics devices.

One can list many; image sensors for medical imaging applications, fluorescence and spectral methods for image-guided surgery, fibre-based solutions for medical imaging, the use of acousto-optic elements for advanced microscopy, and the role of photonics in manufacturing of cell-based therapies, such as photo bio-stimulation of single cells and large-area tissues.

In addition, Photonics-based methods are helping to meet the increasingly demand for rapid, accurate, personalized, and cost-effective healthcare interventions.



[109] Eurostat
[110] "EU project SPOTLIGHT
[111] "National Ignition Facility surpasses long-awaited fusion milestone", The shot at Lawrence Livermore National Laboratory on 5 December was the first-ever controlled fusion reaction to produce an energy gain. https://physicstoday.scitation.org/do/10.1063/PT.6.2.20221213a/full/, 13 Dec 2022
[112] https://ecfr.eu/publication/health_sovereignty_how_to_build_a_resilient_european_response_to_pandemic/
[113] European Commission, 2021 Strategic Foresight Report, 8 September 2021, 21.

Digital infrastructure

Photonic communications are the foundation of our digital ICT infrastructure.

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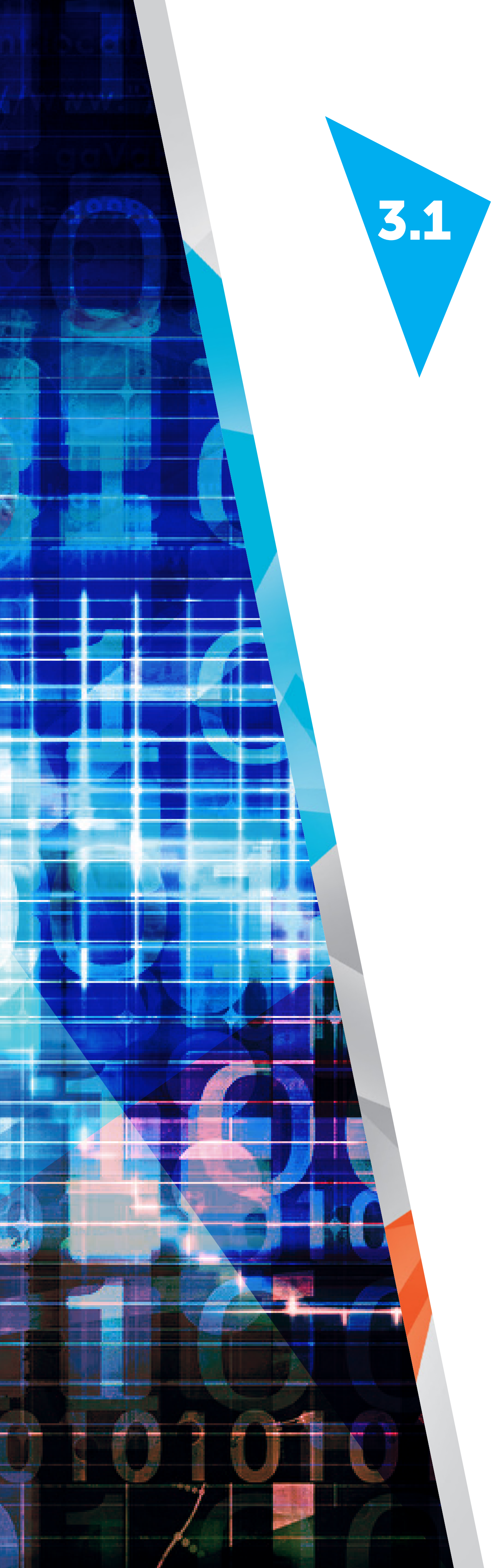

3.1

Main socio-economic challenges addressed

Photonic communications are the foundation of our digital ICT infrastructure. The global pandemic impressively demonstrated the dependency of our economy and society on communication networks, which are ubiquitously available, sustainably scalable, and provably secure. For such infrastructure, network operators, and equipment providers, annually invest more than 15 billion EUR in Europe in R&D, offer 1.74 million highly qualified jobs, and generate a value of 234 billion EUR[114].

While Europe has an industry leadership position on the network and system level, the sub-system and component levels have become increasingly problematic in past years. For commercial successful solutions, network, system, a nd component-related developments need to go hand-in-hand. Yet, design and manufacturing, as well as assembly and packaging capabilities on a commercial level, are what Europe is lacking. Despite excellent research in Europe, a critical dependence on value-chain partners in non-European countries jeopardizes Europe's technological strategic autonomy and supply chain resilience in this area. The long-term success of the European digital industry depends on how Europe can reinforce its presence in the overall value chain, capitalizing on its strengths in delivering digital infrastructure solutions for its citizens and economy.

Over the past few years, numerous unforeseen events, such as the global pandemic, the semiconductor crisis, a shortage of materials, rising energy costs, and geopolitical tensions, have demonstrated the fragility of critical supply chains. They also illustrated how little control Europe could exert to improve such situations, especially when important decisions were made elsewhere. More technological strategic autonomy and supply chain resiliency across the value chain, from the raw materials to the finished ICT products is the only way to minimize the economic and societal impact of unforeseen disruptions in the future.

Technological strategic autonomy is crucial for Europe to develop and produce competitive products and services in a self-determined way while not precluding an acquisition and/or integration of solutions from trusted partners. Strategic autonomy aims at mitigating unilateral dependencies of geographical, political, or economic nature. The prerequisite for technological strategic autonomy is a highly skilled workforce. Profound experience in commercialization and industrial development is equally necessary as excellence in application-oriented research and innovation. To increase value creation

[114] EC, "Digital Agenda Scoreboard – The EU ICT Sector and its R&D Performance", http://ec.europa.eu/newsroom/dae/document.cfm?doc_id=52246

with photonic ICT devices in Europe, focus should be placed on mastering critical design, manufacturing, integration, and design capabilities locally, while showing openness to collaborate with trusted partners in other geographical reasons where necessary and sensible.

Photonics is a key enabling technology for the coming decades and is a technology where European businesses and researchers have a proven track record. Photonics grows with an AGR of 7.5%. The semiconductor industry, including integrated photonics technologies, is particularly competitive, with aggressive subsidies and trade barriers leading to market distortions and unpredictable supply. Europe has a solid manufacturing base in photonics and specialty electronics, but new opportunities in, e.g., silicon photonics are increasingly commercialized in the US, and the outsourced assembly and test industry are based in Asia. Electronic design automation is primarily available from non-European vendors, and US trade policy has an increased impact on the markets available to European businesses. The market share of the European electronics industry has dropped from 37% in the 1990s to 8% in the 2020s.

Presently, the privacy, security, and integrity of our data is permanently at risk. So, security must be an integral part of the design of any communication solution and not an afterthought.

The ICT sector contributes marginally to the carbon footprint: it produces 1.4% of global greenhouse gases[115]. More importantly, ICT solutions have the potential to enable a 15% reduction of emissions in other sectors, which is a third of the required halving of emissions by 2030[116]. However, if future communications networks will be designed in the same way as the current generation, energy consumption would increase dramatically due to the explosion of traffic demand. Research agendas and roadmaps for optical communication systems usually emphasise performance metrics such as high speed and low latency but underestimate the importance of energy efficiency: joule/bit is not considered as important as bit/second to measure the fitness of a network. Actually, improving the network power utilisation efficiency would reduce the OPEX and help maintain its long-term capacity.

The photonics communication industry has a proven track record of lowering energy consumption due to advancements in PIC, CMOS, and packaging technologies. The targets of the green deal as well as raising energy prices in Europe represent a unique opportunity to put novel devices and technologies with the highest energy efficiency and lowest power consumption at the forefront of research and innovation activities.

Resiliency and security are key to the European digital transformation more than ever because recent events (COVID, war) have shown that we need a resilient, reliable, secure, and trustable communication, and computing infrastructure. Presently, the privacy, security, and integrity of our data is permanently at risk. So, security must be an integral part of the design of any communication solution and not an afterthought. Optical communications and networks are essential to protect massive data streams on-the-move, whether by guaranteeing network security from the physical layer (e.g., employing quantum-safe encryption) or by delivering a robust and secure infrastructure.

In this sense, we should be able to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation. Also, since photonics communication will be deployed on a much larger scale, the number of end-point with photonics technology will massively increase. This entails better and more autonomous management of network resources that can only be achieved by introducing a new generation of flexible, programmable, and interoperable communication systems and devices. Also, non-terrestrial (optical) networks (satellite, HAPS) should be considered for an upgrade for resilience and independence.

Another area in connection with cybersecurity is quantum secure communication. Quantum secure communication is almost entirely photonics based. Presently, we rely on encryption codes that are based on mathematical algorithms. However, with the advent of quantum computers, computing power will become strong enough to break codes in a shorter time. This time is called the "post-quantum" era by the data security community, and in anticipation of this event, photonics-based hardware solutions are being developed for the quantum secure communications community. The solutions are based on the generation and detection of entangled single photon pairs. Since it is challenging to

[115] ICT solutions for the climate & learning crisis – Ericsson. https://www.ericsson.com/en/blog/2022/9/ict-is-a-solutions-sector#:~:text=The%20ICT%20sector%20itself%20only,halving%20of%20emissions%20by%202030

[116] ICT's potential to reduce greenhouse gas emissions in 2030 – Ericsson. https://www.ericsson.com/en/reports-and-papers/research-papers/exploring-the-effects-of-ict-solutions-on-ghg-emissions-in-2030

create devices that can efficiently produce these deterministic photons and bring quantum secure communication to the market, more photonics technologies need to be developed.

Major photonics research & innovation challenges

Europe holds a strong research position in photonic integration using both established (silicon photonics, InP, SiN, etc.) and emerging technology platforms (LNoI, polymers, etc.), giving it a competitive advantage over other regions in the world. Using the best-suited material system for each optical function allows for optimising performance, power consumption, cost, and size. The co-existence of a large number of technology platforms has opened up the path to many novel and innovative applications making use of Europe's unique PIC environment. To leverage the investments made in the past and exploit future synergies, research and development should now focus on joining efforts and combining different material systems to facilitate unprecedented PIC capabilities. Since no PIC platform excels in all performance indicators (e.g., silicon photonics offers the most mature technology, InP, efficient active components, SiN, the most minimal loss of passive components, and LNoI may yield the fastest modulators), hybrid/heterogeneous integration of two or more materials will allow an upscaling of performance while allowing more complex applications that could be achieved by a single technology platform.

At the same time, assembly and packaging requirements are expected to evolve towards higher interconnect speeds, lower footprint, lower power consumption, more robust (sub-)assemblies, and lower cost. Novel packaging approaches featuring denser integration of electronic and photonic ICs in so-called Multi-Chip-Modules (MCM) will be critical, leveraging recent advancements in electronic IC assembly and packaging. Particular challenges relating to integration with photonic ICs include miniaturisation, increased temperature tolerance, solder reflow compatibility, and non-hermiticity. Standardised and automated processes for, e.g., optical fibre-chip or chip-to-chip alignment can drastically drive down costs when available for volume production.

Investments into PIC technology need to go beyond one-off "hero experiments". Design for manufacturing, testability, and packaging needs to be considered from the start to obtain innovative solutions that can be commercialised easily without a cost-intensive redesign with uncertain success. Fostering capabilities and fabrication processes for commercial production are required on all experimental platforms (monolithic and hybrid). A credible path towards mass manufacturing can only be demonstrated if a firm commitment of commercial foundry and manufacturing partners exists from the beginning and design tools, process design kits, and commercial manufacturing flows with guaranteed timelines, quality, and costs developed as part of project activities.

The application focus should be on next-generation optical transceivers, albeit other applications, in the field of sensing, optical tomography and LiDAR can also be addressed to exploit platform synergies and increase future manufacturing volumes. Relevant actions may include;

1) Industrial policy to support European investment in European manufacturing. This may extend from financial instruments to the independence of strategic businesses and assets.
2) Talent development and the tighter cooperation between knowledge institutions and industry in the up-skilling of technology workforces.
3) Open innovation infrastructure, building on the European Pilot Lines, and extending these capabilities to serve a wider range of innovators with sophisticated combinations of technologies. This may extend to the development of trusted methods for volume assembly and testing in Europe.
4) Open design and test automation infrastructure, allowing the building of strategic products using fully European supply chains where this is appropriate. This may include defense and security infrastructure. It also enables businesses the freedom to operate

under European trade policy without undue influence from the trade policy of other blocks.

5) The creation of heterogeneous technology hubs that can support multi-technology integration with common design and test methods which is scalable from the first prototype to volume in Europe.
6) The completion of supply chains through championing new entrant businesses that are able to connect new technologies to consumers facing industries with innovative and disruptive products.

A holistic approach is necessary to reduce the environmental impact of next-generation networks, encompassing four research pillars: energy-efficient hardware, energy-efficient software, energy-aware network planning, and sustainable operation of the network infrastructure.

A future-proof optical ICT infrastructure is the key to the sustainable growth of business and society, as well as to support the expansion of new services.

Examples of energy-efficient optical technologies are lumped integrated photonics modulators, low-loss connectors for silicon photonics to fibre coupling, optically powered devices, bistable optical switches, low-loss optical fibres, and, in the longer term, zero-energy devices that extract energy from the environment.

Optical transceivers are components where innovation activities aimed at improving energy efficiency can hugely impact on the whole network. Modern co-packaged optical transceivers have a high degree of integration, providing a bandwidth density of a few Terabit/s in a few millimeters square. By exploiting the latest progress in CMOS fabrication technology and adopting novel design approaches to the transceiver's electrical interface and optical frontend, it will be possible to minimise the need for signal processing and retiming, breaking the pjoule/bit barrier.

Following the progress of silicon photonics and semiconductor manufacturing processes, the cost of coherent optical transceivers will decrease, enabling their use in mobile fronthaul, aggregation, and access networks. This will increase the transmission distance and the number of connected users to the same central office, with consequent energy savings. In coherent optics, the most power-hungry components are the DAC/ADC and DSP. Optical DAC/ADC devices can be made more energy efficient by implementing adaptive control methods for their resolution. Similarly, the DSP ASIC is usually designed to always run at the best performance, but when sub-optimal performance is allowed, the computational complexity can be reduced, leading to much lower energy consumption. More advanced energy-saving strategies can be realised by jointly controlling the modulator driver, DSP, DAC/ADC, modulation format, and coding scheme.

Another important aspect of sustainability deals with the expected utilisation period of devices and systems (Life cycle analysis). Next to the shift to using more sustainable materials, one should also look at extending the operation lifetime of components and sub-systems but introducing more modularity and programmability/reconfigurability into devices, modules, and systems using either software or material manipulations. Increasing the reliability of optical components and systems is also crucial for the sustainability. For example, the low rate of repairs of fibre optics cable (about 50% better than copper cables due to less susceptibility to moisture, freezing, and ageing) reduced the need for replacement and repair trips.

Energy-aware network planning can be enabled by AI techniques and virtual prototyping based on digital twins. AI can also be used for remote network operation purposes to predict irregular behaviours and potential faults, thus avoiding sending personnel in place for equipment repair and replacement.

Finally, enhancing the communication infrastructure with a capillary network of sensors will enable various energy-saving measures, such as turning off lights and heat in vacant spaces in factories, offices, and houses. Optically connected sensors do not contribute to electromagnetic pollution, are immune to electromagnetic interference, difficult to intercept, and transmit a high amount of real-time data at low energy.

A future-proof optical ICT infrastructure is the key to the sustainable growth of business and society, as well as to support the expansion of new services, but it still requires significant research and innovation advances to meet the global sustainability goals.

The ICT infrastructure intended as a single integrated resource encompassing both communication networks and cloud computing is an expensive asset. Sharing it

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among different services and users is advantageous; however, it comes with unseen challenges regarding the quality of service and security. Trusted services will be carried over a single IT and telecom infrastructure while being immune to the rest of the applications, especially when targeting vertical industries.

So, a smart, intelligent, secure, and autonomous network management is needed to ensure the resiliency and security of this important asset. It is critical to derive actionable intelligence, which can be gathered by means of telemetry & sensing for service, network, infrastructure, and environmental monitoring. This enables the protection of data and network infrastructure against information leakage, espionage, natural disasters, sabotage, etc. This way, an intent-based management entity with AI-based tools can be used to handle the different alarms and detection of threats and attacks, achieving fully automated security and fault management. Given that we are facing the management of a critical and expensive infrastructure, it is important to reuse, as much as possible, the available optical network infrastructures to provide these sensing features. In this case, specifically engineered dual networking-sensing optical systems and devices should be researched.

Non-terrestrial optical networks provide additional high-speed links that are expected to help. Nevertheless, this unrolls an entirely new generation of PICs, as new packaging technologies for space applications should be developed together with PIC components and circuits that are able to operate in harsh environments while being immune to radiation.

In terms of resiliency, network automation is critical for fast reconfigurations after a fault or security leak without manual intervention. Different AI-based smart management tools are expected to monitor the performance evolution while also detecting any network anomaly. This evolution will constitute learning patterns to perform prediction of performance and, thus, improve the security, reliability, and resiliency of the network. Nevertheless, this entails an entirely new generation of systems, subsystems, and devices with the right interfaces and abilities to be fully flexible, programmable, and interoperable. This way, we can develop the different elements for high-capacity, lowest latency, full coverage transmission adaptive dynamic networks, encompassing efficient data centre interconnection to reach a unified and resilient IT and telecom infrastructure.

