New Horizons

Securing Europe's technological sovereignty through Photonics

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

PHOTONICS21

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Update of the Strategic Roadmap Europe's age of light! How photonics will power growth and innovation

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Europe's age of light!

How photonics will power growth and innovation

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

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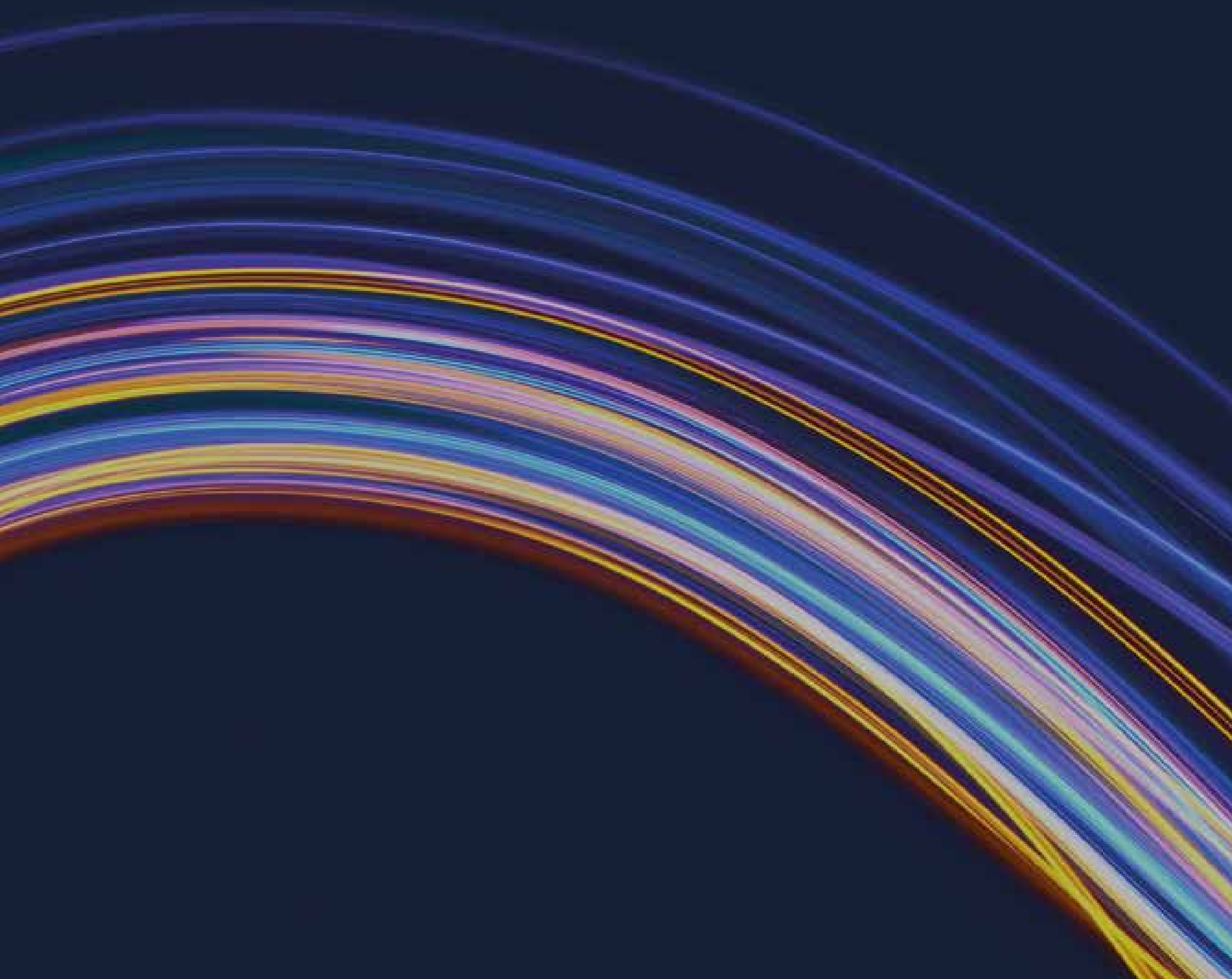
Contents

Photonics is simply essential for powering the future European digital economy.

Nobel Prize Laureates,
Gérard Mourou, Stefan Hell
and Theodor Hänsch



Preface

Photonics and photonic technology enabled products are all around you. Your mobile phone has a photonics camera and a photonics display. Your television has a photonics display and you interact with it through a photonics enabled handheld controller. Your computer has a photonics display, a photonics camera, and your printer has a photonics scanner. Your home has photonic LED lighting and is protected by infrared photonic motion sensors. Everywhere you look, you see photonics and, everyday it is highly probable that you use several or more photonic enabled products.

It is the same in industry, from photonics sensors to allow robots to see, to medical imaging equipment, to the lighting on and in our cars, to laser enabled manufacturing of complex 3D components, and, optical fiber and space communications to transmit data from the shortest distance to around the globe. In fact, our world today, in our homes, in our offices, in our hospitals, in our factories, would simply not function without Photonics.

Photonics is simply everywhere and as a result, is most often taken for granted. This was most dramatically highlighted last year when three European Nobel Prize Laureates in Photonics, Gérard Mourou, Stefan Hell and Theodor Hänsch felt obliged to write to the European Commissioners Gabriel and Oettinger to emphasize that "Photonics is simply essential for powering the future European digital economy" and that Photonics must be strongly supported in the future Horizon Europe and Digital Europe European Commission programmes 2021-2027.

This Multiannual Strategic Research and Innovation Agenda responds to this urgent need to communicate the crucial importance of Photonics to achieving European Union ambitions. In particular, Chapters 1 and 2 are politically orientated, unashamedly so, addressing our public leaders and authorities, in emphasizing the critical importance of Photonics technologies to achieving European Union strategic objectives and targets; from enabling the digital transformation of European industry and strategic economic sectors, to playing a key role in achieving the European Green Deal through revolutionizing energy generation and energy conservation, along with monitoring the effects of both, on the environment and climate.

In parallel, Chapters 1 and 2 also highlight that Photonics technologies are essential for the establishment of a future high-performance, sovereign and resilient European digital infrastructure and will be a key building block in our future quantum communications and cyber-security world. Finally, they show that core Photonics technologies and Photonics solutions will be essential in strengthening strategic value chains across sectors including: Climate, Mobility and Energy; Manufacturing; Agriculture and Food; Digital Infrastructure; Health; and Safety, Security, Space and Defense.

We are pleased to state that the European Photonics community and our Photonics21 partnership are ready to rise to this challenge, to ensure the development and application of Photonics to enable the European Union to achieve its stated ambitions. Our Photonics21 community has already successfully mobilized and submitted to the European Commission a new proposal for a future European Partnership on Photonics in Horizon Europe 2021-2027, entitled *"Photonics for a Healthy, Green and Digital Future"*.

In parallel, a commitment from the Photonics SME industry to invest €100 billion in R&I in Europe over the course of the Horizon Europe Programme (2021-27) should a Photonics Public Private Partnership be launched by the Commission, strongly reflects the active engagement and confidence of the European Photonics industry.

This Multiannual Strategic Research and Innovation Agenda further supports this commitment towards an ambitious research and innovation programme by providing in Chapter 3, a blueprint for the way forward. This chapter details the socio-economic challenges that must be addressed to achieve our European ambitions along with the major research and innovation challenges for our European Photonics community in each strategic sector and, a roadmap and timetable for research and development actions over the 2021-2027 timeframe.

We are fully committed to supporting European Union ambitions leveraging the Horizon Europe Programme, in close cooperation with other key enabling technologies communities, other Horizon Europe partnerships, the broader European academic, research and industry community, all in close contact with citizens and public authorities.

This Multiannual Strategic Research and Innovation Agenda, coupled with the European Partnership on Photonics in the Horizon Europe 2021-2027 proposal "Photonics for a Healthy, Green and Digital Future", and supported by our strong financial commitment, €100 billion in R&I, in Europe over the course of the Horizon Europe programme (2021-27) provides the foundational three pillars to ensure a vibrant European Photonics capacity and capability into the future.

It only remains for us to sincerely thank our European Photonics community for their active contribution to this document, for their tireless work as well as their unique and innovative ideas that are shaping the future of European industry and society. Our special thanks also go to the European Commission for their support of this Photonics strategy process.

Giorgio Anania and Bernd Schulte
Photonics21 Vice-Presidents and spokesmen

sustainability
consumer e-health smart mobility
zero waste
new rules aging society smart city
disrupting challenge global connection
networks
technological change
speed climate change
point-of-care mixed reality
intelligent light smart home quality of life
new competitors
3D printing **#photonics_2027** adapting
assisted learning
future production
information security autonomous driving partners
IoT financing big data connected world change
new business models market-entry-mechanism innovation
urbanisation
car2x industry 4.0 internet
gamification integrated systems
connected
resource scarcity
paradigm
digitisation transformation

Executive Summary

Photonics technologies are at the heart of an increasingly required European sovereign technology capability to achieve our European Union green and digital ambitions, and protect European strategic assets underpinning key European sectors and value chains.

"Photonics is simply indispensable for accelerating the digital transformation of the European manufacturing industry."

In particular, Photonics technologies are now recognised as essential to support and advance four over-arching European Union objectives: the digital transformation of Europe's industry; achieving the European Green deal and a sustainable EU future; the establishment of a future high-performance, sovereign and resilient European digital infrastructure and, strengthening strategic value chains across key sectors.

The recent European Commission industry strategy "A New Industrial Strategy for Europe" clearly recognized Photonics technologies as a key enabling technology for **the digital transformation of European industry** stating, *"The EU will support the development of key enabling technologies that are strategically important for Europe's industrial future...including Photonics"*. Photonics is simply indispensable for accelerating the digital transformation of the European manufacturing industry. Photonics enabled sensor systems will provide 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 will provide the security of data required in hostile manufacturing environments. Finally, Photonics technologies are opening up new manufacturing paradigms such as 3D additive manufacturing, which will secure renewed growth in European manufacturing.

Equally Photonics technologies and solutions have the potential to revolutionize energy generation and energy conservation and as such, Photonics will play a key role **in achieving the European Green deal**. Already solar energy is a key component of the European renewable energy generation portfolio. In parallel, light-emitting diodes for general-purpose lighting is already producing substantial electrical energy savings for lighting solutions and will contribute to energy sustainability and security in EU member states. Photonics will also be a key enabling technology to achieve and deliver European Union aspirations for earth observation monitoring and support numerous EU policies, political priorities and "green deal diplomacy".

In fact, through green energy generation, energy conservation and indirectly through environmental and climate monitoring, the global minimum contribution of Photonics to climate protection based on a recent European study is approximately 3 billion tons less CO_2 by 2030. With this global CO_2 equivalent saving, Photonics will contribute an astounding 11 percent to the 1.5°C climate protection target by 2030 and 22 percent to the 2°C route of the Paris Climate Agreement.

The current German Presidency of the Council of the European Union (1 July to 31 December 2020) states, *"Secure and sovereign, European-based, resilient and sustainable digital infrastructure is essential. Creating this singularly European digital economic realm is key to keeping the EU competitive in a technological sphere dominated by the United States and China"*. Both the European Commission and the European Investment Bank in separate communications have recognised Photonics as one of the two key digital deep technologies that will provide the **secure, sovereign and resilient digital infrastructure** necessary.

Photonics based optical infrastructure will be the central nervous system upon which our European digital society, industry and economy will rely, transporting data at ultrafast rates in millions of extended fiber-optic networks around the European union to every home and business. In addition, Photonics technologies will be a critical building block of Europe's future digital network security via a Photonics enabled quantum communication cyber security capability. Finally, uninterrupted digital connectivity supporting 5G for Europe's future digital society will require both satellite and terrestrial digital enabled infrastructures and technologies. Photonics has been identified amongst the critical space technologies to achieve this space connectivity.

The report of the Strategic Forum for Important Projects of Common European Interest[1] advised the Commission *"to reinforce, to strengthen Europe's industrial base and competitive advantage by focusing on* ***strategic value chains (SVCs) of European importance****"*.

It is sobering to note that Photonics technologies are a critical element of processes, technologies, components and products in ***all*** of the 6 identified European strategic value chains: Connected, clean and autonomous vehicles; Smart health; Low-carbon industry; Hydrogen technologies and systems; Industrial Internet of Things and, Cyber-security. In addition, Photonics technologies are critical in three additional strategic value chain initiatives for batteries, microelectronics and high performance computing.

In the Connected, clean and autonomous vehicles SVC, Photonics technology capabilities will be essential to maintain a European competitive position in future autonomous vehicle markets. For example, lidar, the optical equivalent of radar, but with much quicker response times and higher resolution, is fulfilling a critical need for real-time 3D sensing for autonomous vehicles. This SVC will be addressed by the *Climate, Mobility and Energy application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

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[1] "Strengthening Strategic Value Chains for a future-ready EU industry", Report of the Strategic Forum for Important Projects of Common European (2019).

In the Smart Health SVC, Photonics-based technologies are already helping to meet the increasing worldwide demand for rapid, accurate, personalized, and cost-effective healthcare interventions. These include sensors for medical imaging technologies like MRI, fluorescence and spectral components for image-guided surgery, fiber-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. This SVC will be addressed by the *Health application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

"Photonics-based technologies are already helping to meet the increasing worldwide demand for rapid, accurate, personalized, and cost-effective healthcare interventions."

In the emerging Low-carbon industry & Hydrogen technologies and systems SVCs, Photonics will be a key enabler for the hydrogen economy. For example, solar powered plants will enable photo-catalytic splitting of water molecules, using light instead of electricity, to separate the compound of hydrogen and oxygen atoms, with the energy carrier expected to serve as a large-scale storage for renewable energies. This SVC will be addressed by the *Climate, Mobility and Energy application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

In the Industrial Internet of Things SCV, Photonics enabled optical communications systems will provide the speed and security of data transfer required in difficult manufacturing environments. Photonic technology will also play a significant role in the application of IoT in smart infrastructures, by enabling a huge number of sensors, actuators and other smart devices interconnected with each other by means of omnipresent optical communication systems. This SVC will be addressed by the *Manufacturing, and Digital Infrastructure application work groups* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

In the Cyber-security SVC, European photonic quantum communication components and infrastructure will be essential to protect key digital assets of the EU and its Member States, and will enable European companies to position in new security and defense markets. This SVC will be addressed by the *Safety, Security, Space & Defense, and Digital Infrastructure application work groups* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

In the Battery SVC, Photonics technologies have multiple applications along the battery production value chain, from electrode production to module assembly. This SVC will be addressed by the *Manufacturing application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

"Europe is a recognized world leader in the scientific research, technology development and industrial applications of Photonics."

In the High Performance Computing SVC, photonic technologies could offer a solution to the heat generation and bandwidth limitations that the computing industry is facing with their benefits of energy-efficient passive components, low crosstalk and parallel processing. In the near future, all-photonic quantum computers (super supercomputers) will be developed using squeezed states of light, linear optics, photon detectors, and integrated photonic devices. The EU clearly requires Photonics technology sovereignty. This SVC will be addressed by the *Digital Infrastructure application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

Finally, the pervasive enabling impact of Photonics technologies can also be shown in a more traditional value chain, namely Agriculture & Food. In the agriculture sector, photonic sensing technologies are a critical element in airborne drone or satellite configurations that allow local high performance non-contact monitoring and control of fertilizers, pesticides, fungicides and water in farms along with environmental hazard monitoring. Whilst in the food value chain, Photonics will open up new opportunities such as urban vertical farming, using adjusted lighting to accelerate plant growth and production, and reducing the need for chemicals. This SVC will be addressed by the *Agriculture and Food application work group* in the future European Partnership on Photonics in Horizon Europe 2021-2027.

With appropriate support, the European Photonics community can deliver on all the above promise. Europe is a recognized world leader in the scientific research, technology development and industrial applications of Photonics. Europe can boast four European Nobel Prize winners in Photonics in the past decade alone. From a technology research and development perspective and capability, Europe is home to leading world-class Photonics prototyping facilities in its Technology Research Organizations (RTOs) and industry, some uniquely with a 300mm photonic wafer processing capability. Europe also has a unique European ecosystem that allows suppliers and users to drive innovation, with over 5000 SMEs and a number of large companies, which directly employ over 300,000 people within the EU. All of this is reflected in the fact that Europe remains the world's second-largest supplier of Photonics components and products after China, with a global Photonics market share of 15% to 17%, in a very dynamic and vibrant marketplace that holds the potential for huge market growth with an average CAGR of 8.8% since 2015. This global Photonics market is expected to reach $1000 billion before 2027.

This Photonics Multiannual Strategic Research and Innovation Agenda underpins the ambition of Photonics21 and the European Photonics community to support European value chains by providing a clear blueprint and optimal path for the way forward. This agenda details the socio-economic challenges that must be addressed to achieve our European ambitions in each strategic sector and value chain, along with the major research and innovation challenges for our European Photonics community. It moreover provides an explicit roadmap and timetable for European Photonics research and development actions over the 2021-2027 timeframe, both on the specific Photonics enabling technologies and on the solutions required, that are, inter alia dependent on Photonics enabling technologies.

In short, Photonic technologies are simply indispensible for a European sovereign technology capability, that will enable us to achieve our European Union green, societal and digital ambitions, that will enable us to protect European strategic assets and that will enable European industrial competitiveness in key European sectors and value chains. This Photonics Multiannual Strategic Research and Innovation Agenda provides the route forward to acquire the appropriate Photonics capacity and capability required.

1. Introduction

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More than 300 experts of the European photonics community kicked off the joint photonics roadmap process alongside the Photonics PPP Annual Meeting 2018 based on a workshop series.

1.1 Photonics is a critical key enabling technology to achieve Europe's future ambitions.

The world has changed beyond all recognition since the global financial crisis of 2008. Our world today is far more complex, contested and competitive than before, and is changing at unprecedented pace. The challenges arising from current global megatrends are increasingly visible. Two of these global megatrends shaping our world over the past decade have been Climate change and Digitalization[2,3]. In addressing same, the European Council, the European Parliament and European Commission have agreed on two key overriding European Union ambitions and priorities, the transition towards climate neutrality by 2050 and global leadership of the digital revolution in an increasingly digitised economy and society[4].

Most recently, the EU's Roadmap for Recovery[5] post COVID19 pandemic reconfirmed the above ambitions and stated that the *"Green transition and the Digital transformation will play a central and priority role in relaunching and modernising our economy. ..... Investing in .... digital technologies and capacities, ... will help create jobs and growth and allow Europe to make the most of the first-mover advantage in the global race to recovery"*.