Fibre, wavelength, and spatial cross-connects will guarantee hard slice-ability and service isolation. However, new technologies based on integrated photonics are needed for photonic cross-connects (from core to edge networks) as well as original architectures that are easy to install and configure, especially in end-to-end optical network scenarios, breaking siloed domains. Encryption on the optical layer can enhance the security and save energy and bandwidth compared to current Layer 2 or 3 security protocols. A signal on optical fibre can be easily tapped once physical access to the optical fibre is available. This calls for introducing photonics devices to enable trust and privacy at the physical level.

End-to-end Multi-Cloud based converged communication and IT architecture needs to be enhanced for the Zero-Trust paradigm with omnipresent monitoring and anomaly protection, given the expected relevance of billions of untrusted devices and millions of untrusted sub-networks. An interesting option is to enhance the security of analogue hardware components by means of ML algorithms. In this way, non-trusted malicious nodes and devices can be detected, enhancing the security level of communications and sensing, and integrating trust management and automation with the overall network O&M architecture. Digital communication platforms (e.g., SoCs) are based on multiple hardware vendors. This is not scalable in critical and privacy-sensitive infrastructure as it is difficult to trust all hardware building blocks, and hardware-based trust anchors within the architecture providing secure isolation are required.

One of the emerging approaches for security is quantum-based technology. Critical networks (e.g., government/military) can be supported by a quantum-safe digital infrastructure. Quantum computers based on PIC will enable optical links between qubits (photonic qubit or electron/nuclear spins) that are scalable on chip and between the quantum computers: quantum network. Such infrastructures will need a new generation of high-performance quantum-ready photonic encryption methods (e.g., homomorphic, compact and longer encryption codes) and associated devices, including PICs working at cryogenic temperatures. The development of these devices also unrolls new challenges, for example, the research on ultra-low loss and power components for PICs, non-linear effects in SiN PICs that are suited for visible wavelength, and the heterogeneous integration of unconventional light sources and detectors (e.g., III-V or diamond for light sources and superconducting material for PDs).

Another point related to quantum technologies is the achievable distance in QKD: today the achievable distance of quantum communications is not compatible with deployed/installed optical networks. Therefore, new transmission, reception, and repeaters architectures/ devices should be devised to enable this compatibility. Here, a small quantum computer based on PIC for each node will play an essential role. This way, a realistic deployment of quantum communications coexisting with classical communications can be envisioned in current optical networks without requiring dedicated installations. This effort should be encompassed with the software-defined networking paradigm, keeping in mind the programmability of the systems developed and the integration with the classical optical networks. This will facilitate the adoption of quantum technologies in the current optical networking ecosystem. The long-distance quantum communication system can be extended further to a non-terrestrial optical network.

Cooperation needs with Horizon Europe Missions or partnerships

The activities described above are well aligned with the targets of the IPCEI on microelectronics and communication technologies[117] (IPCEI ME/CT), the key digital technologies joint undertaking[118] (KDT JU), the Smart Networks and Services joint Undertaking (JU)[119] and the EU Chips Act[120]. The IPCEI aims at increasing semiconductor manufacturing and design in Europe, especially in communication, and has a strong focus on commercialisation and first industrial application. The activities in this SRIA are set up to complement with a most advanced research component, which allows looking further into the future and thoroughly investigate critical technical problems. The KDT JU mostly focuses on microelectronics developments. As previously demonstrated severally, photonic circuits and integration can only be successful if the right electronics are co-developed with it. Collaboration between both initiatives facilities further electronics development compared to what is possible within Photonics21 alone. The EU chips act puts a strong emphasis on developing pilot lines, workforce enablement, and creating multi-technology design tools. All these initiatives are needed for Photonics21-related activities as well. While the EU chips act, at the moment, is not yet defined in a very detailed manner, pooling funding may be a good opportunity to obtain a critical mass of resources and increase the overall impact of the activities.

The link with the 6G Smart Networks and Services JU (SNS JU) should also be strengthened. The SNS JU and its corresponding private side 6G Smart Networks and Services Industry Association (6G-IA)[121] work from the network and system level downwards, whereas Photonics21 works from the device and sub-system level upwards. Activities in the SNS JU and the 6G-IA can derive important component and device requirements and also provide relevant test environments for prototype devices resulting from Phototonics21 developments. A close collaboration ensures that network, system, and component developments go hand-in-hand.

It must be emphasised again that the competitiveness of the European communication industry critically depends on the availability of commercial manufacturing, fabrication, packaging, and assembly partners on the electronic and photonic side. While design activities should be carried out in Europe, cooperation with trusted partners in other geographies should be encouraged if suitable commercial partners for research and innovation activities are not available in Europe. It is also recommended to closely follow the activities planned in the context of the US Chips+ program. Cooperation should be possible in areas where gaps exist in Europe and strategic autonomy and resiliency are not compromised.

117 IPCEI on microelectronics – A major step for a more resilient EU chips supply chain | European Commission (europa.eu). https://commissioners.ec.europa.eu/news/ipcei-microelectronics-major-step-more-resilient-eu-chips-supply-chain-2021-12-20_en
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121 https://6g-ia.eu/

Proposed roadmap for 2025–2030

	2025–2027	2028–2030
Photonics Research (R) Challenges, TRL up to 5	• Co-packaged optics (CPO) for intra-data centre applications • Integration of advanced materials (InP, LiNbO3, BaTiO3) with Silicon photonics • Non-linear materials for wavelength conversion • Ultra-low power coherent Transceivers • Quantum communications: coexistence in installed optical networks • Energy-efficient DAC/ADC devices for coherent optical transceivers with adaptive resolution control methods • Large-scale photonic integrated circuits (e.g., hybrid/heterogeneous photonic integrated circuits) • Digitisation of design for hybrid/heterogeneous integration (standardisation of design for interoperability between photonic foundries) • Electronics/photonics co-integration	• Ultra-wide band optical components operating across multiple fibre bands • Integration of materials for advanced optical functionality (isolation, memory, etc.) • Systems and devices for smart management and improved network resiliency • Quantum networks based on PICs • Non-terrestrial optical networks • Optical network subsystems enabled by zero-energy optical components that extract energy from the environment • Energy-aware network planning enabled by AI techniques and virtual prototyping based on digital twins
Photonics Innovation (I) Challenges, TRL starting from 5	• Chiplet- based electro-photonic Multi-Chip Transceiver Modules (MCM) • Scaling of data rates beyond 130 GBd • Multi-wavelength light sources and transceivers • Sub-picojoule/bit multi-terabit/s optical interconnection systems enabled by co-packaged optical transceivers • Energy saving methods in coherent optical transceivers based on joint control of modulation format, coding schemes, signal post-processing, DAC/ADC and modulator driver • High baud-rate TRX • Optical interconnects with high bitrates (3.2 Tb/s and beyond), low power consumption and low €/Tb/s	• Co-packaging of optics with high-speed digital silicon (e.g., in areas of high-performance computing, AI, graphics processing clusters, ...) • Scaling of data rates beyond 260 GBd • Joint sensing and communications • Quantum communications: coexistence in installed optical networks • Enhanced optical communication infrastructure with a capillary network of sensors to enable energy-saving measures • Convergence optical/wireless inside the building • Tb/s PON • Cost-effective photonic components and photonic/electronic integration for Tb/s PON • Parallel systems (arrays of components, large scale WSS/OXC)
Joint actions required with other Horizon Europe Missions or partnerships	• EU Chips Act (workforce development, pilot lines, design tools) • IPCEI ME/CT (research-development collaborations) • KDT JU (electronic drivers, amplifiers, mixed-signal chips, DSP integration) • SNS JU (network & system requirements and testing)	• EU Chips Act (workforce development, pilot lines, design tools) • IPCEI ME/CT (research-development collaborations) • KDT JU (electronic drivers, amplifiers, mixed-signal chips, DSP integration) • SNS JU (network & system requirements and testing)

Manufacturing

Digitalisation and a sustainable and circular approach to production and materials will continue to be the basis for a competitive, sustainable industry in Europe.

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3.2

Main socio-economic challenges addressed

Europe must confront new challenges by herself in all production-related processes, from the materials and logistics to the manufacturing processes. Digitalisation and a sustainable and circular approach to production and materials will continue to be the basis for a competitive, sustainable industry in Europe. However, an essential prerequisite is the strategic autonomy of the production processes and their flexibility. In this context, digitalisation and digitised production processes are indispensable keys to success. And this will require the flexibilisation of existing processes, fully digital production and process integration, as well as innovative new approaches for future applications. The following photonics-based production topics will provide solutions for a forward-looking European manufacturing and machining industry, addressing three main aspects:

1 Strategic autonomy of production
Photonics is a versatile tool to realise the "first-time right" approach with the highest quality and reproducibility. Near-market production capacities are scalable, and process chains can be set up locally, from single products up to mass production, thus shortening and securing the supply chains and achieving a higher level of strategic autonomy for production in Europe.

2 Energy and material efficiency
Photonics is a clean and sustainable tool in production processes, as using the energy provided to a workpiece is specific and selective, i.e., localised and adapted to the process requirements. Application-specific beam shaping and control depending on the interaction in the workpiece thanks to photonic sensing and direct feedback control are, along with energy-efficient flexible laser systems, the key to efficient processes.

3 Digital production
Photonics is a flexible and fully digital production tool using versatile laser systems, related manufacturing systems and self adapted process control devices, which provide a wide variety of manufacturing solutions from single products to mass manufacturing. Through its adaptability to different operating conditions and the use of AI and simulation, flexible, reconfigurable, and transformable production systems and process chains can be realised. Furthermore, interoperability with other tools in the value chains is easily achieved by the fully digital approach.

These approaches will address manufacturing challenges in the automotive, aerospace, shipbuilding, rail, oil and gas, medical instruments, printing, displays, and white goods sectors.

Europe maintains a strong position that will enable her handling these challenges: its strength in industrial photonics is part of the leadership in industrial technology, including machine tools and robotics. The global market for industrial laser systems – the largest manufacturing category for photonics – was worth €17.4 billion ($19.5 billion) in 2019[122] (€11.4 billion in 2016). European photonics companies control roughly one-third of this market.

Our mission is to support industrial manufacturing by implementing photonics-based solutions for a resource-efficient and clean way of production. The products addressed cover a wide spectrum, from tiny PICs (Photonic Integrated Circuits) and sensors to core mobility elements such as fuel cells and batteries, from sheet metal/steel to complex composites, from functional materials such as silicon and compound semiconductors to brittle sapphire and glass. By extending the photonic production processes towards opto-electrical systems, packaging, and integration, the field of quantum technology/computing and optical data processing are accessible.

As a prerequisite new set-ups for laser sources and systems will be necessary to lead to greater flexibility towards multi-purpose systems or universal machines, where subtractive and additive processes such as cutting, drilling, welding, and additive manufacturing are accessible in one system.

In addition and as a fully new tool, ultra-fast high-power laser systems will pave the way to "secondary sources" where photons help to generate specific high-energy particles (electrons, protons, neutrons) and x-ray with numerous new application fields in the future, from industrial diagnostics to cancer treatment up to fusion for energy generation at the far end.

The EUV lithography is an example of an innovative laser-based production technology in semiconductor manufacturing. In this "secondary source", laser radiation of 10.6 µm is converted into light with a wavelength of 13.5 nm to produce structural elements on silicon wafers with dimensions below 10 nm. This technology is essential for highly integrated chips of today's demand with a value chain mainly located in Europe.

The continued implementation of the approaches described here will lead to European leadership in competitiveness and energy efficiency in all production processes and process chains in this technology segment.

Major Photonics research & innovation challenges

Based on the past SRIA for Lasers and Systems for Manufacturing and related processes, a revised version has been set up, and new major photonics research & innovation challenges have been identified. These challenges can be summarised in 5 topics related to photonic systems for manufacturing and photonic processes for manufacturing:

1. Efficient and flexible laser systems and components for sustainable and green production
2. Beam delivery, shaping, and deflection systems for higher flexibility in manufacturing
3. Digital photonic production processes for optimizing process chains
4. Quality control and non-destructive testing using photonic sensors in materials processing
5. New laser-based processes for innovative production chains

> ***Our mission is to support industrial manufacturing by implementing photonics-based solutions for a resource-efficient and clean way of production.***

Laser beam sources: As a key element lasers for Manufacturing in the KW-class with different wavelengths and pulse durations are elementary for improved and also new photonic manufacturing systems. Fibre lasers, high brilliant diode lasers, and flexible disc lasers have become a widely used and cost-effective manufacturing tool. However, due to increasing energy costs, the efficiency of these lasers has to be increased, and new solutions for a cost-efficient photon delivery are needed. One of the solutions is a highly selective manipulation of single and multiple beam arrangements to allow a versatile adaption of the energy distribution with respect to the material interaction. Therefore, laser beam sources with high efficiency and adaptable beam parameters will be necessary to follow industrial needs. Especially the flexible change of wavelength from UV to IR to adapt the energy deposition to the material, or a fast change of pulsing capability from fs to cw in one device, will lead to higher precision and high productivity in laser

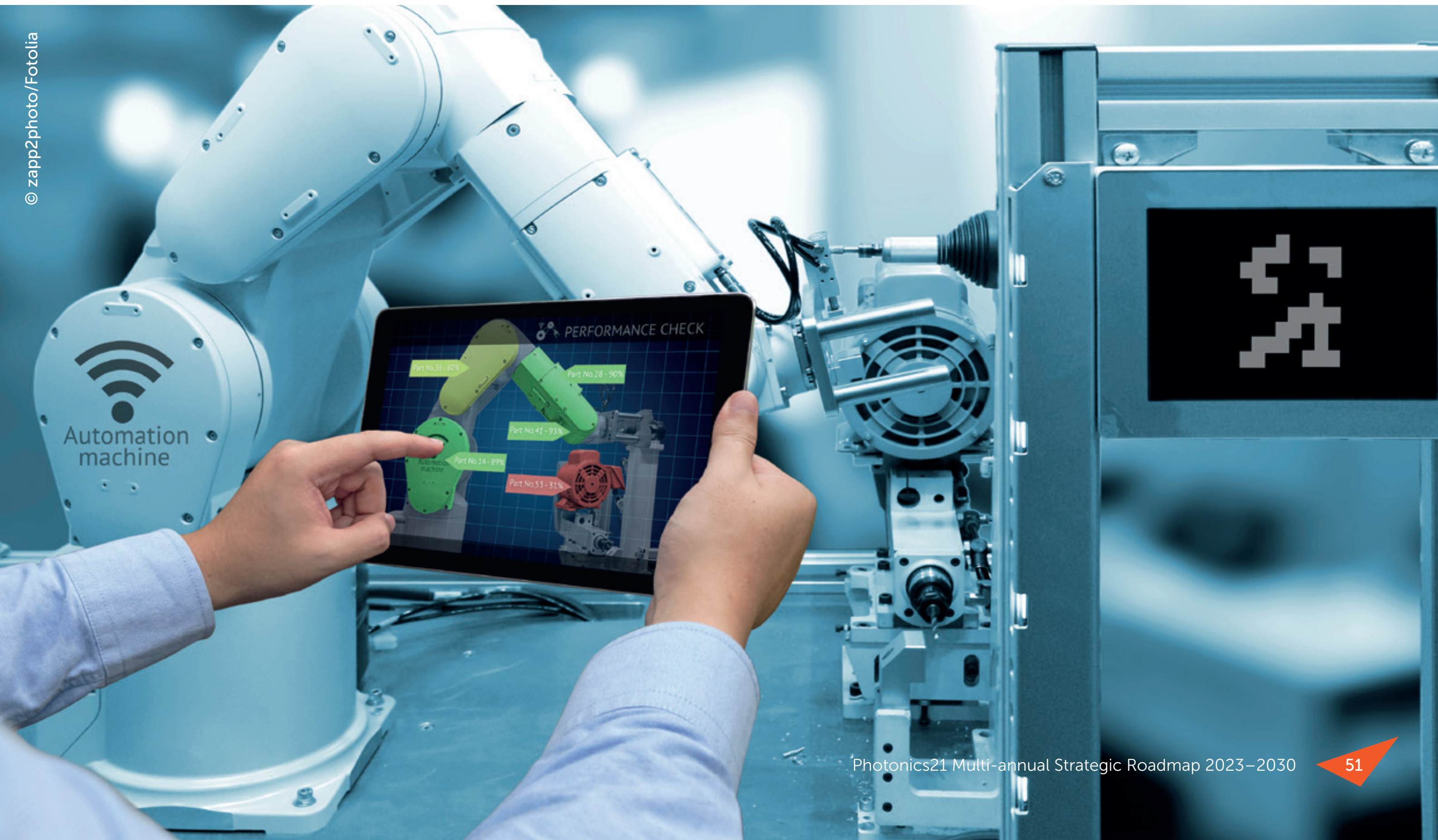
[122] Photonics Market Data and Industry Report 2020, https://www.flipsnack.com/photonics21/photonics-market-data-and-industry-report-2020/full-view.html

manufacturing. Higher beam intensities and process-adapted beam distributions are vital for challenging applications: for example, in high-temperature materials and fibre composites. This improvement will enable fast manufacturing processing that is not harmful to the material.

With the availability of high-power ultra-fast lasers, new manufacturing processes have been established. However, for mass production and large-scale processing, multi-KW-ultrafast lasers are needed with related fast beam guiding and beam modulation systems. For that, new and stable laser materials and laser component materials are required, as well as new design principles with higher power stability. Moreover, highly agile lasers with flexible pulse widths, wavelengths, and pulse energies are needed, which will unlock new applications in electronics, lightweight construction, ceramics, glass, and metal processing, leading to continuous digital and photonic process chains.

As a candidate for wavelength independency, high efficiency and multi-beam approach with the highest potential of improvement, compact and efficient high-performance diode lasers can be used, which are the basis for pumping both solid-state lasers, with a broad spectrum of wavelengths (depending on the active medium), and for direct applications as well.

Beam guiding and beam manipulation: Improving the manufacturing efficiency and quality the deposition of the laser based photonic energy regarding the material to be processed requires a selective choice of wavelength, which leads to a specific absorption length of the radiation. This can be realised by selecting the right laser wavelength, as described above. The process-dependent energy deposition also requires a specific beam distribution in time and space. For the realisation of process-specific beam distributions within manufacturing systems, powerful optical fibres and beam guidance will be required, especially for the extended wavelength and pulse duration ranges that are expected. For this purpose, innovative material systems and system designs have to be developed for the transmission of laser radiation without loss or distortion, even in the mid and far-infrared range addressing the processing of semiconductors and functional polymers. For further integration into machine tool technology, ultra-fast scanning and multi-beam processing systems will be needed for flexible production systems, enabling process speeds beyond 1.000 m/s, with simultaneous high positioning accuracy and flexibility for manageable processes in production lines.



Moreover, for enhanced positional flexibility depending on the variety of parts to be processed and the free choice of energy distribution, ultra-fast scanning devices are required, which should use all-optical scanning principles and switchable multi-beam arrangements. All these new technologies should be available for the use of high-power lasers in the KW-class, for cw lasers, and for ultra-fast lasers.

With adjustable or programmable beam shaping, optimisation by multi-space algorithms, rapid quantitative feedback by photonic sensors, and beam distribution systems with (sub) micrometre resolution and high-performance smart machining systems will be available, allowing a rapid change in production cycles and batch sizes. Additional flexibility might be gained by combining laser sources with different parameters (wavelength, energy, etc.) to have multi-scale functionalisation or multi-function in the same process. Combined with flexible manufacturing systems for multi-beam handling and fast beam switches and also in combination with traditional manufacturing processes, this will result in a new form of machine tool, enabling highly flexible and energy-efficient production and different laser materials processing (for instance, welding, cladding, surface structuring, drilling, surface cleaning, ablation, hardening, and peening)

Digital photonic production: Laser processes are perfectly suited for fully digital production. With fast beam scanning systems and flexible process parameter changes, different applications can be addressed using a single tool. To achieve high production flexibility and production efficiency, new approaches for the hybridisation of laser processes are necessary, such as the combination of additive technologies and fast texturing and AM with mechanical machining.

With digital addressable beam distributions, different components can be processed without changing the manufacturing equipment. Together with self-learning and self- optimising algorithms for selecting processing parameters, autonomous production systems that also combine different laser-based processes can be realised.

Here the use of AI and collective intelligence, as well as technology experience from former manufacturing steps and reverse engineering of beam parameters, will be critical issues for short setup times and highly reproducible production. This first-time-right approach will be a key parameter for transferring production capabilities from abroad back to Europe by shortening and securing the supply chain. As a consequence and necessary prerequisite, novel design tools for advanced photonic processes and optical manufacturing components (metasurfaces, free forms, etc.) are required, which allow reconfigurable manufacturing equipment for high-end products/components. Digital twins of all laser-based production processes and equipment and a general framework to manage, extend and use them will be the ultimate tool for increasing productivity and flexibility.

Photonics is a cross-sector technology, and pan-European cooperation along the entire value chain will be essential for future progress and success.

Quality Control and Non-Destructive-Testing: To realise a fully digital first-time-right- photonic production and a flexibilization of the manufacturing system, a powerful in-process metrology is necessary using advanced VIS/IR and multi- and hyperspectral sensing systems. With these systems, high product yield will be ensured while simultaneously maintaining high quality. This will apply to all laser manufacturing processes like ablation, welding, and additive manufacturing processes, in which defects and deviations from the target geometry must be detected and compensated for during the manufacturing of the components. High-performance sensor and vision systems such as high-speed cameras and efficient algorithms for flexible, inline-use are necessary to acquire the relevant data from the process and product. Together with self-learning intelligent process control, a highly flexible and adaptive production system can be realised.

Large amounts of potentially useful data can be generated during laser-based production. The future challenge is to maximise the value of this data by using artificial intelligence processes. Here, reduced metamodels will allow real-time evaluations and early prediction of product quality going up to lifetime predictions. The information generated will flow into comprehensive databases, thus, potentially reducing process development costs by a significant margin.

New laser applications and processes: Ultra-high-intensity laser processes allow the generation of secondary radiation from the interaction of the initial laser beam with selected materials. Here EUV, x-ray, and other wavelengths can be achieved to realise new micro- and nano-structuring processes or selected material modifications. For these radiation sources, highly stable crystals and affordable pumping sources are necessary. Hard- and soft-x-ray sources require new stable laser and radiation source components to set up new manufacturing systems for pushing the technology for manufacturing, e.g., meta-materials and functional surfaces. In particular, materials with nonlinear optical properties or adjustable refractive index for printed optical systems are needed to adapt the radiation source to the needs of the manufacturing process. This will lead to new production capabilities for new types of sensors and components for the electronic industry.

By using highly efficient laser systems, the energy footprint in production can be reduced with new laser-based processes replacing traditional high-energy consumption systems such as gas furnaces, burners, and even traditional stamping machines. Here the combination of different laser wavelengths and parameters with adapted new material formulations will strongly impact the energy-efficient manufacturing processes. The combination of laser processes with conventional processes (hybrid processes) can result in new manufacturing solutions and a higher degree of freedom in the choice of materials and tools.

Cooperation needs with Horizon Europe Missions or partnerships

Photonic manufacturing is a crucial technology for a large number of applications. Therefore, cooperation is needed with other disciplines and application-oriented partnerships. Photonics is a cross-sector technology, and pan-European cooperation along the entire value chain will be essential for future progress and success. For example, in the production of batteries and fuel cells, laser-based manufacturing is a key element within the process chain, and all relevant players need to be involved in the respective collaborative projects, research networks and clusters, providing novel and innovative solutions to manufacturing problems.

To implement laser-based manufacturing solutions in Industry 4.0, close cooperation with the Partnership "Made in Europe" (EFFRA) has already been established and should continue on many levels. This also applies to the Robotics Partnership, data analysis, artificial intelligence, and machine learning sectors. Moreover, the Batt4EU Partnership, the Clean Hydrogen Partnership, the 2ZERO Partnership, and the Water4All Partnership are potential partners to launch cooperative calls.

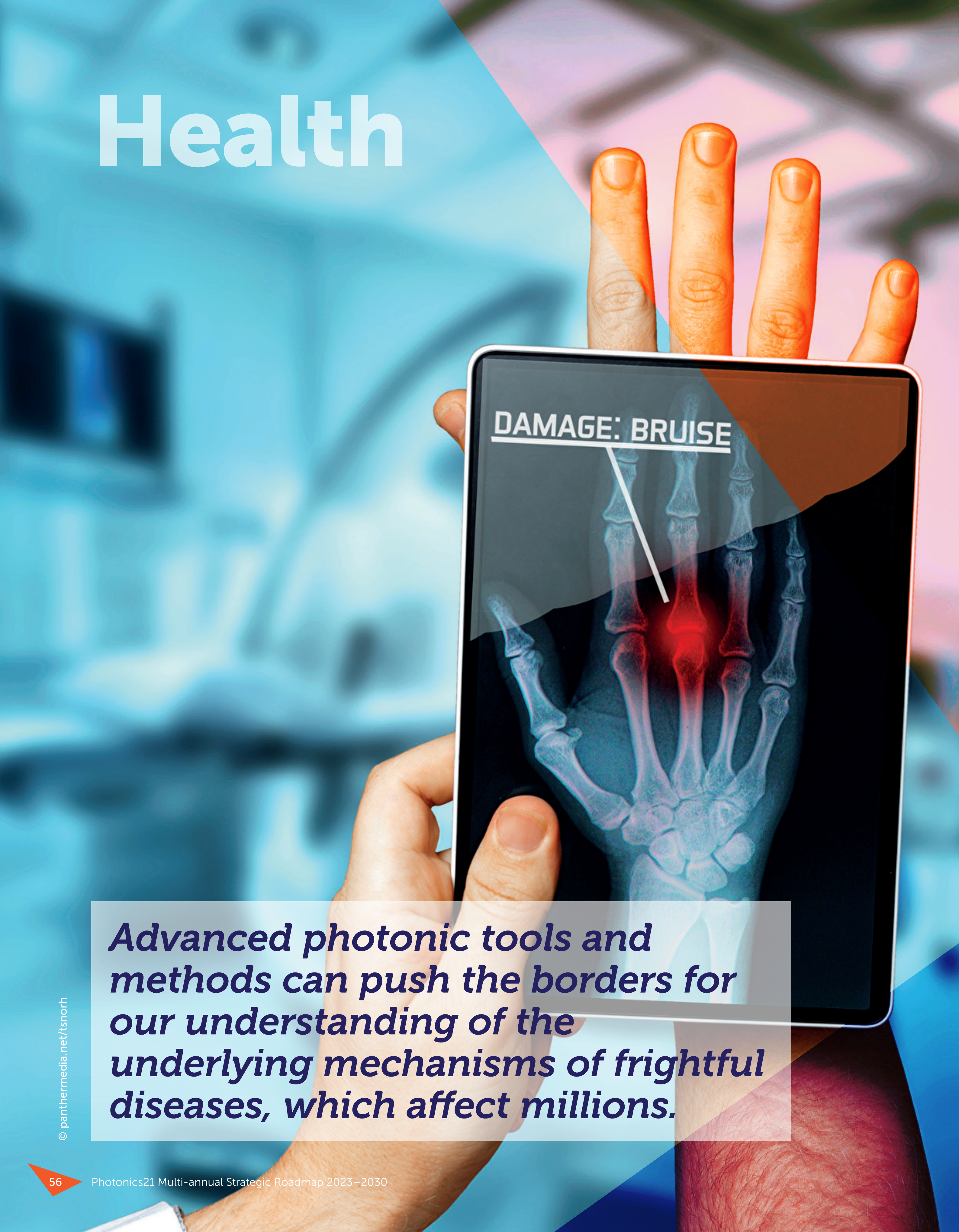
Close cooperation between corresponding work groups within the photonics sector will also be essential. Given that sensors will play a major role in the digitalisation of manufacturing process information and because components and integrated systems will be used in complex process monitoring systems, cooperation with the Work Group Core Photonics will be vital.

While industrial manufacturing touches the realms of food production and health products (for example, in Process Industries or Additive Manufacturing), the Work Group Health will be a formidable partner.
And, given that the Work Group Climate, Mobility & Energy acts as a “customer” of production systems, towards the end of the process chain, cooperation with the automotive and transport sector will be essential.

Proposed roadmap for 2025–2030

	2025	>>>	2028	2030
Overview of technological challenges	**Digital photonic production**	**Energy and material efficiency**	**Production sovereignty**	
Critical technological milestones	Flexible laser sources and high-speed beam deflection systems	Simulation and digitalisation of processes	Connected, digitalised production	
Research and Innovation challenges	**Efficient and flexible laser systems and components** • Laser beam sources with high efficiency and adaptable beam and pulse parameters • Material, coatings, and components for high-power/high-intensity beams • High-energy and highly agile ultra-short pulse lasers • High-performance diode lasers (cw and pulsed) with different wavelengths • Multi-beam lasers **Beam delivery, shaping and deflection systems** • Adjustable beam shaping with controlled energy deposition in space and time • Ultra-fast precision scanning systems (>1km/s) • Switchable multi-beam arrangements • Novel optical fibres for flexible use • High-speed monitoring and quantitative feedback systems • Multi-beam switching and processing • Miniaturised interchangeable optical processing systems • Multi-use focus head for flexible machines **Digital photonic production processes** • AI-assisted processes with adapted parameters and fully digital control • Automated parameter adaption for autonomous production systems • Design tools, simulation, and digital twin for advanced, flexible process chains • Reconfigurable manufacturing equipment for photonic-based production • Parallel processing for high throughput **Quality control and NDT** • Multi-sensor real-time process control for zero-defect production processes • On-line non-destructive testing of laser-manufactured parts • Process optimisation based on novel in-line/at-line photonic measurement • Data analysis, meta modelling, and quality prediction **New laser-based processes** • Ultra-high-intensity laser for secondary sources (EUV, X-ray, particles) • Laser-based processes replacing conventional heating/carbon-based processes • Hybrid processes (combination of laser-based processes with conventional industrial processes)			
Joint actions required	Made in Europe (EFFRA); Robotics; SPIRE			

Health



Advanced photonic tools and methods can push the borders for our understanding of the underlying mechanisms of frightful diseases, which affect millions.

3.3

Main socio-economic challenges addressed

The increasing trend of ageing in the European population is still unbroken: By 2045, the population above 65 years relative to those of working age is expected to double. Accordingly, age-related diseases like Type 2 Diabetes, many cancer subtypes like breast cancer in females and prostate cancer in males, as well as lung cancer for both sexes[123], dementia, macular degeneration, kidney disease, and cardiovascular diseases will increase. Photonic technologies can help to decrease the burden of such diseases and also help to manage less severe (but costly) conditions like, e.g., gastrointestinal or urinary tract infections.

Traditionally, care only sets in once a disease is diagnosed – in 2018, e.g., only 2.8% of healthcare expenditures were spent on preventive care[124]. Well-being could strongly be improved and suffering reduced if we could focus on the prevention of diseases, early risk assessment, or, at least, diagnosis at an early stage of disease, with increased chances for successful treatments. Advanced photonic tools and methods can push the borders for our understanding of the underlying mechanisms of frightful diseases, which affect millions, e.g., neurodegenerative diseases, find ways for early detection of, e.g., cancers and precancerous lesions, or reveal how major global pathogens cause infections, on a molecular, cellular, tissue and organism level. Also, non-invasive photonics tools, of easy application on large populations, could help in studying and monitoring the effects of lifestyle and nutrition on tissue functions and composition. Early intervention starts with diagnosis and therapy in utero, at birth, and beyond for conditions where the social burden increase as the society ages; for example, premature birth and congenital malformations. Here, the major trend is P4 Medicine (Predictive, Preventive, Personalised, and Participatory), for which early diagnosis of major diseases is imperative.

Besides these central themes, further issues have to be addressed. One is that our healthcare systems struggle to keep up with the ever-increasing costs, which will become more difficult due to our ageing society. Healthcare spending already accounts for nearly 10% of our GDP, amounting to roughly €1 trillion per annum. Saving costs has led to the trend of outsourcing pharmaceutical productions to countries outside the European Union, as the Covid-19 pandemic recently demonstrated, and needs to be reversed. Europe has to strive for strategical autonomy, which includes photonics-based bio- and med-tech products. Costs could also be saved, while simultaneously improving the well-being of European citizens if the digital transformation would be further expedited

[123] see, e.g., http://www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/breast-cancer/incidence-invasive#heading-One

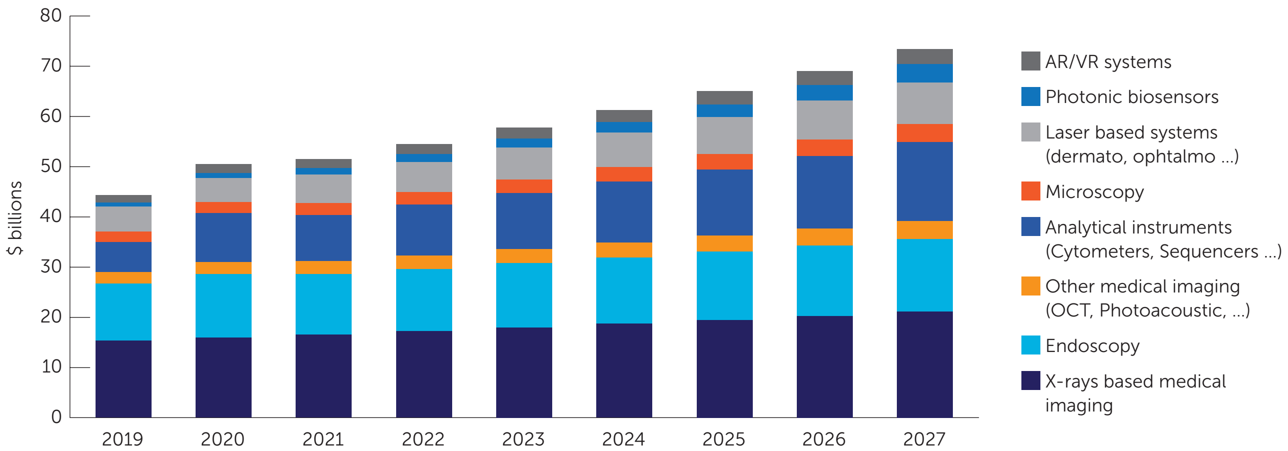
[124] https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210118-1

with regard to patient care. Communicating patients' data between different healthcare entities facilitates effective treatments and helps to develop better healthcare solutions, provided that privacy and data security is appropriately handled. Last but not least, medical technology also must become greener. When possible, disposables should be avoided, and measures should be taken to save energy and water.

European industry is currently among the global leaders in Biophotonics. This market is more mature now, growing at a rate of about 7%, with a total market volume of $87.2 billion in 2019[125]. Photonics systems for healthcare accounted for a total of $44.1 billion in 2019[126] and are assumed to reach more than $73 billion worldwide by 2027, making it not only one of the largest markets within photonics but also one of the more rapidly expanding sectors globally, a tendency to be accelerated by the current crisis. With its rich innovation landscape formed by traditional companies, start-ups, universities, and research institutions, Europe has a unique opportunity to secure a prominent role and lead the corresponding markets if the challenges are met accordingly in the next few years.