As will be shown in the following pages and chapters, Photonics is a unique key enabling technology[6], a key digital technology, with the potential to enable and accelerate *both* the Green transition and the Digital transformation.

A third global megatrend has been brought sharply into focus in Europe following the COVID19 pandemic, namely Geopolitics[1]. For many decades, the international order has been a globalizing world, international trade, and cross-border flows of labour and capital. However, significant and increasingly visible differences in societal values, in trust, in trade flows, and in industrial policy, are now spurring regionalization and in some cases, protectionism. This megatrend has been accelerated by the COVID-19 pandemic, which has highlighted the fragility of global supply chains and strategic cross-border flows. The world is well on its way towards a new geopolitical, geo-economic and geo-technological order[1].

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[2] Global Trends to 2030: Challenges and Choices for Europe report, ESPAS, 2019.
[3] Global Trends to 2035, European Parliamentary Research Service, PE 627.126, 2019.
[4] "Political guidelines for the next Commission (2019-2024) – A Union that strives for more: My agenda for Europe", Political Guidelines of European President Von der Leyen, 2019.
[5] A Roadmap for Recovery; Towards a more resilient, sustainable and fair Europe, https://www.consilium.europa.eu/media/43384/roadmap-for-recovery-final-21-04-2020
[6] COM(2009) 512: Photonics is one of 6 Key Enabling Technologies (KETs).

1.1 Photonics is a critical key enabling technology to achieve Europe's future ambitions.

In part response to this third megatrend, the European Union has placed increasing emphasis on strategic autonomy[7], digital and technological sovereignty, and strengthening European strategic value chains[8].

The EU's Roadmap for Recovery[6] states *"Investing in .... digital technologies and capacities, ... will also help make us more resilient and less dependent by diversifying our key supply chains"*.

As will also be shown in the following pages and chapters, Photonics as a key digital technology also has the potential to underpin a stronger, more sovereign and more resilient European economy by contributing to enabling European digital and technological sovereignty. Photonics technologies are also critical in *all* the identified European strategic value chains and economic sectors.

In short, Photonics technology, sits at the nexus of a required European sovereign technology capability to achieve our European Union green and digital ambitions, and protect European strategic assets underpinning key European sectors and value chains.

The following chapter will highlight that Photonics technologies will be essential to enabling the digital transformation of European industry and key economic sectors from manufacturing to mobility and health. In addition, as Photonics technologies and solutions have the potential to revolutionize energy generation and energy conservation, along with monitoring the effects of both, on the environment and climate, Photonics will play a key role in achieving the European Green deal. In parallel, Photonics technologies are essential for the establishment of a future high-performance, sovereign and resilient European digital infrastructure and will be a key building block in our future quantum communications and cyber-security world. Finally, core Photonics technologies and Photonics solutions will be essential in strengthening strategic value chains across key sectors including: Climate, Mobility and Energy; Manufacturing; Agriculture and Food; Digital Infrastructure; Health; and Safety, Security, Space and Defense.

This "enabling" technology capability is the factor behind the very high economic impact and leverage of Photonics in Europe. The Photonics industry is estimated to bring a positive impact to over 10% of the European economy, with leverage ratios up to 50, between the Photonics market size and the total market size impacted.

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[7] Rethinking Strategic Autonomy in the Digital Age, EPSC Strategic Notes, Issue 30, 2019.

[8] "Strengthening Strategic Value Chains for a future-ready EU industry", Report of the Strategic Forum for Important Projects of Common European (2019).

This potential for Photonics technologies to support European Union ambitions is underpinned by a world-class European capability and capacity in Photonics scientific research, technologies development and applications, and supported by regional, national and European public authorities and industrial associations.

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

Europe is a recognized world leader in the scientific research, technology development and industrial applications of Photonics.

From a world-class science perspective: Europe can boast four European Nobel Prize winners in Photonics in the past decade alone. The 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.

A recent letter from three of these Nobel Prize Laureates, Gérard Mourou, Stefan Hell and Theodor Hänsch to European Commissioners Gabriel and Oettinger emphasized, "Photonics is simply essential for powering the future European digital economy".

From a technology research and development perspective and capability, Europe is home to leading world-class Photonics prototyping facilities in its Technology Research Organizations (RTOs), some uniquely with a 300mm wafer processing capability. European RTOs offer leading edge distributed Photonics foundry capabilities to academic and industrial users across the European Union. This capability has been supported by the European Commission who has invested more than €49 million for EU Photonics pilot manufacturing services. In addition, the European Photonics industry itself has major research and development facilities spanning the full innovation chain from wafer growth and fabrication through fabrication to prototyping and testing.

From an applications perspective, Europe also has a world leading position and competitive edge, thanks to a unique European ecosystem that allows suppliers and users to drive innovation in close interaction between application requirements and the appropriate basic technology. Europe has over 5000 SMEs and a number of large companies. These technology-intensive Photonics companies directly employ over 300,000 people within the EU.

"Europe remains the world's second-largest supplier of Photonics components and products after China."

As a result, Europe remains the world's second-largest supplier of Photonics components and products after China[9], with a global Photonics market share of 15% to 17%, in a very dynamic and vibrant marketplace that holds the potential for huge market growth with an average CAGR of 8.8% since 2015. The global Photonics market is currently $760 billion comprising approximately $100 billion in Photonics components and $660 billion in Photonics products. It is expected to reach between $970.5 billion and $1000 billion over the period 2025[10] to 2027[11]. "If Europe can stay at the forefront of Photonics innovation and capitalize on fast-expanding global markets, a tripling of European production to more than EUR 200 billion by 2030 is realistic[12]".

This European success story reflects well the organization of the European Photonics community and landscape under the umbrella of Photonics21 as the largest technology platform in Europe and the Photonics PPP (Public Private Partnership); the support of EPIC, the European Photonics Industry Consortium representing over 600 European Photonics SMEs and the active participation of national Photonics associations in EU member states. In total, more than 1700 Photonics companies and research organisations back the Photonics PPP with more than 3200 registered personal members in the Photonics21 platform.

Finally, the importance and relevance of this Photonics ecosystem at a strategic national and European level, is reflected in the very strong support by European Union member states[13], with over 93% of the member states underlining the ecosystem's relevance as a key enabling technology developer, 77% stating its importance for their specific industry and 92% of the member states anticipating significant scientific, economic and societal impacts at European level.

1.3 Photonics Multi-annual Strategic Research and Innovation Agenda objectives

This document, the Multi-annual Strategic Research and Innovation Agenda of the Horizon Europe Photonics Partnership, produced by the European Photonics community within the European Technology Platform Photonics21, proposes a vision and path forward, a long-term strategy for the next seven years 2021-2027.

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[9] Note: the global competition from China, even in newly emerging markets is strong; of the $200 billion in new markets created between 2015 and 2019, China has taken over 40% of the revenue generated.

[10] TEMATYS, Paris, France (private communication, study for VDI Technologiezentrum GmbH, Germany), 2020.

[11] New York, Aug. 25, 2020 (GLOBE NEWSWIRE), Reportlinker.com announces the release of the report "Global Photonics Industry".

[12] Photonics21.

[13] European Partnerships Consultation Member States, Presentation to EU Member States, European Commission, 2020.

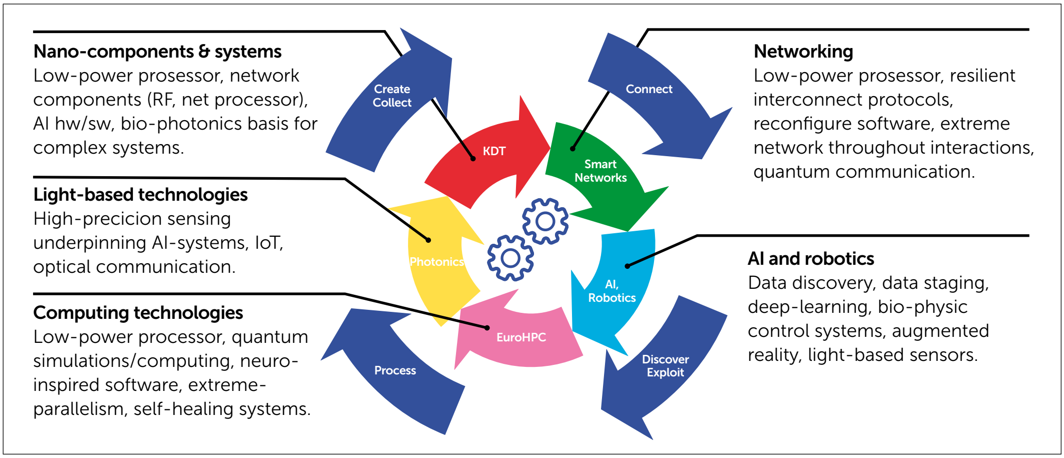
In Chapter 2 the importance of Photonics technologies to enable a stronger, more innovative, more sustainable, more sovereign and more resilient European economy is emphasized. It is shown that Photonics are an essential key technology to achieve our European Union green deal and digital ambitions. The role of Photonics as an enabling technology for European value chains is detailed.

In Chapter 3 the socio-economic challenges that must be addressed to achieve our European ambitions in key strategic sectors of the European economy are highlighted. The major research and innovation challenges for the European Photonics community in each sector are detailed.

A particular focus is placed on identifying both the cooperation needs and opportunities for synergies with other disciplines, major European platforms and EU public private partnerships. As Photonics is a key enabling technology, there is considerable scope for multilateral collaboration, in particular to address the socio-economic challenges of the application-oriented partnerships. The European Commission has confirmed[14] the significant potential for a Photonics partnership to engage with up to 26 other European partnerships on such application-orientated joint calls with end-user sectors and other key enabling technologies. Citing the Photonics example, the Commission states "some partnerships have the potential to play a truly pivotal role in leading and fostering multinational collaboration because of their interdisciplinary focus and /or position in transformational supply chains." An example of the interplay between Photonics and other potential digital centric partnerships is shown below[10].

Figure n°2: Example of inter-play between digital-centric partnerships

Source: European Commission



Finally, in Chapter 3, a roadmap and timetable for research and development actions over the 2021-2027 timeframe is presented for each key sector.

[14] Coherence and Synergies of Candidate European Partnerships under Horizon Europe, DG R&I A4, 2020.

2. Photonics technologies: Empowering a stronger, more more sovereign and more resilient European economy

innovative,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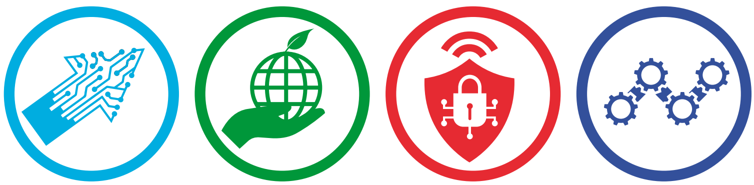
The two overriding European Council, European Parliament and European Commission priorities for an EU transition towards climate neutrality by 2050 and global leadership of the digital revolution, have been transposed into a series of strategies and action plans addressing both challenges:

- The European Green Deal communication[15];
- A new Circular Economy Action Plan for a Cleaner and More Competitive Europe[16];
- The Strategy on Shaping Europe's Digital Future[17];
- A European strategy for data[18];
- A New Industrial Strategy for Europe[19];
- An SME Strategy for a Sustainable and Digital Europe[20].

These European Commission communications either explicitly state Photonics technologies as strategically important in optimal paths forward for Europe's future ambitions or, state digital technologies and solutions are required, that are, inter alia dependent on Photonics enabling technologies.

This chapter focuses on the importance of Photonics technologies to support and advance four key European Union objectives: the digital transformation of European industry; achieving the European Green deal and a sustainable EU future; the establishment of a future high-performance, sovereign and resilient European digital infrastructure and, strengthening strategic value chains across key sectors (including: Climate, Mobility and Energy; Manufacturing; Agriculture and Food; Digital Infrastructure; Health; and Safety, Security, Space and Defense), as detailed below.

The four key European Union objectives



Digital transformation | **Green transition** | **Digital and technological sovereignty and security** | **Strategic value chains**

Source: European Commission

[15] The European Green Deal COM (2019) 640 final.
[16] A new Circular Economy Action Plan for a Cleaner and More Competitive Europe COM (2020) 98.
[17] The Strategy on Shaping Europe's Digital Future COM (2020) 67.
[18] A European Strategy for Data COM (2020) 66.
[19] A New Industrial Strategy for Europe COM (2020) 102.
[20] An SME Strategy for a Sustainable and Digital Europe COM (2020) 113.

2.1 Powering the digital transformation of European industry

The recent European Commission communication on A New Industrial Strategy for Europe[21] was emphatic: *"Industry is central to Europe's future progress and prosperity – It makes up more than 20% of the EU's economy and employs around 35 million people, with many millions more jobs linked to it at home and abroad"*.

The Communication equally stated that *"industry has proven its ability to change and it* ***must*** *now do the same as Europe embarks on its transition towards ... digital leadership in an ever changing and ever more predictable world*".

The European Commission industry strategy further recognized Photonics technologies as a key enabling technology in this digital transformation stating, *"The EU will support the development of key enabling technologies that are strategically important for Europe's future...including photonic*[17] *"*.

The Commission position with respect to the importance of Photonics technologies reflects the fact that Photonics is simply indispensable for driving European industry's digital transformation. Photonics enabled sensor systems will provide both the sensing and measurement functionalities required to achieve Industry 4.0 in smart industrial environments and the broader manufacturing sector. A simple analogy, often cited, is that Photonics provides both the eyes for our robots and the speech capability between our sensors, machines and manufacturing infrastructure. Photonics enabled optical communications systems will provide the security of data required in hostile manufacturing environments. Finally, Photonics technologies are opening up new manufacturing paradigms such as 3D additive manufacturing, which will secure renewed growth in European manufacturing.

More specifically, Photonics will enable industry 4.0, leveraging the Internet of Things (IoT), to develop smart industrial systems and infrastructures. The future broad penetration and widespread implementation of machine-to-machine communications and the IoT will erase the traditional boundaries between manufacturing and telecommunications sectors. In a near future photonic technology will play a significant role in the application of IoT in smart infrastructures, by underpinning a huge number of sensors, actuators and other smart devices interconnected with each other by means of omnipresent optical communication systems (such as communicating via Li-Fi or other).

[21] European Commission, COM (2020) 102 final, "A New Industrial Strategy for Europe".

Similarly, the combination of laser micromachining, coupled with "digital" techniques such as laser additive 3D manufacturing, with 3D digital enabled design, opens up a new era for lower volume European manufacturing of high value product with a high degree of customization, and complexity, that can be produced cost effectively in the European Union. Such Photonics enabled advances in the digital transformation of manufacturing could be a game changer in the European landscape, supporting renewed growth in localized EU manufacturing activity.

"Photonics technologies and solutions have the potential to revolutionize energy generation and energy conservation."

2.2 Enabling the European green transition and environmental sustainability

European Commission President von der Leyen has stated, *"tackling climate and environmental-related challenges is this generation's defining task*[3]*"*. The European Green Deal[11] is a response to the identified challenges and includes a set of deeply transformative policies to achieve the EU's climate ambition for 2030 and 2050. The Communication clearly emphasizes, *"New technologies, sustainable solutions and disruptive innovation are critical to achieve the objectives of the European Green Deal"*.

Indeed, Photonics technologies and solutions have the potential to revolutionize energy generation and energy conservation and as such, Photonics will play a key role in achieving the European Green deal. Already solar energy is a key component of the European renewable energy generation portfolio. Light emitting diodes for general-purpose lighting is already producing substantial electrical energy savings for lighting solutions and will contribute to energy sustainability and security in EU member states.

The European Green Deal communication also states *"to protect Europe's citizens and ecosystems, the EU needs to better monitor, report, prevent and remedy pollution from air, water, soil and consumer products". This in turn will facilitate the emerging Union evidence-based "green deal diplomacy"*. Photonics will also be a key enabling technology to achieve and deliver European Union aspirations for earth observation monitoring and support numerous EU policies, political priorities and "green deal diplomacy"[4]. For example, satellite-based lasers will in the future allow the measurement of the distribution, creation and adsorption of green house gases globally on-line in a similar way to a GPS system.

In fact, through green energy generation, energy conservation and indirectly through environmental and climate monitoring, the global minimum contribution of Photonics to climate protection based on a recent European study is approximately 3 billion tons less CO_2 by 2030[22]. With this global CO_2 equivalent saving, Photonics will contribute an astounding 11 percent to the 1.5°C climate protection target by 2030 and 22 percent to the 2°C route of the Paris Climate Agreement.

More specifically, it is expected that the transition to energy-efficient lighting will reduce the global electricity demand for lighting by 30% to 40% in 2030; with more than 160 million metric tons of carbon dioxide emissions avoided each year. In the European Union, lighting accounts for 10% to 12% of energy usage in households and up to 30% of an average domestic electricity bill. Whilst intelligent and efficient solid-state lighting has led to and will continue to lead to reductions in annual utility costs, the potential impact is far larger. In the future, energy saving associated with higher efficiency Photonics light sources, coupled with optical sensor-based lighting controls will be embedded in industrial and domestic building automation systems and will be omnipresent in urban installations, single new builds and the industrial fabric. One specific example, smart street lighting has helped Oslo in Norway save 70% of its energy consumption and 1440 tons of CO_2 emissions per year[23].

As the EU remains confronted today with a rapidly changing global energy landscape. Given that the EU currently imports 53% of its required energy, the substantial electrical energy savings arising from advanced Photonic lighting solutions would contribute not only to energy sustainability but also additionally and importantly to improving energy security within the EU.

In addition, Photonics already are, and increasingly will be, a key enabling technology for earth observation monitoring of land, marine, atmosphere and climate change. In August 2019, the European Space Agency (ESA) launched its wind monitoring Aeolus satellite, the first wind lidar instrument in space. Its core component – a Photonics UV laser - allowing for the first time mapping of global wind fields in three dimensions; essential for long-term weather forecasting and critical for modeling climate change. But Europe is not alone in having a space Photonics-enabled monitoring capability. The NASA Advanced Tomographic Laser Altimeter System – built around a single laser - provides a height measurement every 70cm along an orbiting track yielding detailed information on Greenland and Antarctic ice sheets, allowing significant evidence input into US climate policy development and decision making.

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[22] "Light as the key to global environment sustainability: High-tech photonics solutions to protect the environment and preserve resources", a study by Spectaris, the Fraunhofer Institute, Tematys and Messe Munchen, June 2019.