The market of Photonics systems for Healthcare is illustrated below:

Global Market for Photonics Systems in Healthcare ($ billions)



(AR: Augmented Reality; VR: Virtual Reality; See-through imaging: mainly X-Ray & Photoacoustic imaging, Surface imaging: OCT, Ophthalmoscope ...)

Source: Tematys

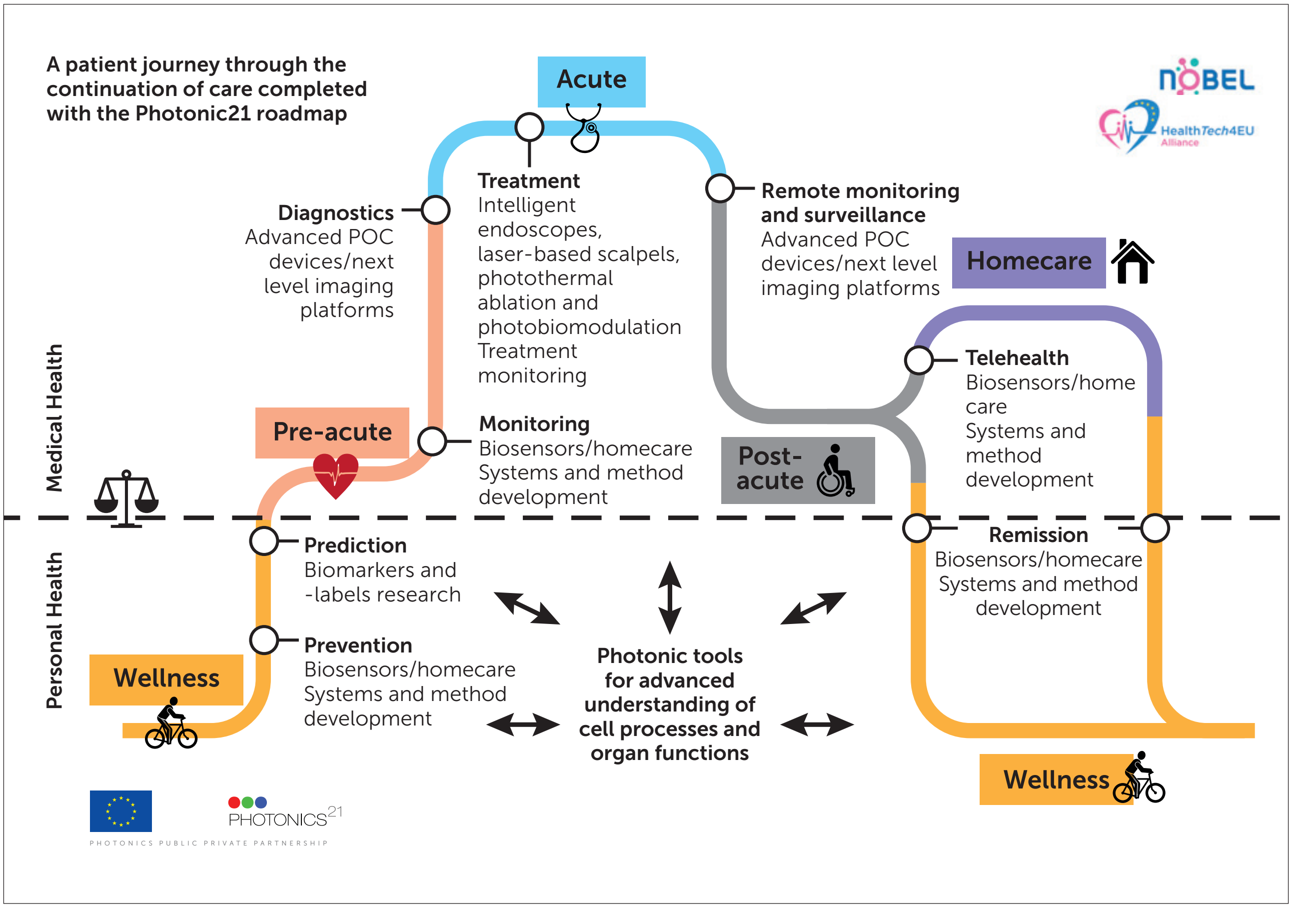
Major photonics research & innovation challenges

The Work Group Health decided to align its major photonics research & innovation challenges along the continuum of care as introduced by the EU project NOBEL and HealthTech4EU:

Accordingly, our goal is to provide photonic tools and methods that can help at all stages of a disease, starting with increasing wellness by helping to prevent and to predict those, ideally before their onset. For the pre-acute phase, mobile biosensors and other sensors, such as thermosensors and imaging sensors, and home care systems shall be developed that are able to monitor vital and health-related parameters and support diagnostics at the onset of the acute phase. Diagnostics requires more advanced equipment, like point-of-care devices or imaging platforms depending on the nature of the disease. For the acute phase, photonic tools and methods need to be (further) developed that support treatment, including monitoring of treatment success. In the post-acute phase, it can be advantageous if such monitoring is carried out remotely. Here, telehealth can play an important role, including using mobile sensors and home care equipment to accompany remission and help to keep a healthy lifestyle to prevent reoccurrence. A central, overarching theme is to better understand the disease mechanisms and how to detect and interfere with them on a molecular and cellular level. Advanced photonic tools can push the

[125] Including spectacle and contact lenses. The figure is extracted from ref. 126 below. Note that excluding lenses and X-ray-based systems, the rest of the market is growing at a fast rate of about 10%.

[126] Photonics Market Data and Industry Report 2020. https://www.flipsnack.com/photonics21/photonics-market-data-and-industry-report-2020/full-view.html



borders for our understanding, which in turn can make it possible to interfere with a range of severe diseases at all possible disease states and, eventually, prevent diseases.

For prevention and prediction, sensors have great potential not only to improve and preserve well-being, but also to prevent the onset and outbreak of diseases. Sensor technology needs to be taken to the next levels in several respects, including increased sensitivity, miniaturisation (photonic integrated circuits), a combination of multiple bands (UV-VIS-IR-THz), and the use of several techniques in tandem. Such equipment does not only allow fast, non- or minimally invasive personalised diagnostics but also scans the environment and surroundings, as well as food and water, for contaminants and micro-organisms. Such surveillance could benefit homes, schools, hospitals, workplaces, etc. In particular, for cardiovascular diseases like atrial fibrillation, wearables like watches have already proved their value, and their usefulness could be extended in the future. For example, in combination with medical databases and artificial intelligence-based methods, data recorded by mobile or stationary sensors are not only for surveillance of the medical status, but also to detect the onset of diseases long before their outbreak. Overall, such methods might also help to remind us to adapt and maintain a healthy lifestyle. The photonics aspects of such instruments may not only focus on gaining averaged data like classical point-of-care equipment, but also include imaging solutions, e.g., for in-vivo non- or minimally invasive assessment of tissues or organs like the eye. The latter is known to offer easy access to photonic methods and can be seen as a window or gateway to body health, even though endoscopic solutions also play a role here. This offers a wealth of possibilities with high potentials that are still largely unused, not only for acute, but also for systemic diseases. Overall, multi-spectral diagnostic sensor technologies, embedded in hand-helds or even mobile phones and wearables like watches or in stationary forms, combined with AI algorithms for data/image processing, have a high potential for a wide range of diseases.

Concerning prediction, we still lack suitable probes and biomarkers for cancer and several diseases like cardiovascular, neurodegenerative, and liver diseases.

Efforts outside Photonics21 have to be made to improve this situation and enable using additional, yet unknown probes. Towards personalised medicine, it may be necessary to boost bioinformatics investigations and methods addressing disease-specific metabolic processes.

In the acute phase, when diagnostics are needed, the ability to measure precisely by light-based methods could help to improve the general diagnostic accuracy, leading to a lower rate of false positive diagnoses, which would avoid unnecessary referrals and treatments. Also, a lower rate of false negative diagnoses would result in having fewer undetected diseases untreated. Optical imaging of ‘difficult to reach’ body parts, e.g., the pancreas, liver, and brain, via minimally invasive techniques would be desirable. Potentially cellular-scale resolution should be reached, which could ultimately be the gold-standard for diagnosis; this will also help to target some very difficult-to-detect diseases and treat them, e.g., pancreatic cancer. Alternatively, photonics and imaging of cellular and tissue samples, as obtained by minimally invasive sampling techniques (e.g., by fine-needle aspiration or combined with endoscopy), can provide a sensitive, specific, yet low-risk and minimally invasive strategy. Currently, fluorescence-, infrared- and Raman-based spectroscopy/imaging technologies are under intense development and have great potential, e.g., to detect cancerous tissue very easily and more quickly, together with, e.g., emerging X-ray imaging technologies driven by femtosecond lasers or quantum imaging with entangled photons. In addition to imaging, advanced gas sensors used for breath analysis, such as multiple frequency gas sensing based on QLC sources and thermal sensors, may allow the immediate diagnosis of various diseases such as cancer, infectious diseases, COPD, asthma, etc. Quickly detecting the host response can become possible with smart-based POC cell sensors.

Photonics technologies offer widespread possibilities for treatment monitoring and upgrading endoscopes. With intelligent endoscopes, i.e., spectroscopic endoscopes combined with AI, spectral interpretation could be used in the future for fast and reliable diagnosis of cancer combined with, e.g., light-based ablation or photodynamic therapy for treatment. Endoscopic treatment could, e.g., replace open chest surgery and provide surgeons with real-time feedback. Overall, lasers could replace scalpels and allow robotic surgeries flanked by photothermal ablation and photobiomodulation. For both methods, it is important to continue to work on the optical dose deposit. In addition, photonic methods can also be used to assist in the fabrication of implants/scaffolds and in tissue growth for replacement organs. Furthermore, light could be used for sanitation purposes, e.g., for illness-prevention photonics tools.

An overarching theme is the advanced understanding of cell processes and organ functions. For this, developing new photonic tools would be helpful, especially new microscopic technologies that can image with higher resolution, higher frame rates, and/or new, informative spectroscopic readout parameters. Regarding the method development, some gaps would need to be closed, e.g., to thoroughly understand tissue optics for biomarker detection and simulation to effectively predict their optical response, calibrate devices, and optimise the effects of added treatment agents.

Lasers could replace scalpels and allow robotic surgeries flanked by photothermal ablation and photobiomodulation.

Objective and reproducible data evaluation solutions (e.g., artificial intelligence-based) need to be developed. Applying ‘explainable’ AI to optical sensors/imaging data is crucial for clinicians to understand why the AI makes certain decisions and can override those if necessary. Accordingly, a framework for allowing simple descriptions of optical features may be needed, e.g., time- and frequency domain spikes that clinicians can understand.

In Biophotonics, like all medical technologies-related fields, translating a proof-of-concept to a final product is very challenging. European regulations (MDR) have considerably changed in the last few years, becoming very complex. The proof-of-concept must show potential for further development into a product that not only passes clinical trials but also fits into doctors’ workflow and gain their acceptance. Otherwise, the corresponding procedure will fail to be reimbursed. All these steps must also be considered in the face of potentially competing technologies. The whole value chain of a new medical device should be accounted for from the first phases of development. Accordingly, technologists should work with clinicians, patients, and regulatory experts in the same environment to avoid promising technologies arrive not too late on the market or in a form not acceptable to the user. Cost efficiency is also important, i.e., technologies must be cost-effective using technologies-of-scale.

Cooperation needs with Horizon Europe Missions or partnerships

Among the Horizon Europe Missions, the EU Mission on Cancer is at the heart of this Work Group's interests since this mission is about "improving the lives of more than 3 million people by 2030 through prevention and cure for those affected by cancer, including their families, to live longer and better." Accordingly, Photonics21 has partnered with this mission towards achieving its goals. Photonics tools and procedures play a critical role in diagnosing, monitoring, and treating several forms of cancer and will most likely continue to do so in the future. Specifically, early diagnosis is crucial to the successful treatment of most cancers, and here, the sensitivity and specificity of photonics-based diagnostic tools can offer game-changing solutions.

Among the other partnerships, there are several overlapping goals, with the Innovative Health Initiative (IHI) being the most prominent. IHI's "core goals are to translate health research and innovation into tangible benefits for patients and society, and ensure that Europe remains at the cutting edge of interdisciplinary, sustainable, patient-centric health research." Correspondingly, we strive at common calls to contribute to technical developments in the first place and to overcome challenges such as regulatory hurdles, standardisation, reimbursement issues, and clinical protocols.

Due to the increasing convergence of technical solutions, with topics ranging from big data to robotics, electronics, biomaterials, fibre, and nanomaterials, which are all involved in the fabrication of sensors and

wearables, a close and structured collaboration with all these stakeholders and the corresponding European Technology Platforms (ETPs) and initiatives is essential. The HealthTech4EU initiative, which we are part of and also partners with IHI, is a result of this insight.

While not neglecting the central role of more fundamental but application-oriented research in developing breakthrough solutions for diagnostics and new treatments, a pending challenge on the European level is the faster translation of the latest health technologies into the market/health care. On a national level, a corresponding initiative is, e.g., Leibniz Center for Photonics in Infection Research. This infrastructure provides an ideal approach to efficiently and quickly develop the potential of photonic technologies for routine clinical processes. On the European level, pilot lines could take over a similar function. Some of these, like MedPhab, "Europe's first Pilot Line dedicated to manufacturing, testing, validation, and upscaling of new photonic technologies for medical diagnostics", will also "accelerate the commercialisation of measurement, monitoring, and diagnostic devices and treatment instruments based on photonics technologies". Further Pilot lines like Phabulous (a pilot line providing highly advanced & robust manufacturing technology for optical free-form micro-structures), MIRPhab (A single-access point to the best miniaturised Mid-IR technology provided by a consortium of leading companies in the field of photonics), initiatives like PhotonHub, as well as academic institutions, RTOs, start-up incubators, and large industrial actors, need to be included to create and provide an innovation-friendly ecosystem, to quickly translate photonic solutions into products serving the benefit of Europe's citizens. Apart from hubs and centres, research projects aiming to launch new photonics solutions for clinical diagnostics, treatment, and treatment monitoring within smaller-scale constellations, including expert clinicians, can offer another, complementary, and viable approach for translating new technologies into the market/health care.

Proposed roadmap for 2025–2030

	2025–2027	2028–2030
Photonics Research (R) Challenges, TRL up to 5	• Advanced understanding of cell processes and organ functions based on new photonic sensing and imaging technologies (label or label-free)	• Sensor and imaging technology miniaturisation, a combination of multiple bands (UV-VIS-IR-THz) and techniques in tandem, spectral x-ray photon counting • New imaging sensors for real-time accurate biological assessment
Photonics Innovation (I) Challenges, TRL starting from 5	• Advanced Photonics-based treatment and monitoring systems and methods	• Next-generation advanced Imaging and POC systems and methods
Joint actions required with other Horizon Europe Missions or partnerships	• Potential collaborations with Mission on Cancer and Innovative Health Initiative	• Potential collaborations with Mission on Cancer and Innovative Health Initiative

Climate, mobility & energy

The European Commission's industrial policy strategy is Strategic Autonomy to make EU the world leader in innovation, digitisation, and decarbonisation.

3.4

Main socio-economic challenges addressed

The European Commission's industrial policy strategy is Strategic Autonomy to make EU the world leader in innovation, digitisation, and decarbonisation[127]. The development of automated vehicle technologies, batteries, charging systems, fuel cells, and infrastructure all need to be emphasised to reach a sustainable society. Photonics plays an important role in achieving these targets.

Climate, energy, and mobility

Decarbonisation is one of the most critical societal challenges faced by the European Union. Transportation currently provides about 14% of 2010 global greenhouse gas emissions[128]:

In line with these goals, the European Parliament and the Council have ruled[129] to decarbonise the mobility sector by reducing carbon dioxide (CO2) emissions from the vehicles sold in Europe. Achieving these targets will likely include the electrification of powertrains in some forms.

Widespread uptake of such vehicles will be needed and require affordable production of sustainable batteries.

With approximately 20,000 annual fatalities on European roads[130], the EU is still far from achieving Vision Zero[131]. This target means we shall have a road transport system where no deaths or severe injuries occur on our roads. One of the most critical game-changers is expected to be the development of autonomous (or self-driving and connected) vehicles of various types, including automated rail or metro-lines, as well as small and large ships. Automation will not only improve traffic safety but also help to reduce energy consumption and avoid traffic jams. Producing, at scale, key technological solutions for this goal will put Europe on course to achieve the 'triple zero goal' of zero emissions, zero congestion and zero accidents[132].

Our concept of mobility and ownership of vehicles is expected to change, into what is generally referred to as Mobility as a

[127] European Commission, 2019. A high-level group of experts presents the report on the future of European industry. https://single-market-economy.ec.europa.eu/news/high-level-group-experts-presents-report-future-european-industry-2019-06-27_en

[128] Global Emissions by Economic Sector, 2019. The United States Environmental Protection Agency, EPA. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector

[129] REGULATION (EU) 2019/631 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2019. Official Journal of the European Union.https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R0631&from=EN

[130] Road Safety: Data show improvements in 2017 but renewed efforts are needed for further substantial progress, 2018. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/IP_18_2761

[131] European Commission, 2020. Mobility and Transport, Road Safety. https://road-safety.transport.ec.europa.eu/eu-road-safety-policy/what-we-do_en

[132] European Commission, 2018. Europe on the Move: Commission completes its agenda for safe, clean, and connected mobility. https://ec.europa.eu/commission/presscorner/detail/en/IP_18_3708


Light projection offers new opportunities for improved driver awareness

Photo: Mercedes-Benz AG

Photo: Mercedes-Benz AG

Service (MaaS), where the use of sensors, connectivity, and IT advances will enable point-to-point fast mobility with service providers holding the vehicle ownership. Correctly managed, this will lead to less congestion and fewer emissions with safer roads for everyone. Central urban areas will be reallocated to other uses when the need for large parking spaces in the city centre diminishes. Such a paradigm shift requires the development and deployment of connected mobility systems, where photonics will play an important role. Thus, autonomous vehicles can bring a real social and economic revolution. The automotive industry is a global industry. It is essential for both Europeans and the automotive industry that Europe can take a lead on the global shift this would bring.