[23] https://www.c40.org/case_studies/10000-intelligent-streetlights-save-1440-tco2-and-reduce-energy-consumption-by-70

Europe has a world-class space system – Copernicus – for Earth observation; but Europe cannot improve monitoring; cannot tighten negotiation positions with respect to EU Green Deal policies, targets and/or milestones; cannot reinforce its role on the global "climate stage" without core assets, capabilities and capacities in Photonics enabled earth observation. In addition, earth observation is the second commercial market in the space sector for EU industry with an estimated €28billion in manufacturing revenue market. Photonics technologies have therefore become a critical capability for future earth environmental monitoring and climate assessment underpinning a rapidly growing strategic market.

2.3 Ensuring future European digital and technological sovereignty, and security

The recent European Commission communication "Europe's moment: Repair and Prepare for the Next Generation"[24] outlining a post COVID19 EU recovery strategy, highlighted that *"Europe will need a stronger industrial and technological presence in strategic parts of the digital supply chain. ..... We are also reminded of the importance of security of technology. This reaffirms the need for Europe to have technology sovereignty where it matters"*.

This focus on digital and technological sovereignty reflects the clear position taken in President von der Leyen's Political Guidelines[3]; the priorities set out by the European Council's Strategic Agenda 2019-2024[25] stating, *"Over the next few years, the digital transformation will further accelerate and have far-reaching effects. We need to ensure that Europe is digitally sovereign"* and; the Commissions recent strategy on Shaping Europe's Digital Future[13].

The Commission communication on A New Industrial Strategy is equally explicit *"Europe's digital transformation, security and future sovereignty depends on our strategic digital infrastructures[17]"*.

The German Presidency of the Council of the European Union (1 July to 31 December 2020) has reiterated this focus on sovereignty in their programme stating, *"Secure and sovereign, European-based, resilient and sustainable digital infrastructure is essential[26]. Creating this singularly European digital economic realm is key to keeping the EU competitive in a technological sphere dominated by the United States and China"*.

[24] Europe's moment: Repair and Prepare for the Next Generation COM(2020) 456 final, (27.5.2020).

[25] A new strategic agenda for the EU (20 June 2019), https://www.consilium.europa.eu/en/eu-strategic-agenda-2019-2024/

[26] https://www.eu2020.de/eu2020-en/eu-digitalisation-technology-sovereignty/2352828

Above: Photonics is the key tool to make our digital society work.

There is thus broad agreement across European leadership that there can be no digital sovereignty, no digital autonomy; no full digital security, without technological sovereignty and security of supply of deep technology. Europe equally recognizes that *"Photonics is one of the two key digital deep technologies*[17, 27]*, that will provide the resilient digital infrastructure necessary and drive the digital transformation of Europe"*.

In fact, Photonics technologies, components and systems are critical for the establishment of a future high-performance, sovereign and resilient European digital infrastructure. Photonics based optical infrastructure will be the central nervous system upon which our European digital society, industry and economy will rely, transporting data at ultrafast rates in millions of extended fiber-optic networks around the European union to every home and business. In addition, Photonics technologies will be a critical building block of Europe's future digital network security via a Photonics enabled quantum communication cyber security capability. Finally, uninterrupted digital connectivity supporting 5G for Europe's future digital society will require both satellite and terrestrial digital enabled infrastructures and technologies. Photonics has been identified amongst the critical space technologies to achieve this space connectivity.

[27] 'Financing the digital transformation Unlocking the value of photonics and microelectronics', 2018, Innovation Finance Advisory, European Investment Bank Advisory Services, Luxembourg.

Photonics technologies will play a key role in future EU 5G networks and strategic digital infrastructure. Photonic networks will allow the transmission and routing of huge amounts of 5G data traffic at an acceptable cost and the transformation of the radio access network. In data centers, photonic interconnect and switching will allow the realization of new architectures able to strongly reduce the energy consumption while providing a high level of flexibility in resource utilization. Finally, in future microelectronic hardware platforms, Photonic chip-to-chip interconnect will allow a significant increase of bandwidth density leading to dramatically scaled up global capacity of those platforms. In all cases, integrated Photonics will be a key technology to realize components and modules at the right costs, while greatly reducing energy consumption and footprint.

"Photonic networks will allow the transmission and routing of huge amounts of 5G data traffic at an acceptable cost and the transformation of the radio access network."

Looking to the future, the key features of a secure and resilient European Union digital infrastructure – will be secure communications and cyber-security. Two revolutionary solutions – quantum communications and quantum computing – are under development worldwide to deliver this capacity, critical to safeguarding our communication and data and keeping our online society and economy running. The European Union and Commission have recognized this: *"the EU will develop a critical Quantum Communication infrastructure designed to deploy in the next 10 years a certified secure end-to-end infrastructure to protect key digital assets of the EU and its Member States[17]"*. Without the appropriate critical Photonics technologies to enable quantum communications – this will not happen in Europe.

The Japanese government[28] has recognized this strategic link between "Photonics" and "Quantum technologies" as reflected in the name of its new national programme to support the development of these essential digital infrastructure capabilities; Cross-ministerial Strategic Innovation Promotion Program (SIP) on *Photonics and Quantum Technology* for Society 5.0.

The European Union cannot therefore expect to lead in quantum communications without a strong core domestic Photonics technology development and Photonics manufacturing capability. The US, Japan and China have already recognized this and are racing forward to put in place domestic capability. A 2019 US report[29] by the National Academies for the Department of Defense states bluntly: *"a strong domestic quantum industry is extremely important to maintaining overall economic and national security... It is essential to foster a strong*

[28] Cross-ministerial Strategic Innovation Program (SIP) on "Photonics and Quantum Technology for Society 5.0", Japanese Cabinet Office, August 8, 2019.

[29] Domestic Manufacturing Capabilities for Critical DoD Applications: Emerging Needs in Quantum-Enabled Systems (2019), The National Academies Press.

domestic workforce, infrastructure and supply chain (in quantum communications and quantum computing). .... In this area, national security and economic security are synonymous".

Finally, Europe's future digital infrastructure and digital connectivity, supporting 5G will require both satellite and terrestrial digital enabled infrastructures and technologies. Photonics has also been identified amongst the critical technologies to achieve the required space connectivity. This is already reflected in the inclusion of Photonics technologies in the European Strategic space technology non-dependence priority list[30], with "optoelectronics, detectors and lasers" all specifically listed in the current 2018-2020 action plan to achieve space technology sovereignty. This Photonics enabled space technology criticality will remain far into the future as multiple competitor countries (China, United States and Japan) are all developing free-space photonic enabled quantum communications for airborne or space applications and national missions.

2.4 Strengthening strategic value chains for a future-ready European industry

The report of the Strategic Forum for Important Projects of Common European Interest[31] advised the Commission *"to reinforce, to strengthen Europe's industrial base and competitive advantage by focusing on strategic value chains (SVCs) of European importance"*. The conclusions of the Strategic Forum were fully endorsed by the European Council. The German Presidency of the Council of the European Union (1 July to 31 December 2020) also confirmed this industrial policy priority in their Council programme: *"We want to strengthen strategic value chains[32]"*.

The six strategic value chains identified by the Strategic Forum report were: Connected, clean and autonomous vehicles; Smart health; Low-carbon industry; Hydrogen technologies and systems; Industrial IoT and Cyber-security. These complemented already ongoing initiatives to strengthen strategic value chains for batteries, microelectronics and high performance computing.

It is remarkable and noteworthy that Photonics technologies are a critical element of processes, technologies, components and products in ***all*** of the above European strategic value chains.

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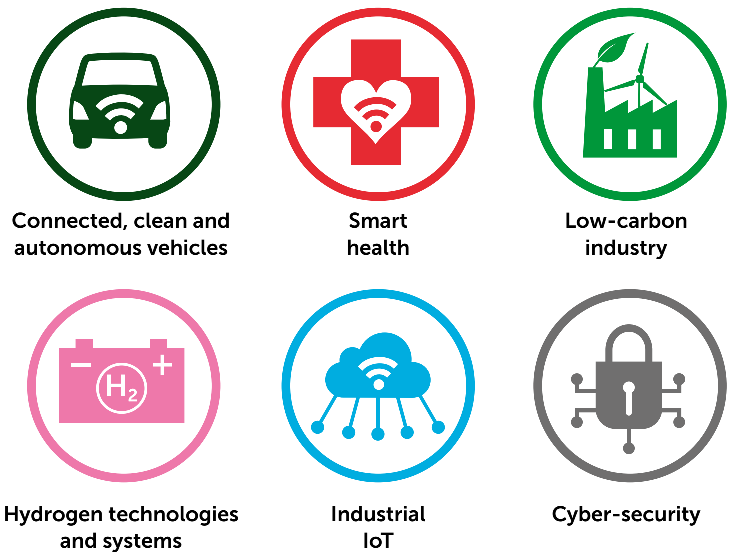
[30] Cross-ministerial Strategic Innovation Program (SIP) on "Photonics and Quantum Technology for Society 5.0", Japanese Cabinet Office, August 8, 2019.

[31] "Strengthening Strategic Value Chains for a future-ready EU industry", Report of the Strategic Forum for Important Projects of Common European (2019).

[32] https://www.eu2020.de/eu2020-en/eu-digitalisation-technology-sovereignty/2352828

Six strategic value chains



"Photonics-based technologies are already helping to meet the increasing worldwide demand for rapid, accurate, personalized, and cost-effective healthcare interventions."

In the Connected, clean and autonomous vehicles SVC, Photonics technology capabilities will be essential to maintain a European competitive position in future autonomous vehicle markets. For example, lidar, the optical equivalent of radar, but with much quicker response times and higher resolution, is fulfilling a critical need for real-time 3D sensing for autonomous vehicles. See further details in the *Climate, Mobility and Energy application work group* report in this strategic research and innovation agenda publication.

In the Smart Health SVC, Photonics-based technologies are already helping to meet the increasing worldwide demand for rapid, accurate, personalized, and cost-effective healthcare interventions. These include sensors for medical imaging technologies like MRI, fluorescence and spectral components for image-guided surgery, fiber-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. See further details in the *Health application work group* report in this strategic research and innovation agenda publication.

In the emerging Low-carbon industry & Hydrogen technologies and systems SVCs, Photonics will be a key enabler for the hydrogen economy. For example, solar powered plants will enable photo-catalytic splitting of water molecules, using light instead of electricity, to separate the compound of hydrogen and oxygen atoms, with the energy carrier expected to serve as a large-scale storage for renewable energies. See further details in the *Climate, Mobility and Energy application work group* report in this strategic research and innovation agenda publication.

In the Industrial Internet of Things SCV, Photonics enabled optical communications systems will provide the speed and security of data transfer required in difficult manufacturing environments. Moreover, photonic technology will play a significant role in the application of IoT in smart infrastructures, by enabling a huge number of sensors, actuators and other smart devices interconnected with each other by means of omnipresent optical communication systems. See further discussion in the *Manufacturing, and Digital Infrastructure application work groups* reports in this strategic research and innovation agenda publication.

In the Cyber-security SVC, European Photonic Quantum Communication components and infrastructure will be essential to protect key digital assets of the EU and its Member States, and will enable European companies to position in new security and defense markets. See further information in the *Safety, Security, Space & Defense, and Digital Infrastructure application work groups'* reports in this strategic research and innovation agenda publication.

In the Battery SVC, Photonics technologies have multiple applications along the battery production value chain, from electrode production to module assembly. Short pulse and ultra-short pulse lasers are used to introduce microstructures into the electrode material so that a significant increase in the performance of lithium ion cells can be achieved by enlarging the electrode surface. A pulsed laser cutting process is also used to separate the materials from the electrode to enable a high quality cut adapted to the flexibility of the shape. A laser welding process is applied for the electrical and mechanical connection of the current collectors in the internal and external contact of the battery cells. See further discussion on Photonics enabled manufacturing in the *Manufacturing application work group* report in this this strategic research and innovation agenda publication.

In the High Performance Computing SVC, Photonics technology could offer a solution to the heat generation and bandwidth limitations that the computing industry is facing with their benefits of energy-efficient passive components, low crosstalk and parallel processing. Already European photonic technology for a direct chip-to-chip, board-level interconnection that overcomes current server board design limitations has been demonstrated that will enable a new green European HPC era. In the near future, all-photonic quantum computers (super supercomputers) will be developed using squeezed states of light, linear optics, photon detectors, and integrated photonic devices.

The EU clearly requires Photonics technology sovereignty. See further information in the *Digital Infrastructure application work group* report in this strategic research and innovation agenda publication.

Finally, the pervasive enabling impact of Photonics technologies can also be shown in a more traditional value chain, not included in the nine identified in the Strategic Forum, but in an equally strategically important sector for the European economy, namely Agriculture & Food. In the agriculture sector, photonic sensing technologies are a critical element in airborne drone or satellite configurations that allow local high performance non-contact monitoring and control of fertilizers, pesticides, fungicides and water in farms along with environmental hazard monitoring. Whilst in the food value chain, Photonics will open up new opportunities such as urban vertical farming, using adjusted lighting to accelerate plant growth and production, and reducing the need for chemicals. See further examples in the *Agriculture and Food application work group* report in this strategic research and innovation agenda publication.

3.1 Digital Infrastructure

Main socio-economic challenges addressed

Early 2020, with the onset of COVID-19, digital infrastructure became an even more essential part of our personal and professional lives, acting as a 'lifeblood' the likes of which we have never seen before. Digital infrastructure had turned altogether into an essential marketplace for food and goods, the facilitator of our children's education, the enabler of teleworking, the storehouse of our culture, the warrant of some of our civil rights, and the intercessor to our friends and family. Overall, the COVID-19 crisis triggered an intense wave of digital transformation, which is expected to last and expand further over the next decade.

Light is the indispensable fuel for this infrastructure: along with the supporting photonics technologies, it will boost the return to growth and steer further development if adapted to the new expectations of the next decade beyond 2020.

The sudden awareness of the criticalness of the digital infrastructure modified the hierarchy of user expectations from the infrastructure. Growing concerns on security, reliability and power consumption have complemented the need for more bandwidth. Photonic technologies show advantages to meet all these expectations and the strong increase in demands for new fibre-to-the-home (FTTH) connectivity after the start of the health crisis, well above demands for new wireless connectivity, could be the first evidence of that.

We will soon enter a new era in which trillions of connected objects will require *smart connectivity*: always available, intrinsically secure, and flexibly scaling as the pre-requisite for zero-downtime in a terabit economy. Soon autonomous vehicles, robots and drones will generate Zettabytes of digital information. Artificial intelligence and machine learning will free us from routine tasks and boost human creativity as well as product innovation. The digitisation of industrial production and working environments is expected to support momentum for creating a million new jobs in Europe.

All FTTH data, wireless data, industry data will have to be carried across a new fibre-based *programmable network infrastructure*, largely photonic too, acting as the 'central nervous' system that the digital society, industry and economy will heavily rely upon. Delivering the required performance, resilience and security levels there too, while satisfying cost, energy efficiency and technology constraints, presents a formidable research challenge for the next decade.

The challenge is even greater when acknowledging the information and the communication infrastructures will cease co-existing side-by-side, and, pervasively merge into a single infrastructure, delivering more and richer services autonomously with minimal human intervention. This new infrastructure will interact with the physical world via a myriad of sensors and actuators, many of which are yet to be developed or invented (connected "things", for example, robots, cars, connected objects, interfaces with users), many of which will rely on photonics.

Large data-centres (central cloud) will be used to perform complex decisions, but are remote and therefore not compliant with the growing need for time-sensitive services, for example, robot control in digitised factory floors. Distributed, smaller datacentres (edge clouds and cloudlets), interconnected by photonic technologies, will provide ultrafast responsivity for time-sensitive applications by pushing intelligence as well as computer and storage capabilities to the network edge. Overall, exchanges between machines (primarily inter-process communication between computers and servers) will be the dominant source of traffic across the whole infrastructure, a paradigm shift from today where inter-server traffic is mostly kept within the perimeter of data centres.

This transformation is expected to completely change the ICT landscape and reshuffle the distributions of players in the IT and communications ecosystem. A plethora of opportunities for established market players and new entrants will be opened, propelling the creation of as yet unimagined services and applications where photonics is a likely enabler.

Photonics technologies are an indispensable pillar of this new secure and resilient ICT infrastructure. Meeting the demanding capacity, energy efficiency and latency targets of the terabit economy and society is only possible if photonics technologies are more widely deployed in all areas of communications. For example:

- 5G and beyond networks are heavily reliant on the availability of optical backhaul and core networks;
- Ultra-broadband residential and enterprise access is not possible without deep fibre solutions;
- Optical wireless emerges as a complementary solution in areas where no fibre is available;
- Data centre interconnects cannot cope with the bandwidth surge without photonics;
- Critical and private infrastructures demand optical networks for security and simplicity.

While photonic communication solutions today are developed somewhat independently, closer integration with sensor and actuator, radio, computing, switch, storage and other functions ("photonics integration 2.0") will be required to take the digitalisation of our industry, economy and society to a much higher level.

Multi-chip modules in which electronics and photonics building blocks ("chiplets") are co-integrated into a subsystem or system will be an important milestone into this direction.

A substitution of electronic functions for photonic functions is foreseen as the next step where additional functionality or more compactness will be delivered, higher capacity, lower latency or better energy efficiency. Integration, assembly and packaging solutions need to be developed to deliver the necessary technology platforms to make this vision a reality.

The digitalisation of Europe depends on information and communication technologies (ICT). Growing market sectors such as the IT industry, Industry 4.0, IoT, and autonomous vehicles need a communication infrastructure which is both competitive and innovative and keeps pace with the service demands.

"Overall, global data traffic has been doubling every 2–3 years over the past 15 years and there is nothing to suggest that this growth rate will slow down."

Overall, global data traffic has been doubling every 2-3 years over the past 15 years and there is nothing to suggest that this growth rate will slow down. Optical communication and network technologies will be essential to accommodate this growth in a sustainable way.

By 2019, the global optical component market exceeded $8.5 billion (Lightcounting), the optical networking equipment hardware markets was in excess of $16 billion (Ovum) and the optical router and switch market surpassed $18 billion in size (IDC[33]), yielding a total addressable market in excess of $42 billion.

The optical component market alone exhibited a CAGR of 11% from 2018 to 2019, showing that despite continuous efforts to lower cost-per-bits, the global capacity increase leads to a healthy increase in market volume.

While the perimeter is changing, Europe has a unique opportunity to capture market share in IT in the new photonics-augmented infrastructure by leveraging its leading position in optical communications. R&D intensity in the optical communication sector is much higher than in the communication sector overall and typically exceeds 10% of revenue[34], reflecting the characteristics of a high-tech market with fast innovation cycles. Six out of the twenty largest optical equipment manufacturers have major R&D centres in Europe. In terms of revenue, they represent more than 30% of the global optical equipment market. Two of the three largest component manufacturers have operations in Europe and more than a hundred SMEs and universities provide complementary research and innovation on network, system, or component levels.

New research and innovation challenges require a continued effort to defend and strengthen Europe's leading position in this space. Without

[33] According to IDC, the global router and switch market was >$45 billion in 2019. With the assumption that 40% of this market are optical routers and switches, this leads to >$18 billion.

[34] Aggregated information from company & analyst reports.

continuous and strategic investment in photonics for information and communication technologies, the digitalisation of Europe's industry, society and economy will be stalled.

Major photonics research & innovation challenges

The digitalisation of Europe's economy, industry and society will require smart information and communication infrastructure. Photonic communication and networking technologies are an important pillar of this infrastructure. From a user and application point of view, the following technology challenges need to be addressed to foster a wide-spread and sustainable adoption:

1. Zero-touch operation

Too often today, the operation of networks and the creation of new services is cumbersome and relies on unnecessary paperwork, manual processes and redundant interfaces. Artificial-intelligence-based automation with fast reconfigurable-photonics is key to achieving zero-touch operation – to drive efficiency and improve agility.

2. Instantaneous response

With the objective to provide quasi-real-time services over a distributed ICT infrastructure, reliance on the network and its service guarantees are increasing. Differentiated services enabled by photonic transport and switching are necessary to deliver a perceived instantaneous network response for each application class.

3. Access anywhere

Ultra-broadband access needs to become a utility such as electricity and water and be available anywhere. However, there are too many areas with no broadband coverage at all in Europe and speed limitations are an impediment for business growth in many regions. There will be no single access technology addressing all broadband needs. What is clear, though, is that optical communication in different forms will be an essential part of any solution.

4. Intrinsic security

In times where privacy, security and integrity of our data is constantly at risk, security must be an integral part of the design of any communication solution and not be an afterthought. Optical communications are essential to protect large data streams on-the-move, be it by quantum-safe encryption or by delivering a robust and secure infrastructure.

5. Sustainable capacity growth

Continued growth in capacity while reducing cost and energy per bit is the primary driver of the communication industry and a necessity to address the myriad of new applications and services brought by the digitalisation of industry, economy and society. Large investment and photonic innovations are required to tackle Moore's law and Shannon's limit.

Above: The digitalisation of Europe depends on information and communication technologies.

1. Zero-touch operation

Photonic networks augmented by AI/machine learning

Contemporary digital optical communication technologies, also known as coherent optics, were turned into product innovation in Europe in 2010. Europe is in a strong position to maintain its leadership should it continue to innovate at a fast pace. Optical communications are moving to use coherent technology everywhere. Once viewed as prohibitively expensive, coherent technologies will expand from long-haul systems into all fields of optical communications.

'Coherent' is the brand name for the introduction of digitisation capable of changing the landscape of communication businesses (telecom, cloud and IT altogether). It will not only open the possibility for 'on-click', optical connectivity as a service for everyone – free from today's multiple, manual, week-long settings – but will also make the automated orchestration of IT, optical and cloud resources possible. Concepts such as self-organisation and dynamic data plane adaptation will be employed. This digitisation is largely inspired by the habits of cloud providers, inside their data centres which are now expanding to all devices, users, and machines worldwide.

As a result, photonic technologies need to be revamped to support ultra-dynamic reconfigurations at orders of magnitude quicker than anything seen before (from minutes to subsecond, or microsecond response time), for lasers, cross-connects, optical amplifiers, for on-chip or stand-alone components. The massive digitisation of optical networks also requires that all devices and nodes are made programmable and controlled with either proprietary technology or open technology (for example, open platforms, open interfaces and APIs) while supplying efficient telemetry and analytics for network operation. Telemetry will be fed with real-time monitoring, largely embedded in coherent transceivers or inside new dedicated photonics sensors. Artificial intelligence will process telemetry measurements to learn and predict for smart control, optimisation, and fault detection of the photonic infrastructure.

Network function virtualisation and disaggregated computing have become the basis for the functions and services that networks offer, requiring increased flexibility and programmability of the network at different levels.

The resulting smart infrastructure uses flexible and programmable networking hardware (HW) and software (SW), combined with artificial intelligence, to pursue the networking industry's visions of autonomous, cognitive and intent-based networking to enable true zero-touch network operations. Although the process of applying artificial intelligence and machine learning mechanisms to networks is still in its infancy, specific use-cases on different levels clearly show the promise of this transformation. This benefit extends beyond the network operators to services providers and users because innovation in network operations is the basis for machine-to-machine, smart things or other IoT connectivity. Artificial intelligence has become a pillar of the IT revolution ahead, which Europe must master to challenge America's and China's ambitions. Optical networks cannot escape the influence of this technology: there is a timely but urgent window of opportunity for the EU to drive changes at scale.

2. Instantaneous response

Low and deterministic latency in the optical network connections
In future communication networks, data exchanges between devices and/or machines will take precedence over data exchanges with humans, calling for much tighter requirements on communication time-delay, or 'latency', but also on reliability, expected far greater than in regular IT networks. This evolution will be crucial, for example, in a network of robots on a factory floor where perfect synchronisation is paramount.

While the success of internet technologies can largely be associated with the best-effort delivery of data, these technologies cannot cope well with congestion when a multiplicity of applications compete for simultaneous delivery, thereby causing data loss, or a delay in data delivery, jeopardising the cooperation of machines and robots. A new digital infrastructure merging high capacity wireless and optical technologies is necessary to link machines, work products, systems and people, and perform IT and robot control over the same converged optical infrastructure (Industrial Internet).

Therefore, time-deterministic and time-sensitive networks need to be developed, with photonics as a 'keystone', key enabling technology ideally placed for the task. Studies on the hybrid use of electronic and optical switching and new switching paradigms are needed, where photonics technologies offer some of the most promising opportunities to offload the packet switches, saving energy, improving bandwidth efficiency, and guaranteeing deterministic low latencies across the network.

Some applications require network resources only for a very short time. Consequently, approaches enabling a faster reconfiguration (of less than 1 millisecond, for example) on the optical layer, taking into account concerns, such as amplifier power transients, need to be developed. While optical switching in commercial applications was so far limited to circuit switching, advances in photonics integration could allow optical flow or packet switching approaches to become practical for the industrial internet.

Meeting those challenges is only possible relying on photonics and evolving the technology to adapt to a sometimes harsh industrial environment (such as within a wide temperature operating range, or in high humidity), where cost and power consumption of transmission interfaces should be close to 50 cents/Gbit/s and some picojoule/bit, respectively.

Similar cost and power-saving reasons are leading to the introduction of new photonic technologies in dense equipment boards that are necessary for real-time control, data analysis and cloud computing of industrial cyber-systems, for example, the Optical Field Programmable Gate Arrays (Opto-FPGAs), namely electrical integrated circuits (ICs) with high-speed optical I/O for replacing the traditional electrical lines.

Photonics will not only fill the gaps of the current technologies but will also pave the way for completely new applications, such as the use of LIDAR (Light Imaging, Detection, And Ranging) to increase the manufacturing accuracy and monitor robots in factories.

According to the European Patent Office (EPO), European patent applications on smart connected objects achieved a growth rate of 54%, far exceeding the overall 7.65% growth[35]. This illustrates the strategic position of Europe in shaping the next industrial revolution: there is a growing awareness across Europe that investing in the digital infrastructure of European industries is a matter of sovereignty.

In summary, photonics offers a wide range of solutions to revolutionise industrial production and working environments, facilitating a fully digital value chain from supplier to customer. The photonic industry created 42,000 new jobs alone during the Horizon 2020 funding period[36]. But perhaps more important is the indirect impact of

"Photonics will not only fill the gaps of the current technologies but will also pave the way for completely new applications."

[35] https://www.epo.org/news-issues/news/2017/20171211.html

[36] https://www.photonics21.org/download/ppp-services/photonics-downloads/Photonics21_3.-edition_Key-Data_Market-Research-Report-2018.pdf

Above: Photonics technologies contribute to a secure transmission of data.

digitisation on the creation of new jobs: an increase in digitisation by 10% results in a decrease in the unemployment rate by 0.84%; a 10% increase in digitisation produces a 6% score increase on the Global Innovation Index for a respective country.

3. Access Everywhere

Fibre-to-the-Home, FttRadio-Antenna, 'Fibre-in-the-sky' optical satellite comms, LiFi

'Always-on' digital connectivity will significantly enhance employees' productivity in a number of industrial and business segments through instant access to information, as well as a multitude of new cloud services – particularly in the context of IoT, smart things or Industry 4.0 use-cases.

These applications create an entirely new working environment and provide a better quality urban life: they require constantly available, high bandwidth network connectivity offering low latency, low power consumption and massive scalability in capacity and numerous connected devices.

Optical solutions are becoming the de-facto standard in the access network. Fibre-to-the-x (FTTx) technologies will displace copper and radio technologies wherever mobility is not required and fibre can be made available. Coherent PON could gain considerable importance with its ability to enable the convergence of fixed access and fronthaul on PON fibre infrastructure that is capillary deployed, particularly in large cities.

Beyond providing communications across an increasingly complete optical fibre network, photonic technologies are expanding into specific wireless use-cases: LiFi is becoming an alternative for more secure indoor communications, satellite communications are using laser light as a "fibre in the sky" technology, free space optics are providing high capacity line of sight connectivity, and optical subsystems could be used for beamforming, and steering, in next-generation radio systems.

With additional research and optimisation, Analogue Radio-over-Fibre (A-RoF) could turn into an alternative technology for the distribution of wireless signals, especially when exploring higher RF frequency ranges in THz communication. Ideally, an A-RoF system acts as a mere medium converter, creating – within an optical fibre – an exact copy of the radio signal on-air, without further processing, with obvious benefits in terms of hardware complexity and power consumption.

4. Intrinsic security

The resiliency of optical network infrastructure, secure transmission of data, complemented by quantum communications infrastructure covered by quantum flagship and other projects (cybersecurity, Sendate)
The ICT infrastructure, intended as a single integrated resource encompassing both communication network and cloud computing, is an expensive asset. Sharing it among different services and users is clearly advantageous however it comes with as yet unseen challenges in terms of quality of service and security.

Trusted services will be carried over a single IT and telecom infrastructure while being immune to the rest of applications, especially when targeting vertical industries.

Fibre and wavelength cross-connects will guarantee hard slice-ability and service isolation. When combined with flex-grid optical technologies, these components can provide new high value-added optical spectrum-as-a-service business models. However, new technologies based on integrated photonics are needed for photonic cross-connects as well as original architectures that are easy to install and configure, especially in end-to-end optical network scenarios, breaking siloed domains.

Communication infrastructure providing access to the same cognitive cloud requires an unprecedented level of security. Encryption on the optical layer can enhance the security level and save energy and bandwidth compared to current layer 2 or 3 security protocols.

The increasing interconnectivity of both individuals and devices not only increases the dependence on the network infrastructure but also the possibility of a threat – and therefore the vulnerability – of every user. A signal on optical fibres can easily be 'tapped', once the physical access to the optical fibre is available, which calls for the introduction of photonics devices enabling trust and privacy at the physical level.

Improvements need to consider quantum-safety, using quantum communication with photons, preferably compliant with optical amplification, while securing the integrity of data. Also, novel research directions like physical layer security for optical networks should be explored, leveraging new forms of distributed fibre sensing to monitor intrusion and enhance fibre network resilience.

5. Sustainable capacity growth

In a 5G and datacentre centric network, capacity in fibre networks has to 'keep-up' – hyper-scalability, power consumption, network cost, operational efficiency, green network
With data centre traffic consuming nearly 2% of all electricity used today and the share of communications technology in overall world energy consumption growing over the last decade, there is an urgent need for a paradigm shift to greener IT technology. This shift can be summarised as reducing the product of power efficiency x capacity (pj/bit x capacity).

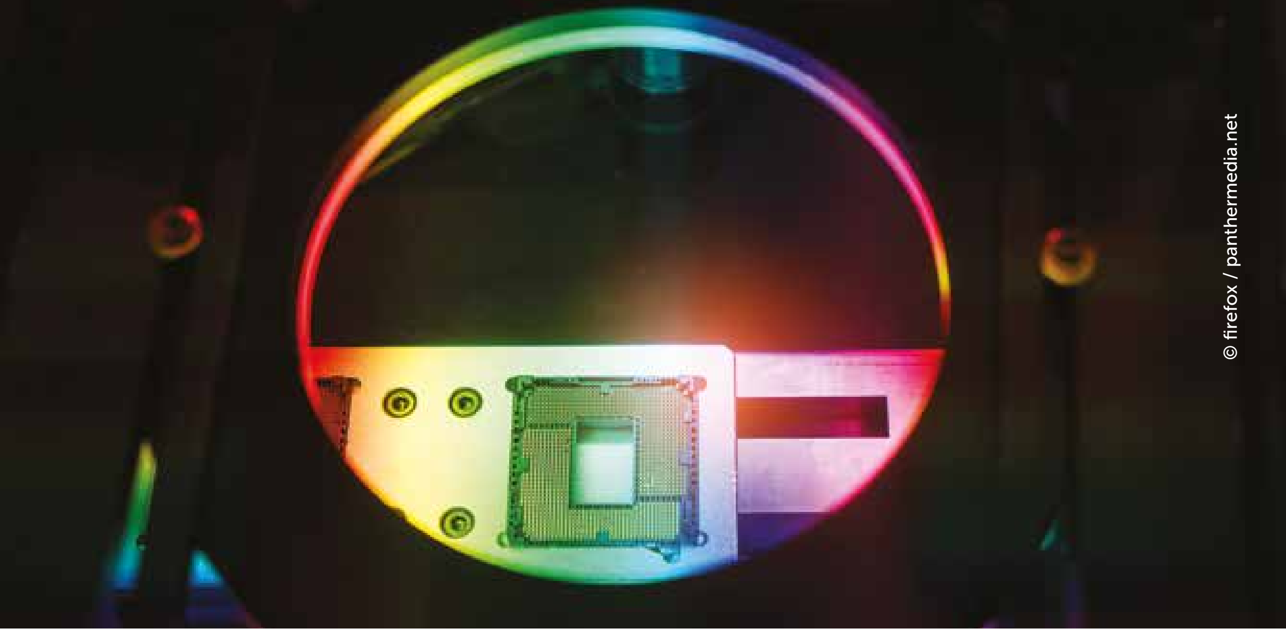
Increasing use of optical technologies within the ICT industry is an opportunity to limit the increasing energy consumption against the growth of overall data capacity that networks and data-centres are handling. Achieving the next level of integration between electronics and optics on a single die, and/or on a single multi-chip module or chipset, provides a significant contribution to lowering power usage and a more efficient network.

On a network level, this closer integration of photonics and electronics enables larger and more efficient switches that flatten network and datacentre architectures.

Extrapolations from today's data traffic predict rates of 10 terabits per second for optoelectronic interfaces and over 1 Petabit per second for optical fibre systems by 2024, calling for a full family of Petabit-per-second-scale photonics.

This evolution stumbles upon the most fundamental limits of physics that are: Moore's law on Silicon integration and Shannon's limit on optical fibre capacity, both of which are considerable barriers to growth.

Urgent research efforts are necessary to avoid system gridlock. There is a clear danger that a two-fold increase in the requested capacity will require doubling in the amount of optical or electronic hardware, which, consequently, will increase cost in a linear fashion and threaten future capacity growth.



Above: Photonics provides solutions for digital information processing.

To expand network capacity beyond the limits implied in Shannon and Moore's laws, we need to exploit all dimensions in space and frequency, opening new optical wavelength bands and space division multiplexing (SDM).

The exploitation of new wavelength bands will require advances in a number of technologies, ranging from optical amplifiers tailored to these new bands, to a wide range of optoelectronic devices and sub-systems. In particular, these technologies extend to tunable lasers, optical multiplexers, couplers, optical mixers, photodiodes, wavelength selective switches and other optical switching solutions.

SDM can offer several orders of magnitude capacity increase, either by multiplying fibre count in cables or by introducing multicore or multimode fibres. Here again, new node and system architectures, new digital signal processing, new space division multiplexers, new switches, new optical amplifiers are needed along with the new fibre types.

For space division multiplexing to become a cost-effective reality, a change of scale in component count per square millimetre in photonic integrated circuits (PICs) will be essential, capable of delivering and processing higher output power. All these elements of technology innovation are needed to scale the optical interconnect capacity along the Ethernet roadmap of line interface speeds (~6.4Tbit/s in 2030).

Besides the trends and evolution, the optical communications industry is looking at even more disruptive changes in technology. A vision relying on quantum photonics in networks and optical computers will be heavily reliant on electro-photonic integration and mass-market, modular quantum optics to become commercially viable.

For sophisticated computing tasks such as natural language processing, machine translation and object or face recognition, neural networks are increasingly being used.

"Photonics, and a photonic enabled ICT infrastructure, are essential to a number of European Commission initiatives to increase the quality of life through innovation across Europe."

Photonic neural networks leveraging silicon photonic devices as "neurons" may improve the speed of information processing a thousand-fold. Combining advances in artificial intelligence, the resulting photonics platforms for fast information processing will open the door to even more advanced network applications, for example, high-speed photonics neural networks and photonic artificial intelligence for neuromorphic computing tasks, and ultimately opening the field of neuromorphic photonics, with processing speeds a thousand times faster than what electronic neural networks can currently deliver.

Cooperation needs with other disciplines or fields

Photonics, and a photonic enabled ICT infrastructure, are essential to a number of European Commission initiatives to increase the quality of life through innovation across Europe.

Optical networks offer unprecedented capabilities in terms of aggregate capacity, service transparency and operational simplicity. These networks are a key enabler for the deployment of the next-generation mobile networks, as addressed in the Smart Networks & Services (SNS) Partnership and also provide unified network infrastructure for both fixed and mobile services.

Activities towards next-generation networks offering smart connectivity are expected to be carried out under the "human-centric internet" umbrella.

Among the key photonic technologies, there are: optical transceivers providing higher capacity at a reduced cost; footprint and power consumption for 5G front hauling and backhauling applications; integrated photonics optical switches in 5G transport optical networks; and cost-effective integrated optical amplifiers to connect 5G radio base stations to fixed access passive networks.

Further significant improvements in capacity and energy efficiency may arise from the adoption of new materials such as Graphene-based devices, like optical modulators and photonic switches, which are already in the scope of the Graphene flagship.