Photonic-driven chemical conversion of the unwanted greenhouse gas CO2 and green H2 to carbon-containing fuels (e.g., CH4, CH3OH) or other high value chemical products (e.g., syngas) has been identified as a promising pathway to a more sustainable and cleaner industry. To ensure a stable continuous chemical process requires the development of tailored energy-efficient light engines and optical components to concentrate and couple light sources with minimum losses.

Lighting accounts for roughly 20% of the world's total electricity consumption (in 2018: 26,730 TWh[133]). It is estimated that the electric energy consumption of the communication and information equipment is about 242 TWh[134]. By using lighting as a backbone for indoor or outdoor communication, it will be possible to reduce this energy consumption and thus reduce the related CO2 emissions. Saving energy with lighting will not be restricted to higher efficiency (conversion rate) of single light sources but will be looked at in a much broader societal sense. Sensor-based lighting control – embedded in building automation systems – will be omnipresent in urban installations, new buildings and used for retrofitting existing buildings.

By using lighting as a backbone for indoor or outdoor communication, it will be possible to reduce this energy consumption and thus reduce the related CO2 emissions.

Resilient supply of technologies and goods

In today's global economy, with a relationship between regional economies and their ecosystems of suppliers, a key success factor for Europe's photonics industry is to maintain and strengthen critical parts of the value chain regionally – from raw materials, hardware, software, energy consumption to production – and its domestic market access. A new focus should be placed on supply and services to be close to customers.

Major photonics research & innovation challenges

Photonic sensing

Innovative sensing and connectivity solutions will be required to increase the safety of future non-Autonomous and Autonomous vehicles. They must have a high range of robustness against environmental influences, especially under low light or adverse weather conditions. The technology must also be power-efficient and cost-effective. 3D sensors will need the required spatial resolution and range that allow motorway travel at normal

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[133] https://www.iea.org/reports/electricity-information-2019
[134] https://www.ericsson.com/en/reports-and-papers/research-papers/global-electricity-usage-of-ict-network-operators---an-extensive-data-set.

traffic flow[135]. Other types of photonics sensing that can provide vital information include polarisation and spectral sensing to assess factors such as road conditions. Means of monitoring occupants will be required to sense the driver's readiness to resume control of driving when required. Novel communication with the driver and other users would be required, involving possible different levels of augmented reality, head-up display (HUD), display projection, and multimodal interaction strategies (for example, eye-tracking). Such systems should be developed according to appropriate standards such as functional safety ISO 26262[136].

For light-driven chemical processes, it is vital to have the right reaction conditions: temperature, pressure, light intensity, chemical composition, etc. Optical fibre sensors could provide a solution to those harsh conditions and also advantages by realising an inert and integrated sensing system for the processes.

Battery health monitoring

Technology for measuring the battery's state-of-charge, health, and temperature should be safe in case of vehicle collisions or other damages to the battery pack. Non-conducting fibre optics should be beneficial. Such battery monitoring may bring additional benefits by extending the useful life of the battery in first and second-life applications.


Photonics has important benefits in the electrification of society
Photo chuttersnap: CHUTTERSNAP/Unsplash

Photonic Integration for Sensors

Key aspects to enable extensive industrialisation are the technologies' scalability, cost, packaging, integration, and robustness to harsh temperature and vibration environments. Affordable photonic sensors can be used for the Internet of things (IoT) of various systems, leveraging on the robustness and the ability to safely embed electrical non-conductive connections in various materials and structural parts to generate the necessary data to enable advanced functions like automated driving, predictive health, or maintenance monitoring.

Communication with Light (V2X)

Headlights are no longer the passive unit we have become accustomed to and have instead turned into an active device that reacts to contextual and ambient conditions. Headlamps and taillights are expected to actively extend their functionalities in future vehicles with adaptive headlight beam shapes that extend the illuminated range while remaining glare-free for approaching cars and other road users. The development of cooperative lighting schemes, where optimal use of cameras, exterior illumination, headlamps, and infrastructure information can significantly increase visibility in darkness or adverse weather conditions, especially for vulnerable road users like pedestrians who often do not carry their own light source for visibility. V2X and IoT are key enabling technologies for cooperative lighting.

The development of low-cost, reliable, and small components for light-based communication (LiFi[137]), together with the implementation of Vehicle-to-everything (V2X) will enable new capabilities of interaction between various users and devices. Automotive lights also allow the sending and receiving of optical energy for data sensing or data emission.

Climate

Reducing energy consumption (and therefore the related CO2 emissions) by 10% could be achieved by making lighting a seamlessly integrated system in buildings, objects, and within structures surrounding us. Light also influences the wellbeing of individuals. A proper combination of energy-saving and wellbeing goals are needed.

Improved monitoring of earth pollution is directly related to the European Green Deal objectives to counteract climate change. Targeted applications are improved weather observation and prediction, better quantification of greenhouse gas and pollutant within the atmosphere – including pollutants coming from human activities, better monitoring of natural resources, and better anticipation and resilience of the EU society versus extreme climate events.

[135] Amendments to UN Regulation No. 157 (Automated Lane Keeping Systems). Economic Commission for Europe, ECE/TRANS/WP.29/2022/59/Rev.1. https://unece.org/sites/default/files/2022-05/ECE-TRANS-WP.29-2022-59r1e.pdf
[136] https://www.iso.org/standard/68383.html
[137] LiFi is a technology for wireless communication between devices using light to transmit data.

Cooperation needs with other disciplines or fields

A human-centric design approach should be beneficial, where the changes introduced by the novel concepts will require intense cooperation of technologists (experts in systems and platforms) and other specialists to properly integrate the different types of sensors and information to ensure the acceptance of end-users to the concepts being introduced.

As lighting becomes more and more connected, collaboration with other Photonics21 Work Groups will become increasingly important. Machine Learning (ML) and Artificial Intelligence (AI) will play a crucial role in lighting to learn user preferences and behaviour to improve the performance of the systems by interpreting the sensor data more accurately and to allow for 'noisier' data.

Finally, high volume, cost-driven industries (such as automotive lighting) require efficient integration of the components, systems, and platforms at large manufacturing scales. Such demands require strict quality assurance and cost control for the successful introduction in the market at the pace required by the current technological change.

Proposed roadmap for 2025–2030

Energy	2025–2027	2028–2030
Overview Technology Challenges	• Extended 2D materials + integration in optoelectronic devices to save resources • Integration of energy generation • Automotive lighting (LED, OLED, laser) • LiFi, e.g., in transportation • Photonic computer simulation models (aligned with experiment) • Lighting for IoT • DC grids for lighting	• New materials (for more energy-efficient light emitters and detectors, …) • Smart GaN for HF/VHF • In-vivo sensors coupled with AI • Photoelectrochemical devices for water splitting • LIDAR for wind turbines • High-efficiency optical transceivers
Critical milestones to move from Science to Market	• Cost-effective integration of passives with usable performance • Single-chip-solution/topology for Lifi receivers • Fast phosphors for LiFi • Energy efficient LED drivers	• High-speed detectors • Low voltage photonic detectors • Long lifetime lighting systems
Photonics Research (R) Challenges up to TRL 5	• Single-chip-solution/topology for light-source: GaN transistor on LED • Extended 2D materials + integration in optoelectronic devices to save resources • Photonic computer simulation models (aligned with experiment)	• Energy-Harvesting concepts based on light (IR, visible-light), temperature and radio • New materials for compacter and more energy efficient drivers • Smart GaN for HF/VHF • In-vivo sensors coupled with AI
Photonics Innovation (I) Challenges from TRL 5	• Phosphor with high time-constant and high efficacy for low light-ripple • Integration of energy generation • Automotive lighting (LED, OLED, laser) • LiFi, e.g., in transportation • Lighting for IoT • DC grids for lighting	• Energy optimisation on system level (especially for matrix lighting etc.) • Photoelectrochemical devices for water splitting • High-efficiency optical transceivers
Joint actions required with other disciplines (e.g., Artificial Intelligence) or fields (e.g., robotics)	• CCAM/automotive industry • IoT • Photonics21 Work Groups • Energy monitoring systems • Energy-efficient Building	• CCAM/automotive industry • IoT • Artificial Intelligence • Big Data • Photonics21 Work Groups • Energy monitoring systems • Energy-efficient Building

Climate	2025–2027	2028–2030
Overview Technology Challenges		• Photonic-driven chemical conversion of the unwanted greenhouse gas CO2 and green H2 to carbon containing fuels (e.g., CH4, CH3OH) or other high value chemical product (e.g., syngas) • Photonics sensing of pollutant gas concentrations
Critical milestones to move from Science to Market		• Tailored energy efficient LED light engines to compensated for the fluctuating sunlight intensity to ensure a stable and high-quality, continuous chemical process production
Photonics Research (R) Challenges up to TRL 5		• Tailored energy efficient light engines • Human centric lighting to reduce total energy consumption
Photonics Innovation (I) Challenges from TRL 5		• Optical components to concentrate and couple natural sunlight and artificial light • Energy efficient lighting systems • Conntected lighting (within office buildings as well as for mobiity applications)
Joint actions required with other disciplines (e.g., Artificial Intelligence) or fields (e.g., robotics)		• Climate • Lighting

Mobility	2025–2027	2028–2030
Overview Technology Challenges	• Energy efficient Adaptive Driving Beam • Projection of information • Photonic Integration for Sensors • Efficient sensing technology for autonomous vehicle	• Battery health monitoring • Communication with Light (LiFi) • Immersive Interaction with displays having new properties • Micro Displays • Mixed use zone surveillance technology
Critical milestones to move from Science to Market	• Daylight vs night-time information projection requirements • Adaptive Driving Beam adverse weather performance • Optimisation and cost reduction of sensing technology for autonomous vehicle	• LiFi Range, bandwidth, and immunity requirements
Photonics Research (R) Challenges up to TRL 5	• All weather sensing technology	• LiFi Wavelength selection, communication protocols and interference handling • Virtual displays
Photonics Innovation (I) Challenges from TRL 5	• High energy efficiency lights	• Augmented reality and congruent displays
Joint actions required with other disciplines (e.g., Artificial Intelligence) or fields (e.g., robotics)	• Human factors, such as physiological effects of lighting and human information projection without causing a distraction	• V2X community

Safety, security, space & defense

The role of safety, security, defense, and space is to mitigate the negative effects that might arise from the EU's actions and to protect the European population.

3.5

Main socio-economic challenges addressed

Strategic autonomy is a growing issue for the EU. A key aspect in maintaining or increasing EU strategic autonomy in critical sectors is securing the resources and manufacturing capabilities required for intra-EU production of key photonic components and systems. This includes both tangible and intangible assets, as well as human resources.

The EU depends on external sources to close gaps in its value chain for photonics components. Examples of such components are lasers or imaging detectors. The gaps include material procurement, crystal growth, infrared optical coatings, packaging, etc. EU development of growth capabilities and research into alternative materials and technologies will drive a level of independence, for example, building objects whose properties are equivalent to material resources controlled by global players. Lastly, photonics components completed with active electronic processing could lead to the same photonics function.

Initial urgent action is required to improve and upscale the means to grow crystals in Europe (gallium antimonide GaSb, silicon carbide SiC, gallium phosphide GaP, indium phosphide InP, Sapphire…) in order to decrease EU dependence on Russia, China, and the United States.

Several key optic and electronic components used by the industry (e.g., lenses, PCB components, housings, etc.) come from extra-EU supply chains. This further amplifies risks in business continuity and resilience of production facilities. In applications related to EU security, this becomes critical.

Gaining strategic autonomy will require workforces, trained people, and educating of European engineers and technicians. These actions are of utmost importance to maintain and develop the European way of doing things.

In this context, the role of safety, security, defense, and space is to mitigate the negative effects that might arise from the EU's actions and to protect the European population from the harm of other state and non-state actors. In recent years, new and unexpected threats emerged, ranging from terrorist attacks on European territory to war near the EU borders. As a result, the theater is expanded from peer-on-peer conflicts to include a multi-domain "conflict continuum" from cooperation through competition to crisis and conflict with no clear front line[138]. Emerging technologies in the consumer market, such as small drones or 3D printing devices also exacerbate the threat to European life-sustaining infrastructure and population,

[138] D. Kilcullen, G. Pendleton, „Future urban conflict, technology, and the protection of civilians," The Stimson Centre, 2021

especially in smart cities. NATO addresses parts of this problem through the "NATO Policy for the Protection of Civilians" adopted at the Warsaw Summit in 2016[139]. Photonics, as part of the wider semiconductor field, plays a major role in improving security while maintaining the safety of the population. The variety of optical techniques is large, ranging from means to identifying people interacting in social media to supporting policing functions through directed optical measures.

The importance of photonics for current and future development of the safety, security, defence, and space sector is illustrated by the Defence Advanced Research Projects Agency (DARPA): more than 20% of the current DARPA's Microsystems Technology Office (MTO) projects include photonics and optical sensing[140].

European Defense Administration, photonic technologies support green defense by adding necessary sensing technologies for decentralized power generation, transport and storage.

The pressure on energy supply is expected to increase over the next few decades as fossil fuel resources dwindle, and the need to reduce the amount of greenhouse gases (carbon, methane) released into the atmosphere is an urgent issue. In parallel with reduction of energy consumption, the protection of power plants, energy fields, and other critical gridded infrastructure becomes increasingly vital. In addition, the "New Space" that leads to an increasing number of satellites orbiting around the earth requires new approaches to identify/remove waste debris in space.

In line with the goals defined by the European Defense Administration, photonic technologies support green defense by adding necessary sensing technologies for decentralized power generation, transport and storage. As an example, adoption of Hydrogen for powering vehicles and forward operation bases requires the ability to detect leakage of Hydrogen in real time, an issue solved by Mid Infrared sensing.

Key applications and domains addressed by photonics related to EU strategic autonomy and security include:

- Networking: This includes telecom technologies (free-space telecom for space sat-to-ground, sat-to-sat, and terrestrial links, secure and high bitrate telecom), space technologies (telecom constellations, sensors for positioning, navigation and timing [PNT], deorbiting capabilities based on photonics for sensing and lasers for action), security based on quantum technologies (quantum key distribution [QKD], quantum sensor, quantum secured encryption with photonics), sensor protection measures against laser radiations, information presentation (screens, Augmented or Virtual Reality)
- Sensing: Sensors for situational awareness, surveillance, and reconnaissance, environment monitoring at long range and from space, CBRN detection to quantification
- Security: Directed energy for anti-drone systems, new threat-agnostic countermeasures.

European defence is an important economic factor throughout the continent: in 2014, the industry had a turnover of €97.3b, with 500,000 people employed directly and 1.2 million indirect jobs[141].

In comparison, the European Space industry is much smaller with sales of €8.8b and direct employment of approximately 43,000 FTEs[142]. The Public Safety & Security markets in Europe represent $100b with a projected world robust CAGR of 9.4%[143].

Photonics technologies will provide a crucial advantage to the defence, space, security, and safety sectors: photonics offers essential enabling technology solutions to all tasks related to the acquisition, transmission, handling, storing, processing, and displaying of data, allowing people and organisations to utilise their resources to full effect. This will be particularly true when photonics-enabled quantum-computing technology will become a practical reality.

139 https://www.nato.int/cps/en/natohq/official_texts_133945.htm
140 https://www.darpa.mil/about-us/offices/mto#OfficeProgramsList
141 Defence Industry – Fact Sheet on the European Union, – 2022 – https://www.europarl.europa.eu/factsheets/en/home
142 Space Market, How to facilitate access and create an open and competitive market? Policy Department for Economic, Scientific and Quality of Life Policies, PE 695.483 – November 2021. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjx_7SQ0YX-AhXQg_0HHV4_Cw0QFnoECA8QAQ&url=https%3A%2F%2Fwww.europarl.europa.eu%2FRegData%2Fetudes%2FSTUD%2F2021%2F695483%2FIPOL_STU(2021)695483_EN.pdf&usg=AOvVaw1sEALMjECYueBzzwAUtaeD
143 Public Safety & Security Market Size, Share & Forecast – 2032 (futuremarketinsights.com), https://www.futuremarketinsights.com/reports/public-safety-and-security-market

Major photonics research & innovation challenges

Optics and photonics are becoming omnipresent in many systems, even when the system is not primarily an optical device. Modern security systems are migrating toward optics-based imaging, remote sensing, communications, and effectors. Optical sensing technology equips them to communicate information at high bandwidths from mobile platforms and can also identify chemical, biological, and nuclear threats, an ability fundamental for security and safety. Photonics is expected to contribute to future spacecraft engineering by replacing or enhancing conventional electrical approaches in digital and RF telecom payloads, sensors, micro-LIDAR, and spectrometers.