In 2008, the Public-Private Partnership for Factories of the Future (FoF) was launched under the European Economic Recovery Plan. The importance of a strong and renewed ICT infrastructure for the future digitised industry and its impact on the European society has been widely discussed in a previous part of this document, as well as relevant photonic technologies.

Here it is sufficient to add that the required level of security expected from the ICT infrastructure could be ensured by novel quantum photonic technologies for encryption and key distribution, such as quantum random noise generators, single-photon detectors, and Mach Zehnder arrays for the manipulation of quantum states, for example.

Only integrated photonics can allow the quantum technologies to move from research labs to the field, reducing interference sources and environmental noise, and enabling operation at room temperature. Quantum communication devices and systems are already in the scope of the Quantum Flagship but, and this also holds for the Graphene flagship, it is important to ensure that any new research or innovation activity is not technology pushed, but pulled by real applications and requirements.

The umbrella provided by the Digital Infrastructure work group of Photonics21 is ideal in this regard, due to the presence of the biggest optical equipment manufacturers in Europe, having close connections with major operators worldwide.

Additional cooperation is also desirable with microelectronics (for example, Key Digital Technologies (KDT) Partnership) to drive electro-photonic integration, and with the robotics field (for example, AI, Data and Robotics Partnership) for low-latency sensor/actuator networks and co-integration of sensor/actuator with optical communication subsystems.

Roadmap for 2021 – 2027

The roadmap is structured in such a way that the technical challenges are described from a user or application view. Solutions to these problems are then provided by the research and innovation challenges summarised below.

A range of base technology and platform developments are required, sometimes in the perimeter of the activities covered by "Core Photonics technology platforms", to turn the Digital Infrastructure Roadmap and vision into practice.

Topics to be addressed under the Core Photonics technology platforms are:

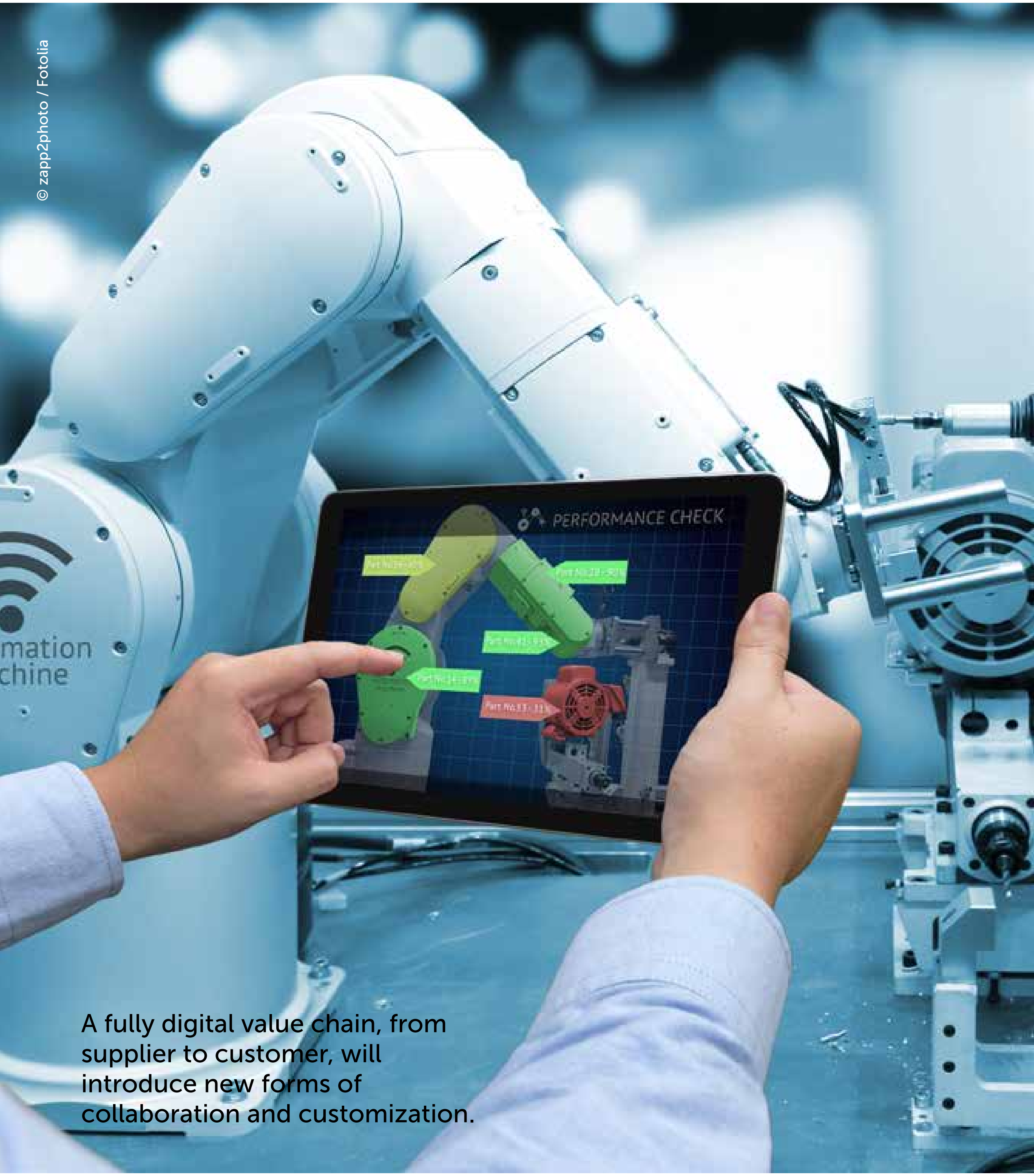
- Multi-chip module technologies combining digital electronic dies with optical 'chiplets';
- Solutions for optical chip-to-chip connectivity and on-chip networks;
- Electro-photonic integration;
- III-V and Silicon integration (uncooled, non-hermetic);
- Integration of new materials into Silicon platforms for improved RF capabilities;
- Adoption of mass manufacturing packaging and assembly technologies leveraging decades of experience from the microelectronics industry;
- High yield manufacturing and assembly processes;
- Optical interposers and optical PCB solutions;
- Robust solutions for optical fibre coupling and alignment (patch cord and pluggable connector based).

3.1 Digital Infrastructure

Proposed roadmap for 2021–2027

	2021	2022/2023	2024	2025/2026	2027
Overview **Technology Challenges *(user view)***	Zero-touch operation	Instantaneous response	Access anywhere	Intrinsic security	Sustainable capacity growth
Critical milestones to move from Science to Market	Open platforms, open interfaces & APIs	The growth of latency critical applications	The rise of cloud & fog computing	Standards, certification, integration	Cost-per-bit & power-per-bit reduction
Photonics **Research (R) & Innovation (I) Challenges**	**AI-enabled optical networks:** • Interoperable optical network nodes based on open HW and SW (white boxes) • Dynamically self-configuring optical network technologies based on AI/ML for control, optimisation, and fault detection • Optical devices enabling energy-efficient telemetry and analytics in optical networks	**Deterministic latency comms:** • Time-sensitive optical networking technologies • Latency-optimised optical interconnects • Optical precision timing solutions • Integrated optical comms for demanding sensor/actuator systems (e.g. 3D machine vision) • Optical robot and sensor networks **Ultra-dynamic networks** • Optical solutions for industrial internet applications • Optical spectrum and Ethernet services with hard service guarantees • Large scale, fast optical and hybrid e/o switches • Ultra-dynamic photonic devices (laser, cross-connects)	**Fibre in the sky:** • Optical wireless access including LiFi and VLC • Free-space optics (FSO) for backhaul, SatCom and aerial vehicles **Deep fibre access:** • Coherent PONs • New Radio-over-fiber solutions for fixed wireless access (FWA) • Colourless transceivers, high output power PICs **Optical radios:** • Optical subsystems for beamforming and steering • Optical concepts to generate and receive radio frequencies in the 100GHz-1THz domain	**Quantum safe comms** • Chipscale quantum RNGs and QKD engines • Pluggable quantum optics • Quantum repeater • Photonic devices for trust & security **Critical infrastructure protection and resilience** • Resilient optical network architectures • Hardened optical infrastructures • New methods for intrusion detection • Hard slice-ability and service isolation	**More than Shannon & Moore optics:** • Multi-band WDM systems • System & subsystem technologies for space-division multiplexing • Petabit integrated energy-efficient transceivers (<pJ/bit/s) • Optical ASICs and FPGAs **Towards optical computing:** • From electronic to optical IT • All-optical data centres • High-speed photonics neural networks • Optical compute functions • Neuromorphic photonics
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	Artificial Intelligence	Factories of the Future, robotics	Human-centric internet	Quantum Flagship, cyber-security	Microelectronics, Graphene Flagship

3.2 Manufacturing



A fully digital value chain, from supplier to customer, will introduce new forms of collaboration and customization.

Main socio-economic challenges addressed

The *Grand Challenges* facing European research are well-documented. Digitisation, and a sustainable and circular approach for manufacturing and materials, will be the basis for a competitive, future-proof industry in Europe. This approach, supported by new technologies, will generate a future European industrial ecosystem with high technological sovereignty. The following photonics-based topics will provide solutions to a future-oriented European manufacturing and machining industry, with an emphasis on export and international visibility in global markets.

Digital	Green	Sustainable
• Fast and multi parallel high power laser beam handling • High-speed digital controlled materials processing • Simulation-based digital process chain development and optimisation • Rapid manufacturing of complex individualised products • Big data and AI-based production and process development • First time right production by high resolution and high-speed metrology and machine technology	• CO_2 emission reduction within the process chain by highly efficient and material-specific laser processing tools • Lightweight and bio-based components and their manufacturing • Substitution of carbon-based production and hazardous materials • Resource optimisation by material-specific usage and processing • Implementation of biological transformation elements in production and end products	• Future proof ecosystem by technological unique selling proposition for flexible and eco-friendly manufacturing • Comprehensive integration of process chain and materials and product life cycle • Manufacturing of affordable individualised complex products • Long-lasting flexible re-use of production equipment in fast product life cycles • Knowledge-based regional and European technical networks

Empowering Digitised and Eco-Friendly Industry with Tailored Light

In line with these challenges, manufacturing in the future will be specifically required to:

- Realise the technical and economic potential of sustainable manufacturing;
- Realise the potential of customised and near to market products;
- Implement technologies and strategies to bring back mass production to Europe.

Europe is in a strong position to meet these challenges: its strength in industrial photonics is part of its leadership in industrial technology, including machine tools and robotics. The global market for industrial laser systems – the largest manufacturing category for photonics – was worth €11.4 billion in 2016, a 7.4% increase upon the previous year. European photonics companies control roughly one-third of this market.

3.2 Manufacturing

"Quality control of manufactured parts will become an on-line capability, driven by the integrated use of sensor technology for parameter monitoring."

Photonics-related industry has a significant and direct impact on strategic targets within Europe, and aims to provide solutions for:

Digital Manufacturing

- Realise flexible manufacturing solutions with minimum implementation efforts;
- First-time right production of single products with highest quality and reproducibility;
- Full use of material-specific properties with optimised process chains.

Green Manufacturing

- Realise highly-efficient and zero-emission manufacturing in urban environments;
- Using the full potential of materials within the product life cycle;
- Optimising and efficient manufacturing of renewable materials for complex products.

Knowledge and Network-Based

- Maximise economic potential using knowledge-oriented technologies, solutions and businesses;
- Strengthen competition in the global economy;
- Implement an innovative culture of work taking into account an ageing population.

These approaches will address manufacturing challenges in the automotive, aerospace, shipbuilding, rail, oil and gas, medical instruments, printing, displays and white goods sectors. By 2030, European factories will be fast, green and flexible, using both existing and new raw materials, making manufacturing more innovative, cost-competitive and resource-efficient. A fully-digital value chain, from supplier to customer, will introduce new forms of collaboration and customisation, new services and new business models – all of which will strengthen Europe's industrial base. To realise the above, the following technological challenges will be addressed.

Results from these technological challenges will help to achieve five missions:

A million new jobs **10% higher productivity** **A truly circular economy**
Photonics as a flagship for innovation **Zero downtime in a digital economy**

As well as being versatile manufacturing tools, new laser systems will address the Grand Challenges of Europe and will be at the heart of fully-digital, connected value chains that allow companies to move between the mass production of identical parts and the manufacture of individualised products. Quality control of manufactured parts will be on-line, driven by the integrated use of sensor technology for parameter monitoring.

Similar sensor technology will provide high-speed feedback, to enable full process control during manufacturing, reducing the need for scrap parts. The industrial production of micro and nanomaterials will grow in the future: laser light will be an enabling technology in both the manufacture of these materials and their subsequent machining.

Laser light is unique in its wavelength, as well as its temporal and spatial form. The way a beam is delivered to the interaction point with the material being processed, combined with its ease of digitisation, means lasers will become the most versatile and flexible machine tools, ready for the next generation of manufacturing. Single photons and multiple beam approaches will evolve into disruptive technologies for fully digital production.

Thanks to these photonic-based technological solutions for green and highly efficient manufacturing, a maximum of energy and material savings will be available. Material adapted wavelengths and temporal

Below: Human-machine interaction in a fully digital production process.

and special energy deposition control will reduce material usage, shortening and simplifying process chains, to reduce overall manufacturing costs and CO_2-footprints.

With its wide network of photonics research, optical products and manufacturing technologies, Europe is in a unique, self-sufficient position providing technological sovereignty in highly productive and efficient photonic manufacturing systems. With the future development of new lasers, optics, digital approaches and material-specific processing strategies, the current European innovation eco-system will be proactive in developing new manufacturing technologies without having restrictions from worldwide supply chains.

Europe has the potential to maintain a leading position in photonics manufacturing. Developing new optical sources, photonic solutions and manufacturing applications, Europe stands in a strong position to address the Grand Challenges it faces to be Digital, Green and Sustainable.

Below: New laser systems will be at the heart of fully digital and connected value chains.

Major Photonics Research & Innovation Challenges

To carry out the missions described above, many technological research and innovation challenges must be addressed which take the "digital", "green" and "sustainable" desirable attributes into account and enable a continuous photonic process chain.

Laser beam sources: due to the increasing demands on process speed and quality, it will be essential to increase system performance – and at the same time increase the quality of optical fibres and elements – in coatings and laser components.

Laser beam sources with high efficiency and adaptable beam parameters will be necessary to follow industrial needs. Higher beam intensities and process-adapted beam distributions are vital for challenging applications, for example on high-temperature materials and fibre composites. This improvement will enable fast processing that is not harmful to the material.

In the field of new pulsed beam sources, high-power, ultrashort pulse lasers – and highly agile lasers with flexible pulse widths, wavelengths, and pulse energies – will unlock new applications in electronics, lightweight construction, ceramics, glass and metal processing, leading to continuous, and digital, photonic process chains.

Starting from today's 100 W class lasers, completely new process technologies are expected from developments in the multi kW class. Power scaling in process technology might be achieved by using parallelised beam sources and distributions.

The central element for these new, high-energy beam sources with ideal beam quality, will be compact and efficient high-performance diode lasers, 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.

With powerful and low-cost diode lasers, new markets will be created outside the traditional industrial areas of application. A pilot plant for laser diode development would foster the exploitation of new technologies in this field. In particular, within the rapidly growing field of additive manufacturing, compact high-power diode lasers will be the key to their widespread use.

In addition, it will be vital to develop flexibly switchable laser beam sources with selectable or adjustable pulse durations, wavelengths, and polarisation or wavefront profiles adapted to the absorption conditions of the different materials being processed. This requires powerful frequency conversion technologies and advanced system technologies.

"Innovative material systems and system designs have to be developed for transmission of laser radiation without loss or distortion even in the mid and far infrared range."

Wavelengths in the mid-to-far-infrared and novel coherent beam sources down to the X-ray range will create additional application areas in manufacturing and metrology with completely new product properties.

Beam guidance and beam shaping: for the integration of the new beam sources, 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. For further integration into machine tool technology, ultra-fast scanning 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.

Enhanced positional flexibility and the free choice of energy distribution will be essential for flexible and controlled photonic production. A more flexible energy distribution will guarantee optimal energy deposition and maximum processing quality.

Using the technological approach of "Tailored Light", the photon energy will only be placed where it has the highest physical, chemical or biological effect. This challenge will require adjustable or programmable beam shaping, optimisation by multi-space algorithms, rapid quantitative feedback and beam distribution systems with (sub) micrometre resolution and high performance. It will facilitate reconfigurable smart machining systems, 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 multiscale functionalisation or multi-function in the same process.

Flexibility and exact adaptation of the energy deposition to material and component geometry are characteristic features of laser processing, with the ability to produce (and monitor) small structures or material modifications in the micrometre and nanometre range on surfaces and bulk. The need for even smaller structures will require new optical systems that overcome the Abbe limit for the Gaussian beam, and thus open up processing possibilities for directly addressing crystals and molecules.

This will allow functional changes and design features to be implemented, not only at the macroscopic, but also at the microscopic, and nanoscale level, with multiscale complex features and multidimensional geometrical arrangements (for example hierarchical surfaces and 3D systems), which are not possible with conventional manufacturing methods.

Combined with flexible systems for multi-beam handling and fast beam switches, this will result in a new form of machine tool, enabling highly

Left: Electrically high efficient and mechanically robust busbar connections with laser welding.

Left: Laser cutting of coated and uncoated electrode foil.

flexible and energy-efficient production at the highest geometric level. In combination with interactive robots and plug-and-play tool changing systems, new manufacturing concepts will be created that follow the basic principle of digital photonic production.

Industry 4.0: here, the key challenge is that laser systems become perfectly embedded in the digital process chain. Intelligent fibre connectors will not only bring the laser light to the right place in the machine but will simultaneously serve for networking complex and flexible systems. In addition to status information about the actual connections, signals from the process zone will also be transmitted to the beam source. An example is the monitoring of ‘back reflections’, but other process signals will be used.

The beam source and its control will be a central element of the production plant. Sensors will not only monitor the actual laser parameters but also check boundary conditions to maintain a smooth production process. Future multifunctional optical fibres – which are, on one hand, intended for power transmission and, on the other, used for signal transmission from the interaction zone - pose major challenges concerning the wavelengths that will be transmitted.

To enable production with high throughput, massive parallelisation is a possible solution. Simultaneous 'flexibilisation', however, requires precise and adjustable control of the individual partial beams. This requires intelligent and networked beam splitting and shaping elements.

From bits to photons: continuous data chains, from concept to the finished component, not only include suitable data formats and CAD modules that make it possible to integrate simulations of the individual manufacturing processes as early as the design phase, but also include innovative self-learning, for example, machine learning methods within the data and process chain. This close connection between processes, devices and systems could be achieved by methods like digital twins.

Quality Control and NDT: for the future, the major challenge is to ensure high product yield while simultaneously maintaining high quality. Fast and reliable, online, non-destructive testing (NDT) methods will be required to achieve high product quality in high yield environments. This will especially apply to additive manufacturing processes, in which both defects and deviations from the target geometry must be detected and compensated for during the layered construction of the components.

The final quality must be also verified as porosity, and cracking in the component's interior must be avoided. High-precision manufacturing, for example, electro-optical components in photonic integrated circuits will require photonic technologies to implement efficient non-destructive testing.

All test procedures should be capable of being used online and in real-time. Here, combining optical methods with the laser processing head will be a challenge.

Large amounts of potentially useful data can be generated during laser-based production. The future challenge is to maximise the value of this data, which is expected to be achieved 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, potentially reducing process development costs by a significant margin.

Laser specific materials development: the short interaction times and high cooling rates involved in laser material processing require materials and alloys specially designed for optimum part performance. During the additive processes, for example, the composition of powder used and the use of multiple powders in the same part will require further development. In the field of electronics, adapted conductive inks will be required and applied to components using inkjet printing to allow functionalisation by laser radiation. In addition to their functional properties, the optical properties of these inks will need to be tailored to the interaction mechanisms, to archive optimised processes.

Skilled people and flexible infrastructure: with its close links to research institutes in the fields of optics and manufacturing technology, photonics plays a key role in promoting Europe as a manufacturing location. However, photonic technologies, as well as impacting machine tool developments, also require well-trained individuals who satisfy companies' needs for personnel capacity, at all levels of photonics-based production.

Lifelong learning is a major challenge. The fast development cycles in laser technology require continual training of employees so that the results from research facilities and development departments can be transferred to production quickly and as smooth as possible.

Establishing photonic science hubs will generate space for creative ideas and developments. These hubs not only provide infrastructure in the form of machines and devices but also ensure the transfer of knowledge through connections with academic research institutions. Such mechanisms will also facilitate opportunities for new business models in cooperation between companies, as well as with universities and research organisations to provide attractive investment opportunities for venture capital.

Cooperation needs with other disciplines or fields

Photonics is a cross-sector technology, and pan-European cooperation along the entire value chain will be essential for future progress and success. All the relevant players need to be involved in respective collaborative projects, research networks and clusters, providing novel and innovative solutions to manufacturing problems.

Close cooperation between corresponding work groups within the photonics sector will 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 Photonics Core Work Group will be vital.

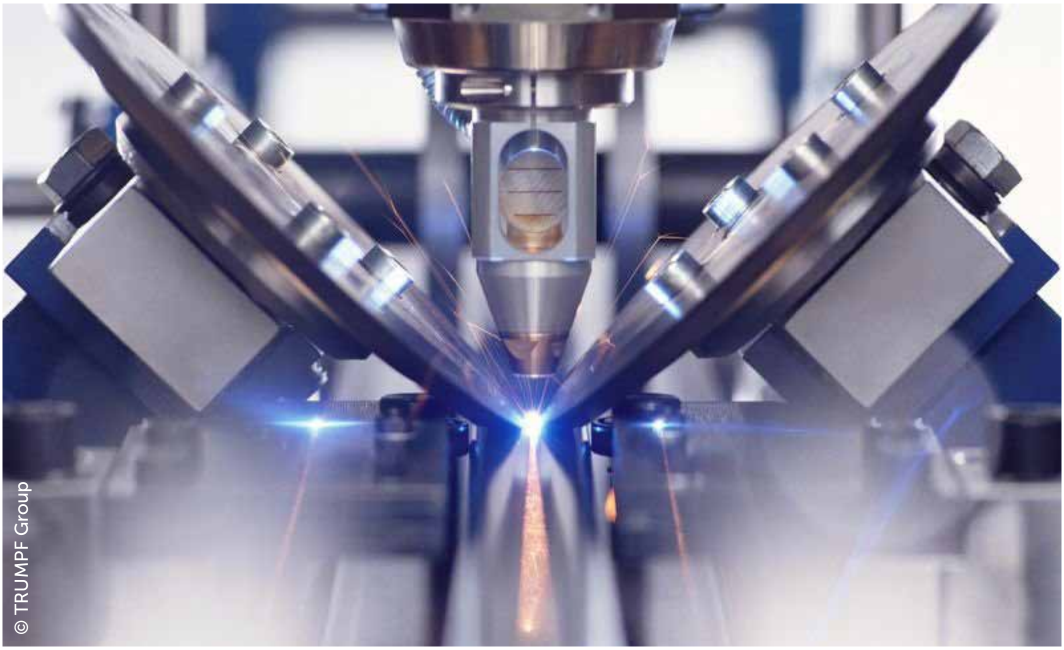
3.2 Manufacturing

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

To implement laser-based manufacturing solutions in Industry 4.0, close cooperation with the PPP "Factories of the Future", now "Made in Europe" (EFFRA) has already been established and should be continued on many levels. This also applies to the PPP "Robotics" and towards data analysis, artificial intelligence and machine learning sectors.

Further cooperation needs should be pursued by integrating aspects of the circular economy, which could be realised by joint projects with the "SPIRE" (Sustainable Process Industry) PPP.

Below: Efficient manufacturing processes by the use of the laser.



Proposed roadmap for 2021–2027

	2021	2022/2023	2024/2025	2026/2027
Overview **Technology Challenges**	**High speed processing** **Weight reduction** **Digitalisation of production** **Agile manufacturing and connected production** **Individualisation and personalisation of products and production equipment**		**CO_2 emission reduction** **Material savings** **Simulation supported production**	
Critical milestones to move from Science to Market	High-speed scanners / tailored beam developments and applications	Simulation and digitalisation	Connected production	Global environmental goals
Photonics **Research (R) & Innovation (I) Challenges**	**Efficient lasers and components** • Material, coatings and components for high power/high-intensity beams • High energy and highly agile ultra-short pulse lasers • High brilliance diode lasers (CW and pulsed) with different wavelengths • Lasers for the generation of coherent X-rays • High power mid-infrared lasers with wavelengths greater than 1 µm • Multibeam lasers **Beam delivery, shaping and deflection systems** • Novel optical fibres for use at wavelengths greater than the UV (and beyond 2µm) • Non-mechanical high-speed beam scanning systems • Re-configurable and programmable beam shaping systems (tailored light) • Rapid monitoring and quantitative feedback systems • Focusing and imaging optics facing the Abbe limit for highest spatial resolution of energy • Multibeam guiding and switching • Miniaturised interchangeable optical processing systems **Industry 4.0** • Connectivity of laser systems for integration in manufacturing platforms (also intelligent fibre connectors with integrated functionality e.g. back reflection or temperature) • Integration of sensors throughout the laser processing system • Parallel processing for high throughput • Data and knowledge management for laser materials processing "standardised" CAM-modules for materials processing • Development and integration of simulation tools into production chains **Quality control and NDT** • Real-time process control • On-line non-destructive testing of laser manufactured parts • Process optimisation based on novel in-line / at-line photonic measurement and multi-modal metrology • Big Data correlation, meta modelling and quality prediction • Data analytical techniques / mathematical methods to optimise information gathered from available measurements (e.g. compressive sensing, super-resolution imaging) **Laser specific materials development** • Alloys and materials for additive manufacturing • Photonic specific materials for electronics • High-performance materials for laser processes			
Joint actions required	EFFRA; Robotics; SPIRE			

3.3 Health

Photonics technologies drive the digital revolution in healthcare.

Main socio-economic challenges addressed

In this chapter, the 'Health' Application Work Group examined *instant diagnosis of major diseases*[37].

The European population is ageing increasingly: the number of people today older than 65 relative to those in the working-age is assumed to double by 2045. Since age is a major factor for a higher probability of becoming ill, a large increase of corresponding illnesses 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[38], dementia and macular degeneration are possible concomitant effects.

However, age is, unfortunately, only one factor for death by disease: worldwide the number of corresponding incidences exceeds 30 million people per year just from the ten leading conditions like Cerebro- and cardiovascular diseases (heart diseases and stroke), cancer, sepsis and obstructive pulmonary disease (COPD). There are not only serious diseases but also less severe conditions that afflict patients like infections of the gastrointestinal system or urinary tract infections, where new methods could help to decrease the burden.

Additionally, the prevention of diseases, early risk assessment, as well as the improvement of well-being are all important and represent persistent challenges that need to be tackled.

This early intervention starts with diagnosis, therapy and interventions in utero, at birth and beyond for conditions where the social burden is increasing as the society ages, for example, premature birth and congenital malformations. Here, a major trend is P4 Medicine (Predictive, Preventive, Personalised and Participatory), for which the instant diagnosis of major diseases is imperative.

However, our patients' illnesses and conditions are not the only issues at hand: our healthcare systems already struggle to keep up with the ever-increasing costs, a fight that 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. In an ageing society, there will also be a decrease in the workforce, a trend that will inevitably lead to near full deployment in the future, which is already the case in many regions in Germany. At present, the supplies of care workers for the elderly and nursing staff are running short, a trend that will be amplified by the ageing of society as more patients require care.

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[37] Note that this mission title does not exclude treatment and treatment monitoring and planning from being in focus. Certainly, diagnostics is always connected with therapy and is not an end in itself.

[38] (see e.g.www.cancerresearchuk.org/health-professional/cancer-statistics/statistics-by-cancer-type/breast-cancer/incidence-invasive#heading-One)

Above: Photonics technologies deliver instant diagnosis and treatment of major diseases at the point of care.

Another non-age-related challenge is mobility. As demonstrated by the outbreaks of the COVID-19 pandemic, high mobility leads to the spreading of infectious diseases over large areas in short periods with huge consequences for our health, well-being and economies. In many developing countries, healthcare is still underdeveloped, with affordable methods of increasing the health and wellbeing of their respective citizens yet to be found. While helping should be imperative, there are also large markets and opportunities outside of Europe, which could be served by European industry and therefore lead to increased growth.

European industry is currently among the global leaders in the healthcare market, growing at a substantial rate of 10.8% CAGR[39], and with a total market volume of €33.8 billion in 2015[40]. Photonics for Healthcare is assumed to reach around €50 billion worldwide by 2021, making it not only one of the largest markets within photonics, but also one of the more rapidly expanding sectors globally, a tendency which will 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.

[39] Biophotonics: Technologies and Global Markets (PHO024A) Publish Date: Dec 2016, BCC Research LLC, www.bccresearch.com/pressroom/pho/global-biophotonics-market-on-the-move-with-double-digit-growth-rate

[40] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Market Research Study, Photonics 2017, Brüssel / Düsseldorf / Tägerwilen, May 2017.

The market of Photonics systems for Healthcare is illustrated below:

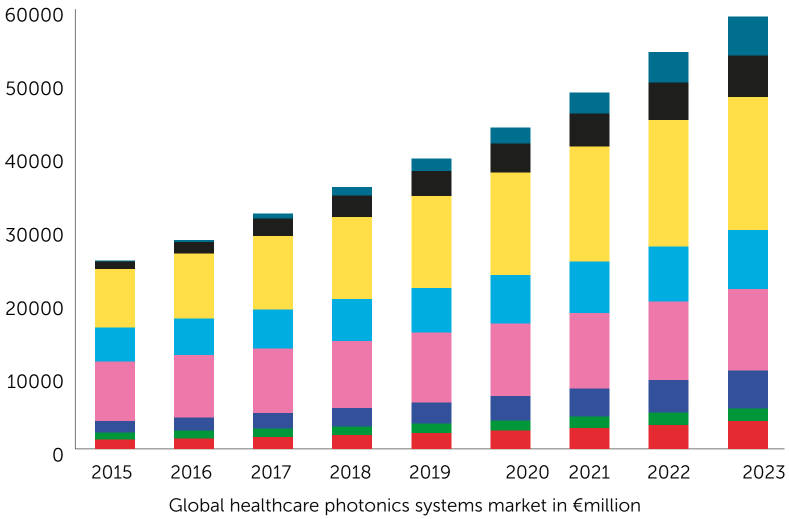


Figure n°5: Global Market of Healthcare Photonics Systems. (AR: Augmented Reality; VR: Virtual Reality; See-through imaging: mainly X-Ray & Photoacoustic imaging, Surface imaging: OCT, Ophthalmoscope ...).

Source: Tematys.

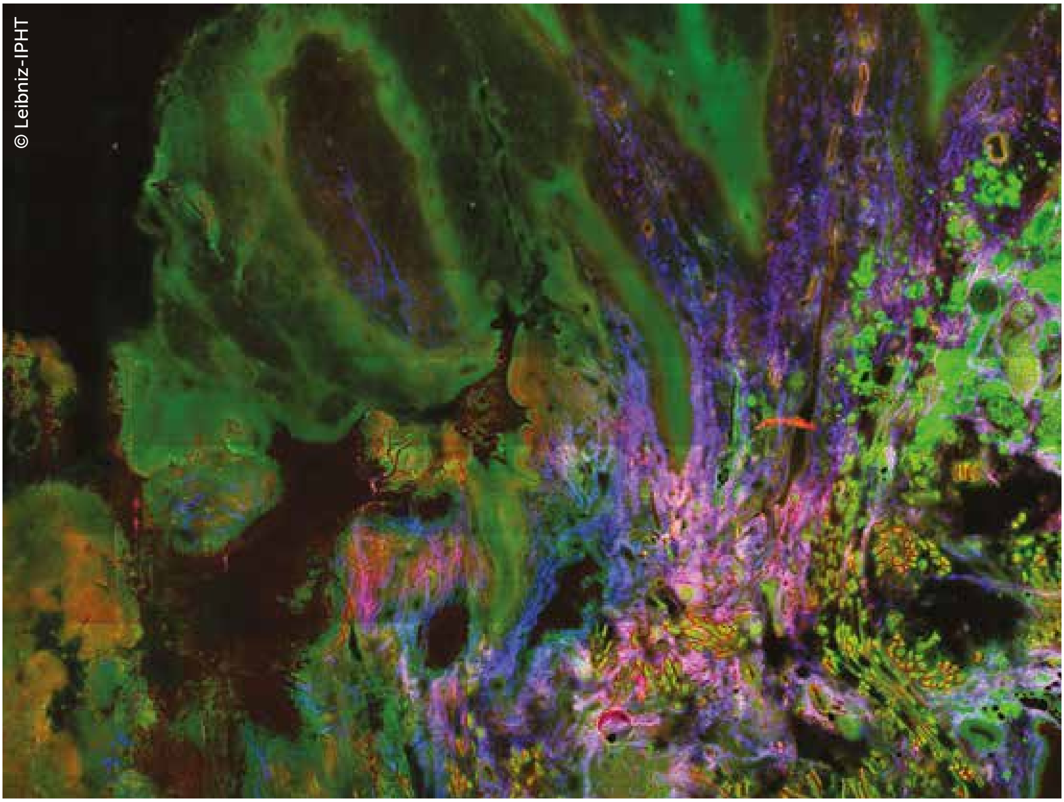
Major photonics research & innovation challenges

Focusing on the *instant diagnosis of major diseases*, Work Group Health identified three sub-missions which will be pursued in *Horizon Europe*:

1. **Advanced Photonic tools for life science industry** as well as end-users (for example, medical doctors or research)
   - Photonic tools for real-time proteomics, genomics, metabolomics;
   - Accelerating and enabling photonic tools for the pharmaceutical industry, understanding, regenerative medicine, personalised medicine, high throughput, high-content screening;
   - Photonic tools for understanding the origin of diseases beyond risk factors, finding pathways for treatment, photonics for health (nutrition, lifestyle, environmental influences, toxicity).

   Echoing the sentiment in a 'Europe fit for the digital age', advanced medical tools that rely on photonics will empower "people with a new generation of technologies". These photonic tools should be extremely reliable with sensitivity and specificity exceeding 90%. While the cost remains an important factor, it is less significant in the case of mobile photonic devices. With self-explanatory measurements, a user-friendly data presentation, operator-independent results and advanced chemometrics evaluation schemes, the devices should allow non-experts to use them freely.

   For imaging-based methods, an increase of both sampling volume (in contrast to POC methods where decreasing the sampling volume and the limit of detection is commonplace), as well as depth (> 1 cm)



Above: Multimodal optical imaging of larynx cancer tissue.

will be key targets. Future, potentially multimodal methods and tools need to significantly improve upon present state-of-the-art approaches.

New *Photonic tools for real-time proteomics, genomics, metabolomics* will enable DNA sequencing in less than 10 minutes and combine the analysis of proteomics, genomics and metabolomics into a single instrument, potentially finding their first application in metabolomics-guided treatment or rehabilitation.

Photonic tools for the pharmaceutical industry and regenerative medicine will be developed to stages where they allow toxicity testing of new drugs in a preclinical phase. The tools will capable of high throughput and monitoring over months with rapid, parallel testing of variants of pharmaceuticals (i.e. >200).

A further potential application is the monitoring of tissue growth for organ replacement. Today, only the completed organ is tested and, given that this is a costly and time-consuming procedure, it would be advantageous to immediately correct malformation.

A third potential application is providing a basic understanding of disease development to create strategies for detecting early disease development. This will include different body fluids as samples, including blood, sweat and lymphatic fluid.

The photonic tools for the understanding of undeveloped diseases' origins have several potential application fields: the development of new drugs for currently incurable diseases, the advanced understandings of brain functions or the search for new biomarkers are exciting areas for light technologies to explore.

Promising tools to investigate the origin of diseases (including cardiovascular diseases, or cancer, for example) with 3D imaging methods are emerging, which will be capable of combining subcellular resolution with a systemic field of view, encompassing entire organs, small animal models or even the entire human body.

"Promising tools to investigate the origin of diseases (including cardiovascular diseases, or cancer, for example) with 3D imaging methods are emerging."

Such instruments could also be used or developed, for example, to study drug diffusion inside the body, or minimally invasive, continuous monitoring of therapies through the skin, which would help to develop new therapeutic protocols.

The challenges for Photonics R&I are diverse depending on the particular methods applied.

At a component level, there is a need for new light sources such as laser-based infrared sources, (Quantum Cascade Lasers, for example), that also cover the ranges beyond the fingerprint region, or, broadband light sources that cover the UV-VIS-MIR range at affordable prices, and, are LED-based.

More sensitive detectors for all spectral ranges and components like filters and beam shapers need to be developed.