When it comes to space, aviation, and defense equipment, size, weight and power as well as cost (SWaP-C), are all important. This holds true when considering unmanned vehicles limited payloads (drones/robots) or man-portable equipment. Proposed technologies to be developed must have the foundation/potential for cost reduction when scaled.

Photonic integrated circuits (PICs) are, in this respect, the preferred option to address SWAP-C issues. As these chips increase in complexity and functionality, they find new applications; miniaturised spectrometers, integrated solid-state gyroscopes, laser beam steering, e.g., for Lidar, complex optical modulation/demodulation, optical switching, and optical beam forming. Besides the targeted SWAP-C advantage, PICs also offers a potential cost reduction (manufacturing, assembly, and qualification).

Currently, indium phosphide (InP) and silicon (Si) [including silicon nitride SiN] are the two mainstream photonic integration platforms. Heterogeneous integration, now maturing, may increase the optical power needed for some microwave photonics applications or reduce losses for quantum communications to meet stringent requirements (QKD). The development of monolithic integration of III-V on Si remains a challenge. Other possible platforms having specific properties (e.g., Silicon Germanium SiGe for wider spectral compatibility, Lithium Niobate LiNbO3 or GaP for non-linearity, polymers for flexibility) allow operation in the MWIR to visible range, which is important for atomic clocks, communications, CBRN detection, quantum and bio-sensors. Furthermore, SiC or Aluminum Nitride AlN wide band-gap platforms will allow to reach the UV for new bio-sensors.

Hybrid/heterogeneous and monolithic integration of various materials and components on these platforms represents a long-term challenge to tackle, but the interconnection of devices produced on different platforms will, in the meantime, permit cost-effective small-to-medium production of devices for specific applications (for example, chiplets).

The assembly of different technology building blocks by 3D integration on optical/electrical interposer, co-packaged

3.5 Safety, security, space & defense

or connected by passive waveguides or fibre routing systems, must be considered, as well as the 3D stacking of sensors and AI chips. Micro-optical technologies (including meta-surfaces, diffractive optical elements, and micro-lenses), eventually at the wafer level, must be developed for optical sensors relevant to small satellites and drone-based monitoring. 3D optic miniaturisation would notably enable quantum sensors based on cold atoms to fit into these limited payloads vehicles.

In parallel with the integration efforts, progress on discrete components is necessary. This is particularly the case for the performance of laser sources. An increase in power spectral density in a wide spectral range (visible to MWIR or even THz) and wall-plug efficiency is required for many applications (long-range 3D imaging, chemical sensing, quantum sensing, aerospace-grade component quality control, …), with additional demanding specifications in terms of noise, linewidth, jitter, tuneability, or modulation bandwidth. The technologies considered include semiconductors, solid-state, and fibre lasers/amplifiers. High-stability lasers are necessary for all pillars of quantum technologies. High tuneability is required for sensing applications. High-speed modulation is required for telecommunications applications.

High-power amplifier coherently combined systems in the kW range will also be needed at 1.5 µm telecom wavelengths for ground-base to satellite feeder links, and PICs can be used to split, phase- or injection-lock the amplifier channels, and steer the output beam far-field. PIC-based coherent combining is also useful at the receiver end to mitigate atmospheric effects.

An increase in the range of active sensors generally implies a large increase in the laser power required, but some architectures may be more advantageous than others from this point of view. For example, the coherent detection continuous lidars (FMCW) compared to pulsed time-of-flight systems, which also provide speed information. The significant efforts made for the development of autonomous vehicles should be leveraged for long-range applications.

Regarding spectroscopic configurations, higher sensitivity, i.e., via compact cells with long path-length or novel sensing modalities (e.g., dual frequency comb spectroscopy, photothermal sensing), could increase the signal-to-noise ratio, thus reducing the need for optical power.

Increasing the sensitivity of photodetectors is also a key point that will limit the need for optical power. The development of efficient, high-bandwidth, low-noise single-photon detectors in the near- and mid-infrared range is critical to secure fibre or free-space communications networks, while the availability of 2D arrays of single-photon avalanche detectors (SPADs) would enable 3D imaging without scanners for situation awareness in defense and security applications, and pave the way for quantum imaging.

Reducing the pixel size of focal plane arrays (FPAs) down to the optical diffraction limit or slightly below will help to improve the resolution or reduce the optic's size. Image processing algorithms based on AI or more traditionally designed will also lead to higher imaging performance, while the integration of spectral filters and polarizers can bring additional benefits in terms of discrimination of objects (decamouflage) or laser wavelengths. Among the other non-exclusive techniques to improve the performance of Detection, Reconnaissance, Identification, and Tracking of imaging systems, one can find: improved signal-to-noise ratio through High Dynamic Range capabilities, thanks to increased charge handling capacity through 3D integration or digital pixels, increased sensitivity for laser pulse detection through Asynchronous Laser Pulse Detection in the pixel readout circuit or other even more advanced design in multifunction pixels.

Incorporating digital image processing functions as a part of the optical system opens up new dimensions in the optical design space.

Advances in optical technologies are driven by size, weight, resolution, cost of imaging optics and by the architectures of sub-systems to point, track, and stabilise the line-of-sight of laser beam directors. High-optical resolution in imaging systems and low-divergence laser beams correlate with the effective diameter of the photon collecting beam forming aperture. Large aperture optics are generally heavy, costly, and induce unwanted optical aberrations. A way to tackle these problems is to use segmented optics and electronic feedback loops to control and manipulate the wavefront across the aperture. Coherently coupled multi-aperture laser beam directors are required for long-range optical data links and directed energy applications. New feedback strategies like target-in-the-loop algorithms need to be devised to control the phase settings on the sub-apertures and shape the irradiance on the receiver/target.

Incorporating digital image processing functions as a part of the optical system opens up new dimensions in the optical design space. Replacing lenses with digital processing functions combined with point-spread function engineering could reduce the number of lenses required for aberration compensation and may improve the performance of the digital image processor. Additionally, freeform and meta-optics are expected to greatly simplify optical systems required for long-range surveillance and reconnaissance operations as well as in small-sized optics for miniaturised mobile platforms.

UAVs are omnipresent in today's conflicts, and the threat of drone attacks in large public events or on critical infrastructures must be seriously addressed. Multi-sensors suites, including photonics sensors, may help to detect and track drones. There are two ways to optically deny the mission of UAVs or other mobile threats: either by dazzling optical sensors with low-power lasers or by sensor-agnostic destruction with high-power lasers. Eye-safe laser development is required for urban scenarios.

UXO (Unexploded Ordinance) can be addressed with photonics using standoff detection and neutralisation. For example, the detection of ordinances on ground could be done by using an airborne-based laser scanner and hyperspectral imaging used for agriculture.

Easy access to advanced semiconductors technologies, especially for PICs, is the key factor of strategic autonomy for the European photonics industry. In that sense, Pilot Lines that, at the same time, serve commercial market niches and safety, security, and defense applications are mandatory. Synergies between commercial and defense applications should be merged in the definition of the coming next Pilot Lines, taking advantage of the Pillar 1 of the European Chips Act.

Cooperation needs with Horizon Europe Missions or partnerships

Photonics is essential for securing Europe's technological sovereignty across the five Horizon Europe Missions:

- Climate-resilient Europe for at least 150 EU regions by 2030
- 100 climate-neutral and smart cities by 2030
- Restore our ocean and waters by 2030
- A soil deal for Europe
- The European Beating Cancer Plan.

The Photonics 21 stakeholders will address innovative photonics solutions related to safety, security, space, and defence to achieve the following objectives related to the Horizon Europe Missions:

(1) Enhance the collaboration between the techno-scientific community and European industry through innovative, attractive, and concrete research projects assuring Europe's transformation into a green, healthy, and resilient continent;
(2) develop photonics hardware, software, and system solutions that facilitate the safe and secure execution of Europe Horizon Missions and defend the transformation process against any adversary;
(3) build low-rate initial production (LRIP) lines for security and defence products whose lifecycles are dominated by characteristics very different from mass market products for daily use.

Through the implementation of the roadmap, the challenges posed by the Horizon Europe Missions will be addressed by a coordinated effort linking the necessary resources via clearly defined, targeted, and measurable activities across different photonics disciplines and stakeholders in research institutions and industry.

EDA CapTech Optronics and Captech TCM: the European Defense Agency (EDA) currently organises its R&T priorities in 11 Capability Technology (CapTech) groups, which are networking fora for experts from government, industry, SMEs, and academia, moderated by EDA[144]. Close collaboration with the EDA CapTech Optronics (also called EOST – Electro-Optical Sensors Technologies) and Captech TCM (Technologies for Components and Modules) would be highly beneficial given the importance placed on dual-use technologies by these CapTech. A major task of this CapTech is to elaborate SRA documents, including "...forecasting future civilian technology development in electro-optics relevant to military users, identifying areas where civilian technology development will not be sufficient for the needs of the military user...". Therefore, the joint elaboration of SRAs involving dual-use optical technologies is highly beneficial.

European Defence Fund: the European Commission establishes a dedicated fund with the EU budget, the European Defence Fund (EDF)[145], to support collaborative research and development of key products and technologies for the security and defence of Europe and its citizens. The multi-annual budget of the fund is about €8b for the framework 2021–2027, with 1/3 for research actions. As concluded from a review of DARPA activities, photonic technologies will play a major role in many areas of EDF. Consequentially, the joint elaboration of dual-use optical technologies for Safety, Security, Space, and Defence applications will be beneficial, reducing the duplication of efforts and maximising the synergistic effects of joint planning (and possibly execution) of advanced dual-use photonic technologies.

[144] https://eda.europa.eu/what-we-do/all-activities/activities-search/captech-optronics
[145] https://defence-industry-space.ec.europa.eu/eu-defence-industry/european-defence-fund-edf_en

Proposed roadmap for 2025–2030

	2025–2027	2028–2030
Photonics Research (R) Challenges, TRL up to 5	• Sub-systems based on emerging PIC platforms with hybrid and heterogeneous integration of various materials and components, allowing operation in the MWIR to UV range, for applications in atomic clocks, communications, CBRN detection to quantification, quantum and bio-sensors • Development of efficient, high-bandwidth, low-noise single-photon detectors in the near- and mid-infrared range • Low-noise lasers for quantum technologies • 2D arrays of single-photon avalanche detectors (SPADs) • New approaches incorporating digital processing functions as part of the optical design space for imaging systems/laser beam directors • Study of space hardened very high data rates transceivers based on complex modulation schemes (type DP-QPSK…) for space FSOs (free space optical coms) • Research of alternative materials (including metamaterials) to replace scarce or hazardous ones for existing and new photonics applications	• Sub-systems based on PIC platforms with monolithic and heterogeneous integration of materials and components • Quantum PIC chips (QPIC) • 2D SPAD arrays with embedded processing • High power 2D phased-array semi-conductor lasers
Photonics Innovation (I) Challenges, TRL starting from 5	• Assembly of different technology photonic building blocks by 3D integration, on optical/ electrical interposer, co-packaged or connected by passive waveguides or fibre routing systems • Micro-optical technologies (including meta-surfaces, diffractive optics, micro-lenses, filters, polarizers), eventually at the wafer-level • Photonic technologies for satellite constellations: space tolerant sensors for positioning, navigation and timing (PNT), inter-satellite distance measurements • Free-space telecom systems for the Quantum Secured Network (QSN), based on novel photonic components • SWAP-C innovative sensors for long range situational awareness, ISR[146], 3D imaging and chemical sensing (CBRN) • High power eye-safe laser developments for emerging threat countermeasures, including dazzling, jamming and neutralizing capabilities • Sensors protection against laser radiations • Growth of crucial III-V and oxide materials for photonics and exploration of advanced processing techniques	• Demonstration of fused optics/electronics imaging systems • 3D stacking of sensors and photonics AI chips. • Miniaturized PNT sensors including quantum-based sensors for Quantum Information Network (QIN) • Miniaturized long range sensors exploiting quantum technologies • SWAP-C eye-safe high power laser effector systems • Large size III-V substrates and epitaxial wafers • Space hardened very high data rates transceivers (DP-QPSK)

[146] ISR: Intelligence, surveillance, and reconnaissance, i.e., monitoring an assigned area consistently over a given period of time to build up operational knowledge.

Agriculture and food

There has been a hugely increasing focus on sustainability in the last years, targeting agriculture, food production and processing, and forestry.

3.6

Main socio-economic challenges addressed

There has been a hugely increasing focus on sustainability in the last years, targeting agriculture, food production and processing, and forestry. This is due to the mounting global challenges of climate change and its risks, supply chain stability from a geo-political perspective, lack of specialists in all working fields, guaranteed food availability for a growing population, and a need for digitalisation in all socially relevant areas. Therefore, the photonics application roadmap for fields in agriculture, forestry, and food has to address the diverse challenges, taking into account the actual and foreseeable geo-political and economic developments. The visions, trends, and framework conditions that need to be considered in our future Photonics strategy will be the following:

- How can we contribute to the large EU Objectives/SDGs?
- How can we contribute to the EU Missions?
- Which technical developments do we currently foresee?
- How do we expect market conditions will change?
- Are there any socio-economic conditions changing?
- How should we react to changes in the Political and Policy areas?

The Work Group Agriculture & Food now needs to turn these visions into a series of roadmaps, which will develop advanced products and services that meet the short- and long-term needs of this diverse ecosystem, bearing in mind the technological autonomy and a level of self-sufficiency in a global manner.

This means that by 2030, the technology must be able to feed a world population of 10 billion, cut down food-borne illness, increase food safety and quality issues, and reduce the environmental footprint of agriculture, forestry, fisheries, and aquaculture needs while also protecting forests, oceans, fauna and flora against climate change impacts and paying attention to animal welfare following the Council Directive 98/58/EC. Photonics has already contributed to the supply of safe, nutritious and highly-quality food and has an increasing impact in establishing a sustainable value chain from farm to fork. But this value chain is highly-sensitive to any geopolitical and pandemic influences. Also, increasing production costs should not be shifted to an unaffordable food supply.

- Feeding a fast-growing global population will require a dramatic increase in food production while simultaneously using highly innovative technologies to reduce climate impact. New technologies and new ways of production have to be boosted, such as vertical farming close to urban spaces with controlled atmosphere, reduced energy and water consumption, reduced logistic needs, and increased production independent of environmental influences.

3.6 Agriculture and food

- The increase of life-stock animals due to the growth in world population, leading to intensive farming practices, also leads to overconsumption of antibiotics, potentially leading to the development of antibiotic-resistant bacteria that can cause foodborne infections via contaminated meat, milk, or eggs.
- Increased energy process has led to record-high input fertilizer production costs. (The UK-produced ammonia nitrate fertilizer has increased by 152% since May 2021.) Rising natural gas price in Europe has caused widespread fertilizer production cutbacks, and due to reduced usage, crop yields will be impacted in the coming years. Photonics technology can contribute to precision fertilizing and better soil quality testing. Precision fertilizing means high density analysis of soil and plants, which will result in a high density of sensors (these should be low cost and degradable) or ultra-fast low density sensors of high quality that can scan large areas.
- Consumers are placing much greater emphasis on food safety, quality, and the value chain transparency with regard to, e.g., reduced food waste, animal welfare, and CO_2 footprint, which clearly require photonics technologies to support these consumer expectations.
- Europe is the world's largest exporter of agricultural and food products besides, the export of food processing machinery, which includes optical technologies and sensors for in-line monitoring. But export and import strategies need to be rethought and adapted to restricted market access; strategic autonomy and self-sufficiency have to be a priority.

- Europe is a pioneer of high-tech precision farming. In this framework, photonics technologies provide a powerful toolbox for a significant technological shift in the ways farmers grow food and for thinking out-of-the-box ways to increase food production globally. Increased autonomy and decision-making tools in farming will also make farming a more attractive profession for future generations. This will require extensive data interpretation and model creation to turn data streams from real-time photonic sensors into actionable insights.

Major Photonics Research & Innovation Challenges

The following challenges have to be in the focus of major research and innovation topics:

Predictive, proactive, preventive Agri-Food[147]
On a farm, e.g., microscopic as well as hyperspectral (e.g., VNIR (400–900 nm), SWIR (1100–1700 nm)) or 3D imaging (e.g., using LIDAR: SWIR, i.e., 1300/1500 nm) are technically able to detect the earliest onset of fungus, mildew, pests, and disease, thus potentially reducing the need for agricultural chemicals and food waste in general. Spectrometry and laser scanning can, in principle, detect product ripeness and determine the optimum time to harvest and ship food. Yet these tools are barely affordable and require specialist users.

In fruit and crop processing, hyperspectral imaging (e.g., VNIR (400–900 nm), SWIR (1100–1700 nm)) combined with intelligent software can identify and remove defects and foreign matter that traditional cameras and laser sorting machines have missed. Photonics-based sensors such as, e.g., laser interactance spectroscopy in the 500–1000 nm range can help to reduce fruit losses independent of their ripening behaviour. For products that do not ripen anymore after picking (such as strawberries), spectroscopic sensors could quantify (objectively and quantitatively) the ripeness stadia of the fruit. When mounted on an automated picking robot hat drives through the greenhouse, these sensors will not only enable the picking of the fruit at the correct stage of ripeness but will also allow the performance of harvest prediction calculations based on the captured data. Many of these promising techniques, however, lack scalability and, consequently, still come with a high cost and have a steep learning curve. In addition, there are many unaddressed or currently unattainable sensing needs.

[147] For simplicity, the diverse ecosystem encompassing agriculture on land, livestock, aquaculture, fisheries, food processing, forestry, environment, is shortened to "Agri-Food" in the following text.