Affordable pulsed sources and detectors that cover a broad spectral range should also be pursued, to take advantage of the more informative content of time-resolved data.

2. **Affordable photonics-based real-time diagnostics** to stratify and classify disease status monitor and assess treatment response for the practical implementation of precision medicine; optogenetics for the treatment of brain or heart diseases, for example; photonics for physiological treatment or photonic-assisted physiological treatment; photonics for interventional guidance (augmented reality); multiscale access to the body (depth of penetration/optical resolution)

   3D-imaging with a wide, organ level, deep view (> 1 cm) and a high resolution will enable 3D, label-free[41] histopathology in combination

[41] Label-free or based on already approved labels, as completely new labels would first need FDA approval, which is a very time-consuming process.

with an AI-based identification of conspicuous tissue areas and volumes. Imaging will be possible down to the cell level (diffraction-limited), by combining different photonics modalities. This will allow precision surgery with real-time discrimination and selection of surgery targets as well as a targeted treatment. In the corresponding surgical microscope, photonics sensing and augmented reality – for example, by light-weight near-eye visual displays with very high resolution and very wide field of view – will be integrated.

The laser source, as well as all-optical components, will serve all imaging and treatment modalities ("laser surgery"). At the same time, all components will be compact to allow the system to be mounted on a cart, similar to the ultrasonic imaging devices used in hospitals today. The system will use open data formats and fit into the workflow in the operating theatre.

Advanced haemograms will be possible by the in-vivo counting and identification of cells like immune or cancer cells as well as the assessment of functional parameters. The corresponding tools and methods will also allow screening for risk-assessment and treatment response in highly curable diseases like breast cancer (such as chemotherapy monitoring), Alzheimer (glymphatic system monitoring) or infectious diseases (pathogen identification and antibiotics resistance determination). Instruments and algorithms for the analysis of tissue composition (for example water, lipids, collagen content) or detection of newly identified biomarkers will also play an important role. Overall, the tools and methods for advanced haemograms (as well as instruments and algorithms) will enable to monitor label-free pathophysiological conditions and the wellness and health of patients.

Optogenetics methods will be developed to enable neural re-wiring, for many different procedures: for deaf or blind patients, for prosthetics, for the functional recovery of cells or for determining brain oxygenation to an accurate level, perhaps tenfold in comparison to today.

Depending on the application, the corresponding systems will have to be robust, accurate and allow real-time measurements. The systems will need a reliable design, to survive under harsh environmental conditions in the long term. Adapted photonic components such as light sources and detectors will need to be developed for new biophotonic systems, which have to be configured to operate under standard procedures that do not yet exist. Advanced computing methods will be required to manage and evaluate the large amounts of data generated and render the corresponding instruments user-friendly.

3. **Mobile photonics devices and advanced biosensors** for instant point-of-care (-use) detection/diagnostics and treatment, that measure the patient's medical condition, transportable photonic devices for monitoring environmental parameters

   Applications for mobile photonic devices could quantitatively assess blood sugar for diabetes, or monitor vital signs like pulse, blood pressure, blood oxygenation. Mobile photonics could evaluate the quantity of new specific and local biomarkers, as well as control the pharmacokinetics of pharmaceuticals and the progression of pathologies.

   Such devices could be carried or even implanted within the body. In the case of the latter, the device volume should not exceed 1 cm^3, while weighing no more than a few grams. Ideally, the device should have low power consumption, connected with self-charging abilities, and have a manageable heat loss. Generally, materials must be fully biocompatible.

   Mobile photonics devices could be used for pathogen identification and support doctors on visits to enable fast medication. A mobile device should produce reliable results accurate enough for their purpose, but much faster and cheaper than conventional analysis tools. Specialised devices should continuously record (or at low time intervals) the wearer's vital signs, which should be analysed daily to allow the early detection of diseases related to age or lifestyle or for the prediction of drastic events.

   Other specialised devices should be able to follow disease progressions and give the wearer, or the doctor, information to adapt medication to the patient's needs. Implantable devices should be reprogrammable and have wireless connectivity. Wearable devices could replace watches, be woven into clothes or be in the form of eyeglasses. Add-ons for smartphones will be developed to transform them into cost-effective handheld devices for imaging applications, enabling personalised services based on the available data.

   To enable these mobile biosensors, new miniaturised light sources are needed, able to cover multiple wavelengths or large wavelength ranges, (for example LEDs as well as tunable or pulsed laser sources) that are cheap and robust. Detectors will have to be miniaturised and new optical filters may be needed.

   The interrogation of appropriate biomarkers (which may yet need to be identified) should be label-free and fast. Further integration of photonics and electronics and microfluidics is necessary to allow

"Mobile photonics devices could be used for pathogen identification and support doctors on visits to enable fast medication."

for stable detection conditions either on or within the body. For the user, data provided by the sensors must be easily understandable. Data must therefore be locally processed and/or safely stored or transferred where necessary.

Data evaluation must be performed objectively, by trained neural networks and corresponding software solutions need to be developed. Special care needs to be taken to avoid external unauthorised data read-out and manipulation.

In Biophotonics, as in all medical technologies related fields, the translation of a proof-of-concept to a final product is very challenging. The proof-of-concept must have the potential to be developed further into a product which is not only capable of passing clinical trials but also of fitting into a doctor's workflow and gaining 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.

In the past, many projects were funded that never made it into a product because these requirements were not sufficiently considered and factored in the development process. As well as market access and market acceptance, adherence to standards where they exist needs to be taken into account properly. If such standards do not exist, the proposed project needs to contribute steps toward standardisation.

Overall, it is already a prerequisite for proposals and research projects, and increasingly for innovation projects, to demonstrate that these points have been taken into consideration through the involvement of key stakeholders along the value chain that appropriate measures are taken to increase the chances for translating the idea into an accepted product.

Right: Photonics technologies provide solutions in healthcare.

Cooperation needs with other disciplines or fields

Cooperation with all healthcare stakeholders is essential, given that Healthcare is always accompanied by developmental impediments along the way from basic research to a marketable product, (such as regulatory hurdles, standardisation reimbursement issues, and standard protocols).

While there are different stakeholder communities with topics that range from big data to robotics, electronics, biomaterials, fibre and nanomaterials which are all involved in the fabrication of sensors and wearables, for example, a close and structured collaboration with all these stakeholders and the corresponding European Technology Platforms (ETPs) and initiatives is essential.

When considering interdisciplinary collaboration at a Pan-European level, an initiative of significant note is the "Emerging Smart Technologies for Healthcare" (ESTHER), in which Photonics and the corresponding ETPs of Nanomedicine, EU Robotics and BIG DATA Europe all play a significant role.

Photonics21 is in the process of building a meta-initiative with relevant technology organisations to enable a common and coherent effort towards enabling innovation in health.

ESTHER, and all the healthcare stakeholders involved, strive for "sustainable Health and Wellbeing for all European citizens" through the "digitisation and convergence of the Key Enabling Technologies" as well as a "holistic concept based on the inclusion and consent of all stakeholders" with the aim of "Providing integrated, innovative and smart healthcare solutions for all European patients by promoting an innovative European Health Technology Industry".

Photonics21 A-WG "Health" is fully committed to this vision and the need for cooperation among the different stakeholders to achieve the final goal of making Europe ready for the healthcare challenges of the future.

Within Photonics21, cooperation with A-WG "Safety, Security, Space & Defence" is planned in the context of its focus on "multi-analyte pervasive AI-supported photonic bio-sensing".

3.3 Health

Proposed roadmap for 2021–2027

	2021/2022	2023/2024	2025/2026	2025/2026	2027
Overview **Technology Challenges**	Mobile Biosensors	Photonic diagnostics and intervention	Understanding diseases and prevention	Photonic sequencing	Photonic screening and guiding
Critical milestones to move from Science to Market	Biocompatible materials need to be found/investigated. Further convergence and integration of photonics, electronics and microfluidics: • Miniaturisation of optical components to enable smaller on-chip solutions (in-body devices with volume < 1cm3) • Low cost miniaturised broadband sources and detectors • Demonstration of higher effectiveness for state of the art reliability and specificity in in-vivo conditions	Miniaturisation and integration of optical components to build a • 3D label-free histopathology and treatment modality • Imaging platform to measure cell/brain oxygenation mountable on a cart • Integration of optical, electronic and microfluidic components for POC systems for advanced analysis of body liquids to fit in a shoebox	Further development of photonic components:[42] • broadband pulsed laser sources UV-Vis-MIR • more sensitive detectors for all spectral ranges and components, broadband detectors spanning UV-Vis-MIR • development of corresponding, novel 'green' and/or low-cost optical components (for example, freeform) and system integration • Phantom development and standardisation (imaging applications)		
Photonics **Research (R) & Innovation (I) Challenges**	Improve optical contact for on-body/in-body biosensors (stable, reproducible and continuous) (R) Biomarkers research (R) Develop mobile biosensors to the next level (body liquids, but also portable image systems) (R & I)	3D label-free histopathology and treatment modality relying on augmented reality – • photonic components (R) • system (I) Advanced POC Device for fast analysis of body liquids (I) Imaging platform to measure cell/brain oxygenation (10x more precise than current gold standard) (R)	Photonic tools for the development and toxicity testing of new drugs, advanced understanding of cell and organ functions, health (nutrition, lifestyle, environmental influences, toxicity)(R&I)	Real-time proteomics, genomics, metabolomics for DNA sequencing in less than 10 minutes employing one instrument (R)	Photonic tools for long-time testing of or searching for new drugs with high throughput (i.e. higher sample volumes in shorter measurement time)(I) Monitoring of tissue growth for organ replacement/Bioreactors, (R) Photonic tools for researching disease development/early disease detection and diagnosis (R)
Joint actions required with other disciplines (Artificial Intelligence) or fields (robotics)	ETP: EuMaT for biocompatible materials ETP 4 HPC for the development of data handling and evaluation ETP Nanomedicine (biomarkers)	ETP Nanomedicine (biomarkers); European Technology Platform on Smart Systems Integration EPoSS, ETP 4 HPC for the development of data handling and evaluation	ETP 4 HPC for the development of data handling and evaluation ETP Nanomedicine (biomarkers)		

[42] In principle, these milestones apply to all 5 challenges. Their vague formulation derives from the abundance of different techniques used and methods applied. Where possible, as in "Photonic diagnostics and intervention" and "mobile Biosensors" more specific milestones were added.

3.4 Climate, Mobility & Energy

Main socio-economic challenges addressed

Photonics plays a role in the targets of Decarbonisation towards Zero Emission Road Transport, Clean Energy Transition, the Industrial Battery Value Chain, Renewable Energy with photovoltaics, energy saving by Smart Lighting and saving the rainforests by Vertical Farming with horticultural lighting.

Role of mobility in the decarbonisation and sustainability of our society

The European Commission's industrial policy strategy is to make EU the world leader in innovation, digitisation and decarbonisation[43]. The development of automated vehicle technologies, batteries, charging systems, fuel cells and infrastructure will all need to be emphasised to reach a sustainable society. The World Economic Forum has published three principles for action on electric mobility[44]: to take a multi-stakeholder and market-specific approach; to prioritise on high-use vehicles; to deploy critical charging infrastructure today while anticipating mobility transformation. The two latter steps involve (1) electrifying public and commercial fleets, (2) complete electrification of the public transport system, (3) enable the integration of autonomous vehicles (AV), (4) reducing range anxiety and promote interoperability between transport modes, (5) energy-efficient charging hubs and smart charging, and (6) digital end-to-end customer experience to enhance easy access to charging services.

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[45]: Greenhouse gas emissions from this sector primarily involve fossil fuels burned for road, rail, air, and marine transportation. Nearly all (95%) of the world's transportation energy comes from petroleum-based fuels, namely gasoline and diesel. Smarter and more efficient technical solutions are important factors in the path to reducing and eventually eliminating the need for fossil fuels in the transport sector. Both the transport and the automotive sectors need to decrease their environmental footprints, reducing carbon dioxide (CO_2) emissions in production and use[46].

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[43] European Commission, 2019. A high-level group of experts presents the report on the future of European industry, https://ec.europa.eu/growth/content/high-level-group-experts-presents-report-future-european-industry_en retrieved 01.06.2020

[44] Electric Vehicles for Smarter Cities: The Future of Energy and Mobility, 2018. World Economic Forum. http://www3.weforum.org/docs/WEF_2018_%20Electric_For_Smarter_Cities.pdf retrieved 29.05.20

[45] Global Emissions by Economic Sector, 2019. The United States Environmental Protection Agency, EPA. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector retrieved 25.05.2020

[46] Reducing CO_2 emissions from passenger cars, European Commission Climate Action. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en retrieved 25.05.2020

In line with these goals, the European Parliament and the Council have ruled to decarbonise the mobility sector. The ruling[47] involves reducing carbon dioxide (CO_2) emissions from the vehicles to be sold in Europe.

In line with the EU's commitments under the Paris Agreement[48], the regulation stipulates that new cars should emit 37.5% lower CO_2 emissions by 2030 compared to 2021, while new vans[49] will need to reduce their emissions by 31%.

Achieving these targets will likely include the electrification of powertrains either in purely electrically-powered vehicles or in hybrid vehicles containing an electric motor and another form of engine, usually an internal combustion engine.

Widespread uptake of such vehicles will be needed, and require affordable production of sustainable batteries. Battery production is, therefore, a strategic means for the transition to clean energy and the competitiveness of the automotive sector which is an important economic engine of Europe[50].

The automotive industry is a global industry that strives to develop clean cars. It is essential for both Europeans and the automotive industry that Europe can take a lead on this global shift. The measurable CO_2 targets provide incentives, and although ambitious, these goals are enforceable with the appropriate tools. EU standards to reduce CO_2 emissions will not only be effective for climate targets to meet the EU's commitments under the Paris Agreement but will also increase energy efficiency by reducing fuel consumption.

Safe and sustainable mobility

Other key factors are connected smart and safe mobility. With approximately 25,000 annual fatalities on European roads[51], the EU is still far away from Vision Zero[52]. The goal of this ambitious project means we will have a road transport system where no deaths or severe

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[47] 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 retrieved 29.05.2020.

[48] 2015. United Nations Framework Convention on Climate Change, UNFCCC. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement retrieved 29.05.20.

[49] European Commission, 2018. Europe accelerates the transition to clean mobility: Co-legislators agree on strong rules for the modernisation of the mobility sector, https://ec.europa.eu/clima/news/europe-accelerates-transition-clean-mobility-co-legislators-agree-strong-rules-modernisation_en, retrieved 2020-05-28.

[50] European Commission, 2017. European Battery Alliance. https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en retrieved 01.06.2020.

[51] 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 retrieved 29.05.2020.

[52] European Commission, 2020. Mobility and Transport, Road Safety. https://ec.europa.eu/transport/road_safety/what-we-do_en retrieved 01.06.2020.

injuries will occur on our roads. 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[53]. Electric and automated vehicles will not simply happen by themselves: here, the key factor to achieve the best possible return on the investment in the digitisation and decarbonisation transition is to focus on platforms instead of individual solutions. Smart electrified mobility also requires smart integration with power grids. This in turn demands many levels of digitalisation of the involved systems – from energy systems to connectivity to support optimised, shared and autonomous driving.

Role of lighting to achieve sustainable energy

It is estimated that the electric energy consumption of the communication and information equipment is about 242 TWh[54]. By using lighting as a backbone for indoor or outdoor communication it will be possible to reduce this energy consumption and therefore reduce the related CO_2 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.

New lighting technologies have the potential to save up to 70% of the energy consumption and since lighting accounts for roughly 20% of the world's total electricity consumption (in 2018: 26.730 TWh[55]), this gives an energy saving of up to 3.742 TWh or 1.500 megatons of CO_2[56], which would be approximately one-third of the EU's total carbon dioxide emissions equivalent[57]. Over 3 billion trees would need to be planted to compensate for this amount of CO_2[58] (an amount that would correspond to 0.1% of all the trees in the world[59]).

53 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 retrieved 01.06.2020.

54 https://www.ericsson.com/en/reports-and-papers/research-papers/global-electricity-usage-of-ict-network-operators---an-extensive-data-set

55 https://www.iea.org/reports/electricity-information-2019

56 https://www.klimaneutral-handeln.de/php/kompens-berechnen.php

57 https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-3#:~:text=In%202017%2C%20the%20EU's%20greenhouse,2%20%25%20from%202017%20to%202018

58 https://www.naturefund.de/wissen/co2_rechner

59 https://www.washingtonpost.com/news/energy-environment/wp/2015/09/16/the-countries-of-the-world-ranked-by-their-tree-wealth/

Supporting technologies to reach the climate, mobility & energy goals

Supporting technologies will be needed to reach climate, mobility and energy goals. The emissions regulation compliance will require better and more widely deployed measurement systems, where photonics sensing is a prime candidate that could be used both in vehicles as well as within targeted infrastructure locations, (for example, photonics sensors in the form of portable emission measurement systems, or fibre-based sensors that can monitor the health and charge conditions inside the battery). Photonics sensors and fibreoptic interconnects can also provide EMC resistant and resilient low-cost data transmission between different sensors to a centralised board computer. Free space optical sensing and communication in the presence of obscurants in the atmosphere can enable weather resilient sensing where radar sensing cannot provide the required resolution. Other photonic developments will be needed in high sensitivity avalanche photodetectors and arrays for light detection and long-range active imaging. The sensing technologies will support use cases demanding a wider field of view to support surround-view demands. Such requirements have implications for detector size and other properties. Other developments

Below: Photonics is the key tool to make our mobile and digital society work.

will be needed in terms of high-efficient, low-cost lasers also in more eye-safe wavelength bands above 1400 nm, capable of operating at high temperatures (85°-105°C) without cooling.

Technology for measuring the battery state of charge, state of health, and inside temperature can also be built on photonics and fibre optics. The current uncertainty relating to battery temperature and health forces manufacturers to use safety margins built into today's battery monitoring systems preventing the complete battery capacity to be utilised efficiently, slower charging, increased safety risks, and lack of information of remaining battery life. The current lack of battery health monitoring makes it hard to set a resale price of batteries and is also difficult for the seller to grant a warranty or establish a cause of a malfunction. As a consequence, secondary use will be associated with large uncertainties and hence economic risk. Such a scenario results in a poor secondary market for batteries with increased risk of premature scrapping and hence a poor use of nature's resources. A sensor providing a history of the battery and the ability to measure the battery capacity much more exactly will allow a user to reliably assess the remaining battery life. This improved sensing will allow secondary pricing and warranties with less uncertainty, which in turn will pave the way for a commercial secondary market for batteries. Integration of sensors into and onto the cells may therefore enable an extension of the useful battery life in first and second life applications, while dramatically improving safety[60].