For fruits and vegetables that still ripen after their harvest (such as apples, pears, bananas, and tomatoes), sensors must be developed, allowing the continuous monitoring of their quality properties during their storage under controlled conditions. Primarily, these sensors ensure that the products can be sent to the retail shops at the most optimum time.

Regarding food processes, the inherent variation in raw material quality reduces the process efficiency and increases waste. The raw material costs make up about 70% of the total cost of the final food product, so a critical factor in reducing waste and increasing profitability is to control and handle the raw material variation in the best possible way. Photonics sensors can provide valuable data on food quality and is a very complex concept, comprising a vast variety of chemical and physical attributes, as food materials are notoriously heterogeneous. They can also enable food package inspection and transport monitoring to improve food conservation and reduce/prevent food losses.

Innovative photonics are needed to get more knowledge about plants' genetic profiles, thus making adaptions to the changing environmental conditions possible.

Furthermore, food fraud is an increasing topic (e.g., honey diluted with water, the Toscany olive oil fraud) where photonics sensors can play an important role (e.g., fluorescence with excitation wavelength at 350nm detection in visible or VNIR absorption spectroscopy). Fluorescence, Raman, MIR, and FTIR spectroscopy are able to monitor amino acids, vitamins, allergens, and other components in foods using different emission wavelengths adapted to each specific study case. Their complexity (hardware and data analysis) and/or cost currently hamper widespread use. It is important to make these methods more robust for the industry in terms of sample presentation, speed, and Signal to Noise Ratio. These optical sensors and methods should also support improved soil analysis for optimising soil fertility and precision farming: e.g., MIPS-based pesticides detection; MIR fibre lasers for molecular analysis; fibre sensors for, e.g., root growth monitoring, water retention, soil moisture monitoring, and storage monitoring; generally, nitrogen absorption features near 1450, 1850, 2250, 2330, and 2430nm.

Finally, providing shops, warehouses, online suppliers, and consumers with better technology for sorting fresh food products, which complements and/or optimises 'use-by- and 'best-before' dates, can contribute to waste reduction later in the value chain.

A multidisciplinary challenge

Combining different expertise and technology fields: agricultural and food sciences, optics, mechanics, synthetic biology, chemistry, material science, ... are all part of an overall solution. To cover the full range of predictive, proactive, and preventive monitoring, so-called multimodal sensors need to be developed, combining different optical detection techniques (e.g., absorption and light scattering or light fluorescence or optical fibre plasmonics sensors used for chemical sensing elements). Furthermore, an innovative combination of different sensor technologies is needed, e.g., gas sensor solution (more accurate monitoring of ethylene in a range of 3.1–3.3 um or 10.6 um to prevent food waste; monitoring of emission gases such as ammonia at 1.52 um and methane at 1.65 um), biosensors, and new sensing transduction materials. This is because of the broad range of application fields that must be monitored (sensors at the tree, sensors for hydro-/aquaculture, plant monitoring in agroforestry, handheld systems for field farming, in food production lines, and for fire prevention) and the different properties that must be sensed in the products. To achieve more automation/autonomy, it is essential to have combined development of photonics and robotics, especially in terms of sensor-enabled robots (e.g., navigational) and robot-enabled sensors (e.g., robots that move sensors to/around measurement scenarios). There are many factors and areas of expertise that need to be considered in research projects beyond the core photonics technology, for example, sample handling and presentation, technology useability, the effects of motion on sensors, robustness over time, system calibration, predictive model development, seasonal variation, biological variation. The measured data needs further improvement in data analytics, data sharing, and digital twins.

Explicit attention to health & safety and authenticity

Improving plants on specific genetic components should focus on reducing the high amount of food loss during production and processing. Therefore, innovative photonics are needed to get more knowledge about plants' genetic profiles, thus making adaptions to the changing environmental conditions possible.

To begin with, food and farming systems require highly-sensitive water ("the source of life") quality monitoring with regard to, e.g., pesticides, algae, micro-organisms, halogenated materials and endocrine disruptors. Water is used for the irrigation of fields, in hydroponics and aquaculture, and also for livestock animals' nutrition. The types of envisioned sensors to monitor the water quality are diverse, ranging from miniaturised, multi-parameter handheld sensors that are used to analyse a water sample to sensors that are implemented in-situ. The latter could be sensors that are put into service in the water distribution pipeline for safe drinking water for human consumption and field irrigation purposes or sensors that are monitoring during summertime, the quality of the water in drinking tanks of livestock animals. For both in-situ applications, monitoring of biofilms is a point of attention. Finally, drone sensors that target stress and growth monitoring of field crops could be extended, providing information on irrigation needs.

Photonics can play a major role in supplying compact, cheap… and high-throughput sensors to select the type of antibiotics needed to kill a pathogen type.

Safe food production and processing need highly-sensitive monitoring of, e.g., pathogen, antibiotics, drug residues, acrylamide, mycotoxins, and livestock animal sensing along the entire supply chain from farm to fork with regard to a sustainable way of traceability. Therefore, photonics sensors such as MIR or phosphorescent sensors could be integrated into food packages to detect VOC, diseases, pests, and pathogens: quality monitoring with handheld sensors should be provided up to retail stores and consumers. In crop storage, QCL-laser-based phosphene detection could be applied, and photonics sensors should be implemented for monitoring drone-based operations (e.g., spraying) or autonomous processing. Moreover, photonics such as UV LEDs and lasers could be implemented as disinfection methods for reducing the microbial and viral load of surfaces, food, or airborne pathogens in supply/exhaust air. For all these approaches, sensor and other data standardisation are of high importance for quality management in the food industry to optimise food production.

In the fight against antimicrobial resistance (AMR), a revamped legislation on veterinary medicinal products currently applies in the EU. Adopted three years ago, this legislation is now a cornerstone to support the achievement of the objectives set in the European One Health Action Plan and in the Farm to Fork Strategy against AMR. The legislation also consolidates the EU's leading role on the global stage to act against AMR. The new rules will ensure that antimicrobial treatments for animals will be administered when, and only when, there is a real need for them. Photonics can play a major role in supplying compact, cheap (if needed in-situ applicable and easy to handle), and high-throughput sensors to select the type of antibiotics needed to kill a pathogen type together with the lowest concentration of an antibiotic at which bacterial growth is inhibited.

New food production, farming, and forestry techniques preserving environmental impact and adapted to climate change

Image-based systems are still and will be key innovation drivers in agriculture and food and are suitable to be included in all future production, farming, and forestry systems. Agricultural systems should be deployed in harsh environments – they demand very high robustness for their photonic systems due to the production-related outdoor conditions, e.g., crop and weed, weather, soil conditions, dust, rain, vibrations, sun, wind, etc. High-speed detectors with high-speed background correction are an essential part of this and achieving high SNR for low-intensity signals that compete with sunlight. To combine economic and ecological improvements, data with high spatial and temporal resolution should be available for interpretation and instructions. Robust imaging can fulfill this approach by using a broad range of optical sensors, such as colour/greyscale cameras, shadow imaging (light curtains), 3D-Imaging (laser, stereo, time-off-light), multi/hyperspectral, and thermal imaging. The corresponding data analysis includes (classical) image processing, machine learning, sensor data fusion, smart sensors, simulations, human-machine interfaces, remote and satellite imaging as well as low-cost imaging. Thus, imaging systems strongly support process automation.

The following list shows examples of new approaches for climate change adapted and more sustainable ways in food production and forestry/environment preservation:

- Laser-based weed management: using imaging techniques for differentiating between cultured crops and weeds, multidimensional data analysis, and automated systems to destroy the weed by high-power lasers (currently done by CO2 lasers)
- Multi-sensor systems for optimised management of water, resources, and environmental impact: using different sensor technologies to monitor

photosynthesis (e.g., fluorescence-based and detection in VIS) of a given culture, plant stress, environmental influences, soil/nutrient quality, and earlier detection of pests and diseases to prevent environmental impact and evaluating the carbon balance of a cultural model
- Robotics and autonomic rovers: using autonomic technologies on the field, forestry, and hydro-/aquaponic indoor agricultural systems connected with sensor technologies making monitoring and crop management more objective and less labour intensive
- Photonics sensing tools for smart picking/plucking: the idea is to pick/pluck only the relevant crop, avoiding waste and stress on the plant and lowering the biomass exported from the plants
- Symbiotic agriculture: combining different agricultural systems or cultures to benefit from symbiotic advantages or exploit lack of space or time in cultural sequences, such as agroforestry, regenerative agriculture, aquaponic systems, indoor farming
- Smart animal welfare monitoring: to optimise feeding, detect decreasing welfare (e.g., MIR for breath analysis of ruminants), automatic feed mixing linked to animal needs, automatic alert with the start of conspicuous/unusual/sickly animal behaviour
- Photonic sensors aboard aircraft, satellites, and automated drones to monitor forestry and fire: Light-based technologies help forestry managers to monitor tree growth with high precision, identify which species are present and spot the first signs of disease, decide the optimum point to cut down the tree and plan clearance with the minimum use of resources; measurements are made before the tree is removed from the forest thus the lumber yard can monitor its incoming material and plan production accordingly
- The technology that can control and optimise new industrial bioprocess (e.g., hydrolysis and fermentation) producing novel proteins is needed. These processes significantly increase the value of food by-products and reduce waste. Currently, inline control of these processes is challenging.

Need of skilled professionals in the agri-food sector with photonics awareness

Addressing future challenges in agriculture and food systems hugely demand highly trained and specialised professionals. Yet the farmer population is ageing and decreasing. Therefore, agricultural education/training has to be reformed and adapted to a multidisciplinary approach: on the bioeconomic and the technological

side. This could be achieved with continuous training, including end-users cooperating with industrial partners by organising industrial agri-food photonics-focused conferences/events and implementing agro-photonics farms where photonics technologies can efficiently blend and field tested with agricultural technologies/practices. To get the technological people more aware of the needs in agriculture, forestry, and food industry, they should be involved in specific interdisciplinary events with a strong awareness to the agri-food sector such as, e.g., photonics hubs to connect photonics experts with agri-food technology of companies.

Summary: Small, cheap, and robust photonics sensors should be able to monitor water quality, oxygen and salt content, early development of pests and diseases, and the quality of the product itself. Even more challenging topics for agri-photonics are monitoring soil health, including compaction levels and the concentration of organic matter, nutrients and chemical residues. For food processing, photonic sensors will enable real-time process control based on the composition of the food process stream, instead of process control based on parameters such as temperature, time, and pressure.

On a longer-term, Photonic sensors may become available to enable control of pathogens and contaminants that are present in low quantities. In the next step, more and better opportunities must be implemented for proof-of-concepts and to test ideas at an early stage (for photonics and agri-food collaborations). Consequently, standardisation of agrifood-related photonics devices, multi-sensor systems, and data analysis approaches is mandatory.

Furthermore, these cheap technology tools should be easily accessible to private individuals (e.g., a large part of the EU forest is not exploited and belong to private individuals) and smaller farms (according to estimations, 94 % of global farmers have fields smaller than 5 ha). Therefore, low costs solutions in the area of precision farming are of high importance.

Compared to the automotive and other industries, agricultural machines navigate, communicate and work under harsh but very different and varying conditions and “noise” sources (such as crop and weed, weather, soil conditions, dust, rain, vibrations, sun, wind, etc.), which leads to the demand for robust photonic systems that work in outdoor conditions.

Cooperation needs and opportunities with Horizon Europe Missions or partnerships

To face the actual and future challenges, photonics experts need a much closer cooperation with experts from the agricultural and forestry domain, such as farmers, crop production scientists, and animal health experts. Besides this application-oriented cooperation, cross-technological cooperation is needed for outside-the-box approaches. Although photonic sensors need to become "smart" through AI-empowerment, on the one hand, they must still be affordable, smaller, with higher sensitivity, robust in the means of using them in all kinds of environmental influences/applications, and produced in large amounts.

The following cooperation issues should be addressed by the Work Group Agriculture and Food:

- Close cooperation with agro-food (and forestry) oriented PPP to connect with application experts
- Close cooperation with the EU Missions, such as:
  - Adaptation to Climate Change
  - Restore our Oceans and Waters by 2030 (One major challenge is to reduce plastic circulation in nature/oceans through new food packaging materials supported by research progress in innovative photonics monitoring to still ensure the quality and safety of packed food during storage and transportation.)
  - A Soil Deal for Europe
  - European Green Deal
  - The European One Health Action Plan (2022–2026) and the Farm to Fork Strategy
- Close intercross-cooperation with all the other Work Groups of Photonics21
- Cooperation with other technology fields, such as:
  - sensor technology
  - agriculture and food sciences
  - mechanical engineering
  - nutritional science
  - chemical and microbial industry
  - machine learning and AI approaches
  - robotics, e.g., for agrobots that can be equipped with photonics sensors
  - veterinary industry

Proposed roadmap for 2025–2030

	2025–2027	2028–2030
Photonics Research (R) Challenges, TRL up to 5	• Laser-based & integrated photonics (R) • Open-loop sensing system innovations (R)	• Closed loop systems (R) • Closed-loop autonomous control systems using photonics (R)
Photonics Innovation (I) Challenges, TRL starting from 5	• Imaging & traditional spectroscopy (I) • Multi-modal sensing technologies (I) • New sources (illumination, treatment, management) (I)	• Integrated photonics-based solutions (I) • Open-loop and multimodal sensing systems (I) • Autonomous treatment (I)
Joint actions required with other Horizon Europe Missions or partnerships	• Workshops with EU missions, related PPP's and cross-interdisciplinary technology fields • Communicate advantages of photonics for related application fields (especially for agriculture, forestry, and food industry) • Exploit crossover calls	• Joint tests of ideas, proof -of-concepts, field tests • Improve education of skilled professionals in the interface of agri/food/forest & photonics • Continuously focus on improving standards • Adjust program to new challenges (geo-political, socio-economic, environmental) and investigate on regulatory aspects and innovative technology developments

Core photonics

Fabrice Devaux @FEMTO-ST

The Core Photonics activity works both 'top-down' from applications needs and market analysis and 'bottom-up' from research and technology innovation, typically starting from low technology readiness levels.

3.7

Left: High dimension spatial photon entanglement for quantum processing.

Introduction

In the preceding chapters, we have examined numerous application areas where photonics plays a critical role and have identified specific research and innovation actions that are needed to ensure that these applications reach their full potential. Each of these application areas makes a major contribution to economic life in Europe and to the health, well-being and prosperity of its citizens. It is the responsibility of the Work Group Core Photonics to identify areas of commonality between these various application domains and to propose research and innovation actions that underpin multiple topic areas. In this way we will maximise the effectiveness of our investments and ensure that we have command of the technologies that will be strategically important in the future. We may accordingly state our objective as follows:

The aim of the core photonics activity is to identify the technical and organisational measures that can bring benefits across multiple application domains, thereby maximising synergy, accelerating progress and achieving maximum efficiency with regard to funding and investment, with the following outcomes:

- Fully exploit the potential of photonics for a digital, green and healthy future in Europe
- Secure technological sovereignty for Europe
- Maximise international competitiveness
- Secure adequate infrastructures and a skilled workforce

While the major economic and societal benefits of the Core Photonics activity will be achieved through the exploitation of its technical developments in specific application domains, we note that production of photonic components, modules and materials constitutes a significant industry in its own right, with revenues of $95.2B in 2019[148].

Methodology

The Core Photonics activity works both ‘top-down’ from applications needs and market analysis and ‘bottom-up’ from research and technology innovation, typically starting from low technology readiness levels (TRL). All members of Photonics21 are automatically members of the Work Group Core Photonics, as well as of whichever Application Groups they choose, and are invited to participate in Core Photonics workshops. In addition, the chairs and deputies of the Application Groups are invited to share their key technical needs, as derived from consultation with their own members, as a basis for building consensus on which areas will benefit from joint actions or from actions that could underpin multiple domains.

[148] Photonics Market Data and Industry Report 2020. https://www.flipsnack.com/photonics21/photonics-market-data-and-industry-report-2020/full-view.html

3.7 Core photonics

In common with the Application Groups, the Work Group Core Photonics kicked off its SRIA activity with a workshop in Brussels on 1st July 2022, held in conjunction with the Photonics Partnership Annual Meeting. More than 200 individual inputs and recommendations were received at that meeting, and key outputs from the applications group workshops were also captured. An editor group comprising twelve experts in different areas of photonics: industry, academic and research community, as well as the Work Group Core Photonics chair and deputy, was formed to analyse these data and propose the way forward. A discussion meeting with the applications group chairs and deputies was held on 10th November 2022, and a further open workshop on 18th November 2022, where themes were reviewed and new inputs received from members. Based on all these inputs, key topics and proposed activities have been identified, which form the basis of this chapter.

Photonics has proved to be a major enabling technology to target the challenges related to the four critical goals of our strategic agenda.

In parallel with the Core Photonics workshops and related discussions, a joint activity with the EPoSS society has been underway, with the intention of identifying the opportunities and priorities for Integrated Photonics within the context of the European Chips Act and the likely formation of a Chips Joint Undertaking (JU), which will build on the existing Key Digital Technologies (KDT) JU. This joint activity has appointed an expert group drawn from the EPoSS and Photonics21 communities and held an open workshop in Amsterdam in November 2022, within the framework of the European Forum for Electronic Components and Systems (EFECS). Following this workshop, as well as several expert group and editor group meetings, a white paper has been created[149], which will inform the EC and KDT JU on Integrated Photonics activities for Europe and help shape policy for the Chips JU. As integrated photonics is crucial to our photonics strategy, key messages from this activity have been included in the planning of the Core Photonics agenda described here.

We note that photonics is a critical enabling element for second-generation quantum technologies, including quantum computing, secure communications and sensors. Recognising the importance of this application field, a joint Work Group was set up by Photonics21 and the European Quantum Flagship programme to examine the needs and priorities of systems based on quantum technology. Initial outcomes from that study are reported in a white paper[150], the conclusions of which have also been considered here.

Main socio-economic challenges addressed

In this section, we briefly state the key aspects of the top-level challenges that are addressed by the Core Photonics activity, as background to the selection of major research and innovation challenges discussed in the following section.

Societal needs and policy have developed significantly in recent years, with much deeper attention to the green deal, digital transformation, technological sovereignty, and competitiveness. All these aspects are considered crucial for sustainable development and for the wellbeing of European citizens. Photonics has proved to be a major enabling technology to target the challenges related to the four critical goals of our strategic agenda:

1. Fully exploit the potential of photonics for a digital, green and healthy future in Europe
The preceding chapters have provided an extensive analysis of the many ways in which photonics will contribute to the creation of a digital, green, prosperous and healthy Europe. By providing critical components, systems and processes for next-generation applications, the Core Photonics activity seeks to underpin the development of solutions to the societal and economical challenges that we face. Specific examples include sensors for electric vehicles and battery technology, renewable energy generation and efficient agriculture. Key considerations in the choice of underlying technologies include their impact on the environment and reduction of energy use. We will note specific examples in the next section, Major Photonics Research & Innovation Challenges.

2. Secure strategic autonomy for Europe
Over the last few years, the geopolitical environment has changed significantly, and the desire to have independence of action, as well as minimising dependence upon other countries, has become an imperative. This is particularly true of strategically important materials and manufacturing

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149 White Paper on Integrated Photonics, Joint Work Group of EPoSS and Photonics21, April 2023.
150 https://www.photonics21.org/2022/position-paper-on-quantum-pics-available-for-download-now%21

capabilities for photonic devices and systems that are sourced from countries whose interests may not be aligned with our own or are influenced by countries in that category. This is a major thrust of the initiative behind the European Chips Act and is reflected in similar actions in other countries, notably the USA.

Recent developments have emphasised the need to review the trend in recent decades towards globalisation of supply chains. It has become commonplace for components to be designed and developed in Europe and then manufactured, either wholly or in part, in other countries, especially in Asia. Whilst this model has been successful in many respects, it clearly opens up significant vulnerabilities which should now be addressed.

In order to secure strategic autonomy, it is vital to ensure that the intellectual property associated with key technologies is secured within Europe and that the means of production is also available in the EU, so that European countries have clear freedom of action in all markets. Technological sovereignty also puts Europe in a stronger position when it comes to negotiating specific technological cooperation with third countries, with a mindset of a balanced win-win outcome.

In the section on RD&I challenges, we propose several actions to address vulnerabilities arising from a lack of specific materials and production capabilities within the EU. We also note that, in many respects, strategic autonomy and international competitiveness are closely linked.

3. Maximise international competitiveness
It is our aim to ensure long-term job and prosperity creation in Europe, not only for the photonics industry itself but also for the up- and downstream industries utilising photonics technologies. In this context, the need to increase the uptake of technology and its translation into new products and services is also addressed. Accordingly, we have captured key technology requirements from the applications scenarios that have been analysed in the foregoing sections and propose appropriate RD&I actions to ensure that solutions are available in a timely manner.

4. Secure adequate infrastructures and skilled workforce
Adequate infrastructures and a skilled workforce are vital both to secure strategic autonomy for Europe and to maximise international competitiveness. Not only must we seek to establish independence in terms of fabrication capabilities and technological platforms, but also set in place adequate education and training programmes, covering vocational training as well as academic curricula.

Major photonics research & innovation challenges

In this section, we identify and provide high-level description of the key activities required to address the imperatives of technological autonomy, concern for the environment, digital society, industrial competitiveness and skills and workforce development.

Strategically important photonic materials, devices and production techniques
We have identified the following areas as critically important for European autonomy in photonic systems:

- Semiconductor wafers and infeed materials, including compound semiconductors for different wavelength ranges, which are presently sourced from outside the EU. A strategic review of these materials should be conducted, leading to policy decisions and investment in European sources where appropriate.
- Production technology, including epitaxy, wafer fab tools, assembly and packaging. We need to ensure that there is a complete European supply chain in place for critical manufacturing tools needed in the photonics industry. We note that European tool suppliers have world-leading positions in some areas (e.g., lithography, epitaxy), which must now be extended to the full range of critical equipment.
- Production techniques that minimise the use of resources such as energy, water and scarce or strategically vulnerable materials, whilst emphasising re-use.
- Leadership and European sourcing of infrared detectors, semiconductor lasers, photonic integrated circuits (PICs), high-power/high-speed devices, micro-optics and new optical fibres, needed across multiple application areas. Specific examples are given in the next section.
- Advanced materials, heteroepitaxy and large area epitaxy, as well as heterogeneous integration technologies on silicon, where European leadership will minimise dependence on other countries and enable major advances in cost-efficiency and industrial competitiveness.

Integrated Photonics/PIC/semiconductor device technology
We address how the boundaries of the field should be continually extended in terms of wavelength,

photon intensity (from single photons to high power), modulation frequency, functionality, complexity and price, including:

- New wavelength domains (UV, visible, near-IR, mid-IR and long wavelength IR), and extreme temporal regimes (ultrafast pulses), needed to address the full range of sensor and power delivery technologies identified by the Application Groups relating to health, agrifood, manufacturing, energy, mobility and climate, as well as security, space and defence.
- Unprecedented power efficiency and environmental compatibility, including high-temperature operation, thereby avoiding active cooling, and effective thermal management. These factors are vital in almost all application scenarios, as they facilitate smaller, cheaper and more highly functional devices (e.g., for the internet of things), as well as mitigating the growing energy demands of our digital society (e.g., the energy use associated with communications and data centres).
- Support for complex functional integration, e.g.,
  - coherent beam combining for high-intensity light sources, e.g., for manufacturing processes, surgery and defence
  - beamforming and beam-steering for free space communications and active optical imaging in industrial, automotive, avionic, security and space applications
  - very large scale integration (photonic VLSI), supporting high-performance computing, data management and AI systems
  - wafer-level camera integration for all wavelength domains
  - programmable, reconfigurable, and adaptive optical systems.
- Speed and bandwidth compatible with the demands of emerging digital systems, which will exceed 1Tbit/s within the current decade.
- Quantum-compatible performance and functionality, including:
  - single photon/entangled photon generation and detection, including imaging arrays and supporting technologies
  - photonics support in complementary quantum systems, e.g., ion traps, magnetic qubits
  - ultra-low linewidth lasers, extremely high extinction switches and modulators, precise optical couplers
  - cryogenic operation.
- Photonics for demanding environments and for extreme reliability. Many applications of photonics are highly demanding in terms of their operating environment (including operating temperature range, shock, vibration, humidity and radiation) and reliability requirements (low failure rate, long operational lifetime). We propose activities to address the environmental and reliability requirements of automotive, space, avionic, medical and ICT applications, including systems incorporating multiple optical and electronic elements. Failure mechanisms should be considered for every class of new device and integrated circuit/subsystem.

Codesign and manufacture of photonics with microelectronics and other key technologies
Photonics, electronics and related system design need to be interconnected in order to build industrially attractive solutions at an acceptable price. More R&D is required on novel co-design and manufacturing methods, connecting PICs and electronic integrated circuits by hybrid or heterogeneous techniques.

> ***Photonics, electronics and related system design need to be interconnected in order to build industrially attractive solutions at an acceptable price.***

We must also embrace integration with other technologies, e.g., micro-electro-mechanical systems (MEMS) and bulk/micro-optics, for micro-displays, wafer-level cameras, scanning imaging systems, and segmented and adaptive optics. Technology combinations of this kind are required for augmented reality/virtual reality displays, medical imaging, free space communications and LIDAR systems for automotive and robotic applications, amongst others.

Actions should address the full product chain, from design, device fabrication, assembly and packaging, through to the delivery of complex, high-performance systems.

Design approaches for technology re-use across multiple application domains
We have noted that several photonic techniques, including spectroscopic sensors and active imaging (LIDAR), have applications in many fields, including industrial, automotive, medical, natural resources, biological sciences, agrifood and defence. We propose programmes that actively seek synergistic development across these fields, maximising common development and ensuring that the differentiating factors (which could include wavelength, temperature, resolution and sensitivity) are dealt with in the most efficient way.

Ubiquitous access to leading-edge technology, with seamless transition from R&D to production

Leading-edge products often exploit leading-edge technology. This has been the rule in microelectronics for many years and is also true across a wide range of photonics products and innovations. Accordingly, there is a vital need for measures that ensure that European industries, from specialised SMEs to large-scale system manufacturers, have effective access to technology at the highest level, embracing the whole development cycle from concept through prototyping to volume production. In particular, we should further develop the concept of pilot lines in photonics and electronics, pioneered in previous EU frameworks, to ensure:

- Cost-efficient possibilities for prototyping and low-volume manufacturing, including access to design and fabrication services for SMEs, with exemplary user support and rapid turnaround of new designs
- Effective linking of the entire value chain, including materials, design systems, front-end wafer fabrication, heterogeneous integration, back-end test, assembly and packaging
- Low barriers to entry, with clear pathways to high-rate or low-rate volume manufacturing
- Support for high TRL and scale-up, ensuring production autonomy and minimising the impact of geopolitical issues
- Drive to low cost in volume, enabling mass-market products.

Skills and Workforce Development

To support future photonics innovation, we must first define the skills needed, including those required for emerging applications of photonics, e.g., quantum photonics. We then need to set up a suitable education and training framework through a strong collaboration of academia and industry, and to promote the development of photonics courses both in high-level academic education and in training for professionals. Pervasiveness of photonics courses in all STEM curricula should also be addressed, while vocational training and life-long learning should be guaranteed, so as to secure a competent and adequately skilled workforce. These initiatives should span the whole range of skills, from craft/technical personnel to researchers and technical experts, and link schools, technical colleges, universities and industrial concerns.

Roll-to-roll integration of optofludic devices.
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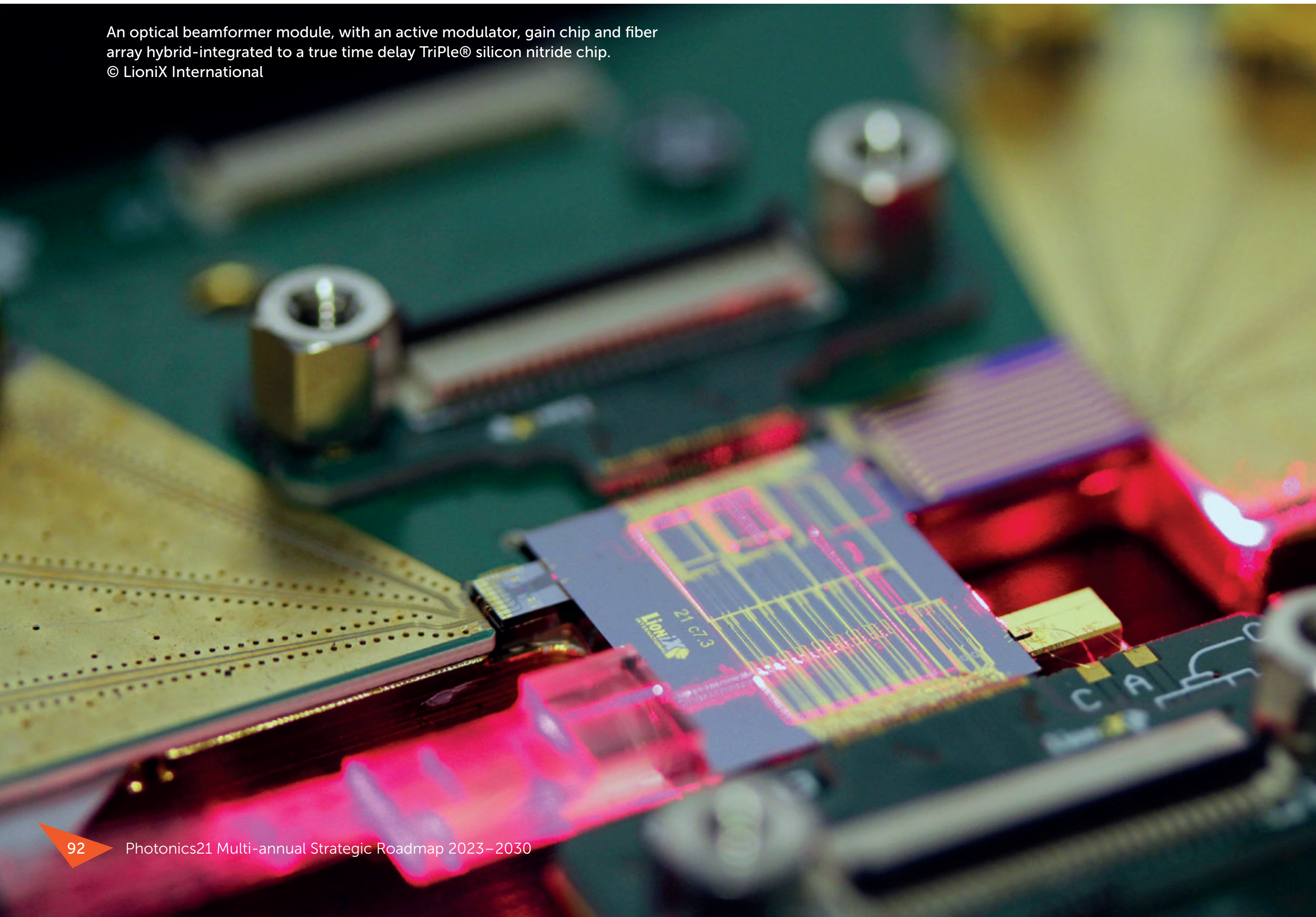
Cooperation with Horizon Europe Missions and Partnerships

Since the role of the Work Group Core Photonics is to provide the technology that underpins the application areas, our most vital cooperation is with the Application Groups within the Photonics Partnership, with whom the programme for technology and development will be agreed and who are primarily responsible for building collaboration in their specific user domains.

We recognise that the aims of the Photonics Partnership are often best achieved in collaboration with other European initiatives. In addition to those partnerships identified by the Application Groups, we specifically identify here the cooperation established over the last two years with the Quantum Flagship programme and with the Key Digital Technologies JU, which will be incorporated into a new Chips JU during 2023. White papers developed in partnership with both organisations have recently been published (refs 2, 3). We are willing and eager to engage with other European programmes and missions and welcome discussions towards this objective.

Given the vital importance of education and skills development, we welcome partnerships with other European initiatives in this domain. As well as building on the achievements of European programmes such as the Marie Skłodowska-Curie Actions in developing a highly skilled cohort of experts, we need to enhance understanding of and excitement for science and technology, particularly photonics, amongst people of all ages, starting with children at school. It is only by doing this that we will have sufficient people wanting to pursue a career in photonics, whether as a production technician, an expert designer, or an applications specialist, and sufficient people amongst the general public who can participate in an informed manner in democratic processes relating to scientific, environmental and other issues.



An optical beamformer module, with an active modulator, gain chip and fiber array hybrid-integrated to a true time delay TriPle® silicon nitride chip.
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Proposed roadmap for 2025–2030

	2025–2027	2028–2030
Photonics Research (R) Challenges, TRL up to 5	• Semiconductor devices, integrated photonics and PICs for extended wavelength ranges, power efficiency, modulation speed, extreme environments • Co-design and manufacture with microelectronics and complementary technologies	• Hetero-epitaxy and integration approaches for all wavelengths, UV to mid-IR • Approaches to photonic VLSI • Photonic neural networks with high energy efficiency • Optical fibres with very low loss and high stability, operating across wide wavelength ranges; special fibres and fibre devices • Neuromorphic, adaptive and programmable photonics
Photonics Innovation (I) Challenges, TRL starting from 5	• Production tools and techniques; Pilot lines for advanced integrated photonics and PIC technologies, electronic-optical systems • Development of active sensor technologies for multiple application domains	• Scale up for multi-technology pilot lines • Production tool development and deployment in industrial trials throughout product value chain • Pilot production for 'quantum-compatible' photonics
Joint actions required with other Horizon Europe Missions or partnerships	• Development of joint programmes with Quantum Flagship and KDT/Chips JU, addressing R&I challenges in quantum PICs and multi-technology integration • First pilot lines for key semiconductor and quantum technologies • Education and training actions	• Evolution of pilot lines to full value chain of photonic devices, circuits and systems, including semiconductor devices and PICs, assembly and packaging • Tackling the challenges of manufacturing at scale with multiple technologies including electronics and optics • Wider education and training actions

Klearia • K-Loops S.A.L. • Kungliga Tekniska högskolan • Lasea France • Laser Engineering Applications S.A. • Laser Zentrum Hannover e. V. • LaVision BioTec GmbH • Leibniz-Institut für Photonische Technologien e.V. • Leonardo - Società per Azioni • LIGENTEC S.A. • Light Conversion, UAB • Lightcore Technologies • Limbak 4PI S.L. • Linköpings universitet • LioniX International BV • LPKF Laser & Electronics AG • LRE Medical GmbH • Luceda • Ludwig-Maximilians-Universität München • Lumensia Sensors S.L. • Lumiphase AG • LUNOVU GmbH • L-up SAS • Maier S.Coop • Maier Technology Centre S.Coop • Maraîchage Sol Vivant Normandie • Max-Planck-Gesellschaft zur Förderung der Wissenschaften e. 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