Impact on the EU's economy

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 services owing to the importance of being close to customers and to speak their languages. Competitors from the Far East will then find it harder to be successful.

Further integration of photonic components and devices into objects or structures (for example the displays in windscreens) provides the opportunity to the European industry for novel, value-added products.

The European lighting industry is still the leading global player with companies like Philips/Signify, Osram or Zumtobel Group and can therefore significantly influence the global energy-saving and climate impact. Additionally to the energy saving in lighting, there is also a significant contribution to the energy generation by organic

"The European lighting industry is still the leading global player with companies like Philips/Signify, Osram or Zumtobel Group and can therefore significantly influence the global energy-saving and climate impact."

[60] 3beLiEVe EU project, 2020. https://www.3believe.eu/#about retrieved 01.06.2020

Figure n°11: Automotive industry in Europe: key figures (Courtesy ACEA.BE).

EMPLOYMENT		
Manufatcure of motor vehicles (EU28)	2.5 million people = 8.3% of EU employment in manufatcuring	2016
Total (EU28 manufacturing, services and construction)	13.3 million people = 6.1% of total EU employment	2016
PRODUCTION		
Motor vehicles (world)	98.9 million units	2017
Motor vehicles (EU28)	19.6 million units = 20% of global motor vehicle production	2017
Passenger cars (world)	80.2 million units	2017
Passenger cars (EU28)	17.0 million units = 21% of global passenger car produtcion	2017
REGISTRATIONS		
Motor vehicles (world)	97.9 million units	2017
Motor vehicles (EU27)	17.5 million units = 18% of global motor vehicle registrations/sales	2017
Passenger cars (world)	79.8 million units	2017
Passenger cars (EU27)	15.1 million units = 19% of global passenger car registrations/sales	2017
Petrol (EU15)	49.4%	2017
Diesel (EU15)	44.8%	2017
Electric (EU15)	1.5%	2017
VEHICLES IN USE		
Motor vehicles (EU28)	298.9 million units	2016
Passenger cars (EU28)	259.7 million units	2016
Motorisation rate (EU28)	587 units per 1,000 inhabitants	2016
Average age (EU25)	11 years	2016
TRADE		
Exports (extra-EU28)	€138.6 billion	2017
Imports (extra-EU28)	€48.3 billion	2017
Trade balance	€90.3 billion	2017
ENVIRONMENT		
Average CO_2 emissions (EU28)	118.5g CO_2k/m	2017
INNOVATION		
Automoibles and parts sector	€53.8 billion	2016
TAXATION		
Fiscal income from motor vehicles(EU15)	€413 billion	2016/17

photovoltaics (OPV) where Europe plays a leading role. In 2020 the market size of photovoltaics is >130 gigawatts peak and growing at 25% CAGR[61]. By 2026 it will reach > $300 billion USD[62]. In organic photovoltaics (OPV) Europe is still the global market leader and therefore has a great chance for green growth in the energy generation.

The global smart home market is estimated[63] to grow from $24.1 billion in 2016 to $53.4 billion by 2022. Acting as the 'intelligent backbone', Lighting is in a strong position to contribute to this growth, connecting the increasing number of IoT devices via short transmission distances to the next lighting node, and minimising the necessary transmission power. Battery lifetimes of the IoT devices, therefore, rise and electromagnetic interferences decline.

The importance of the automotive industry for the EU's economy is crucial. Figure 11 summarises the key figures of the automotive industry in Europe: the EU is one of the largest exporters of vehicles and vehicle components in the world. The automotive sector generated a trade surplus of €90.3 billion, which far exceeds the trade surplus of goods for EU-28 – €22.9 billion in total in 2017 – while the trade surplus for services was €133 billion in 2016[64]. Automobile taxation is a vital source of government revenue with €413 billion in fiscal income from motor vehicles in EU15 alone, compared with the total EU budget of €172 billion. Transport is critical to the EU economy: with a total of 13.3 million jobs (6.1% of all EU jobs) automotive manufacturing directly employs 2.5 million people (8.3% of EU employment in manufacturing) and another 900,000 in indirect manufacturing jobs.

EU automotive investment in R&D has increased to an annual spend of €53.8 billion, making the automotive sector the European Union's number one investor in R&D, and responsible for 27% of total EU spending on innovation. The EU is, therefore, the world's largest investor in automotive R&D[65]. The majority of the annual €54 billion spent on innovation comes from private sources. In comparison, the total budget for Horizon 2020 (FP8) during its lifetime period 2014-2020 was €74.8 billion (nearly €80 billion today), of which Smart, green and integrated transport received 8.23% (€6.3 billion)[66]. Therefore,

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[61] Bloomberg 2019.

[62] Fraunhofer ISE, June 2020.

[63] https://globenewswire.com/news-release/2018/08/03/1547019/0/en/Market-Size-of-Global-Smart-Home-Industry-Predicted-to-Reach-USD-53-45-Billion-by-2022.html

[64] The EU in the world – international trade, Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php/The_EU_in_the_world_-_international_trade#Balance_of_payments_.E2.80.94_share_of_world_trade retrieved 2020-08-28.

[65] Key Figures, ACEA, the European Automobile Manufacturers' Association https://www.acea.be/automobile-industry/facts-about-the-industry retrieved 2020-08-28.

[66] Factsheet: Horizon 2020 budget, European Commission, Research and Innovation. https://ec.europa.eu/programmes/horizon2020/sites/horizon2020/files/Factsheet_budget_H2020_0.pdf retrieved 2020-08-28.

"Connectivity is a crucial factor in the development of driverless vehicles and electrification."

EU-funded research represents less than 2% of the money spent on automotive innovation, yet the EU innovation funding is essential to promote further innovation to ensure the European automotive industry, and its suppliers, maintain and strengthen its market position.

Spending on innovation for the automotive industry grew by 7.4%, which is substantially higher than both the growth rate of the EU economy and the EU automotive vehicle production volume. The level of spending on innovation should help lay the foundation for future higher value-added products. The automotive industry is, therefore, a key sector for safeguarding existing jobs and for generating new, high value-added jobs, growth and, by extension, wellbeing in Europe.

Driverless, connected vehicles and electrification are technological changes to address the societal challenges of traffic-related injuries and fatalities, pollution and congestion. Driverless and connected vehicles also have the potential to promote social inclusion with mobility to all efficiently[67]. Connectivity is a crucial factor in the development of driverless vehicles and electrification, but will not be enough: vehicle-based sensors remain the chief enabler for this future mode of transport.

Sufficiently performing photonics sensors are one of the main roadblocks that prevent Europe from deploying fully automated and connected vehicles at scale. Even though radar technologies continue to evolve, with improvements made in radar technologies with multiple emitters and receivers (MIMO), improving resolution and higher frequencies, there are physical limits that prevent radar from achieving the same resolution as a photonic sensor.

Human drivers will continue to play a vital role in the foreseeable future at automation levels 1-4. The best possible visibility to the driver will be essential for improving safety: smart illumination in darkness and inclement weather conditions will allow better lighting of the road ahead while minimising glare. Efficient information exchange is also necessary to promote safety and fight driver distraction. Europe, therefore, needs to be prepared for this major transformation of mobility.

The following objectives will therefore be considered in this context.

[67] On the road to automated mobility: An EU strategy for mobility of the future, European Commission, COM (2018) 283 final. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0283&from=EN retrieved 2020-08-28.

Main societal objectives driving the challenges

Main societal objectives involving photonics technologies that are driving current societal challenges:

1. **Cleaner mobility** in all aspects, such as electric vehicles or other forms of low emission vehicles, will be essential. Each generation has grown in mobility needs, requiring more cars per person, and with each person driving greater distances. While increases in mobility provide social benefits, they have severe impacts on sustainability and create more greenhouse emissions. Both the transport and the automotive sectors, in general, need to reduce their environmental footprints and CO_2 emissions, both in production and use[68].
2. **Autonomous vehicles and improved road safety** will transform the automotive and transport sector. Their development could take several different forms: autonomous vehicles could take over the driving process entirely in all conditions; in other automation levels they could take over some or all of the driving in selected circumstances, and in other areas, the systems will only supervise human driving, preparing to intervene or aid whenever specific risky situations arise. EU statistics show that 25,300 road users died in 2017, and an estimated 135,000 people are seriously injured on Europe's roads every year[69]. Consolidated progress towards accident-free road transport, therefore, has substantial societal benefits.
3. **Reduced transport congestion (including Urban Freight Transport – UFT)** that optimises available road infrastructure is coinciding with a growing need for cleaner mobility and with it a critical improvement in the quality of life for citizens and goods. Cities and urban areas are becoming more and more concentrated, with enormous implications for citizens' mobility. The cost of road congestion in Europe is estimated to be over €110 billion a year, equivalent to 1% of GDP[70].
4. **The digitisation of the mobility industry and (real-time) availability of in-vehicle data**, with a variety of services to road users (such as finding available parking in an area), is expected to be closely linked to economic growth and jobs for a mature, traditional sector of transport. Novel connectivity will develop services and modes of transportation by using V2X – communication (vehicle-to-vehicle, vehicle-to-infrastructure, or vehicle-to-other road users like pedestrians or cyclists). This connectivity provides new services for drivers and

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[68] Reducing CO_2 emissions from passenger cars, European Commission Climate Action. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en retrieved 2020-08-28.

[69] 2017 road safety statistics: What is behind the figures?, European Commission – Fact Sheet. http://europa.eu/rapid/press-release_MEMO-18-2762_en.pdf retrieved 2020-08-28.

[70] Measuring road congestion. European Commission, Joint Research Centre. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC69961/congestion%20report%20final.pdf retrieved 2020-08-28.

passengers which, in turn, create a wealth of jobs and economic opportunities. Mobility-based apps and novel functions which can be added to a better-connected vehicle have enormous economic and societal implications and enable the more efficient cars of the future.

5. **Better quality of life with adaptable light** when future lighting systems will adapt to the user and provide the lighting when and where needed and therefore save energy and provide additional features supporting the health of the users.

6. **Better quality of life for the ageing society** which poses special challenges to ensure that people have a high quality of life as they progress into their 80s and 90s. Human Centric Lighting (HCL) will support Ambient Assisted Living by improving the circadian synchronisation, giving daytime structure to the elderly. A personalised and easy-to-use interface to the lighting control system will be critical to their success.

7. **Healthy food in urban areas** for a population with rapidly increasing urbanisation, 'vertical farming' (see image below) will become increasingly important[71], and perhaps even mandatory to provide sustainable food production. Lighting technologies are essential building blocks: adjusted light can make plant production much faster, produce less waste, decouple heating from lighting, and reduce the need for chemicals and genetically modified plants. Additionally, local photovoltaics in the windows and building facades can reduce the CO_2 footprint compared to conventional production.

Horticultural lighting for vertical farming - Photonics technologies contribute to healthy food in urban areas.

[71] http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-5069445.pdf

"One of the most critical game-changers is expected to be the development of autonomous (or self-driving and connected) vehicles of various types."

To implement these trends will require determined efforts, where photonics technologies will play a key role in sensing or communication[72]. Addressing these societal challenges above in the years to come, supported by technology advancements in Horizon Europe, will provide real, positive impacts on society from 2030. With these technologies, our mobility system will transform and provide industrial jobs and growth in Europe. Such economic values have already been detected by large IT companies (for example, Amazon, Apple or Google), which are developing autonomous technologies outside of Europe. It will, therefore, be essential to keep European competitiveness and leadership in the industry to sustain jobs and economic progress.

Significant photonic research and innovation challenges

The trends presented could be achieved due to the convergence of a group of disruptive game-changers currently appearing in the market. Such developments involve advances in the hardware, the software, and even the business models that were commonplace in 2018. The disruptive technology changes will shape the mobility industry for the future, where a vital European industry will have to face the emerging global competition to keep and grow its present industrial weight.

One of the most critical game-changers is expected to be the development of autonomous (or self-driving and connected) vehicles of various types. Automated railways or metro-lines are increasingly used for public transport in larger cities, but other transportation modes (for example, cars, shuttles, buses, tramways, small and large ships) will likely follow the automation trend. The most disruptive autonomous vehicles – socially and economically – are however expected to be in the automotive field.

Vehicles with levels of automation that allow a driver to take their eyes off the road[73] are ready for introduction, once the legal issues have been resolved. This trend is progressing and consolidating as more and more pressure will be directed to development teams to advance the level of automated control of the vehicles further.

The vehicle complexities and costs are expected to increase with rising levels of automation on roads. As a consequence, a revolution in our concept of mobility, and ownership of vehicles is expected. It is generally referred to as Mobility as a Service (MaaS). In contrast with the

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72 Photonics and our daily life, European Commission, policies, information, and services. https://ec.europa.eu/digital-single-market/en/photonics-and-our-daily-life retrieved 2020-08-28.

73 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE SURFACE VEHICLE RECOMMENDED PRACTICE J3016, Jun 2018. https://www.sae.org/standards/content/j3016_201806/ retrieved 2020-08-28.

current situation with mainly individual ownership of cars, mobility will be turned into a service where the use of sensors, connectivity, and IT advances, enabling point to point fast mobility with service providers holding the vehicle ownership.

Self-driving vehicles are expected to be moving 80% of their time and will be easily shareable, while a private car is parked, on average, 95% of the time[74]. Correctly managed, it 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 will diminish. The autonomous vehicle has the potential to bring a real social and economic revolution.

Such a development will require novel concepts of vehicle capabilities in all transport modes related to connectivity. Such a paradigm shift requires the development and deployment of connected mobility systems (V2X) which enable vehicle to vehicle communication, vehicle to infrastructure and the communication of the vehicle with other road users, especially with vulnerable road users like pedestrians and cyclists.

Photonics is an important sensing mode that allows the necessary high-resolution 3D imaging, providing the relevant environmental perception and detection. Furthermore, future communications between other vehicles, road users and infrastructure could be enabled by photonics.

Moreover, photonic sensors can be used for the integration of sensors into the vehicle's subsystems, leveraging on their robustness and ability to be embedded in materials and structural parts, to generate the data necessary to enable advanced functions like automated driving, predictive health monitoring as well as predictive system and equipment. As for IoT products, vehicle components have to become smart components, with multi-physical sensors (like temperature, pressure, force, strain) used for their monitoring and control functions.

Technological needs to address identified photonic challenges

The identified technological needs involve the following key developments:

Photonic sensing

Improved and robust sensing capabilities at affordable costs are required (see example point-cloud image in following image). A considerable gap to be covered is to get an improved, fully performant lidar sensor, with the required spatial resolution and range that allow motorway to travel at normal traffic flow.

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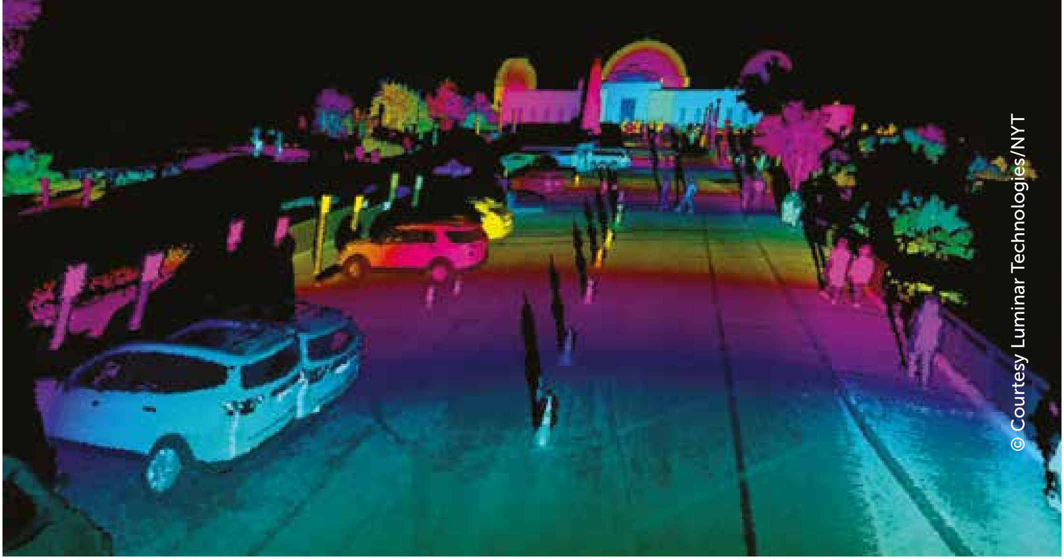
[74] Today's Cars Are Parked 95% of the Time. Yahoo finance. https://finance.yahoo.com/news/today-cars-parked-95-time-210616765.html?guccounter=1 retrieved 2018-10-16.



Left: Example of point cloud data generated by a lidar.

This component is a key enabler in the future self-driving vehicle market but also essential for many other applications. The proposed technological advancements for increased performance include areas of beam steering, light-emitting, and light receiving devices. All those components must be finally integrated efficiently in novel platforms.

Further requirements:

- The sensing capabilities developed should be fully performant under different real-world environmental conditions that a vehicle faces, which include: rain, snow, fog, dust, water spray (from preceding traffic) and immunity to other lidar interference;
- As the vehicle relies on more and more sensors, tools to evaluate its condition will be required. A reliable evaluation of system state and performance, and the use of redundant systems to allow for the fault-tolerant and resilient operation is needed for the sensor-set of the vehicle. Graceful degradation of sensor performance, for example, when exposed to adverse weather conditions, will also be essential;
- Finally, the efficient combination of various sensing modes for complementarity and redundancy is expected to be critical. Photonic-related developments of sensing are expected to be further driven by sensor fusion. The complementing inputs from other sensors in an integrated sensing platform contribute to increased overall performance and improved robustness of the system. Sensor fusion may affect individual sensor requirements. Such sensors systems will be developed according to functional safety, considering sensing redundancy and system development according to relevant standards, such as ISO 26262 for automotive.

Battery health monitoring

Technology for measuring the battery state of charge, state of health, and inside temperature should be safe in case of vehicle collisions or other damages to the battery pack. A beneficial approach appears to be based on fibre optics which are not electrically conducting. Such battery health monitoring may bring additional benefits:

- A sensor that provides a 'battery life history' and the ability to measure the capacity more precisely will improve the safe utilisation while extending the useful life of the battery in first and second life applications;
- The current uncertainty relating to battery temperature and health forces manufacturers to use safety margins built into today's battery monitoring systems, that prevent the complete battery capacity to be utilised efficiently, slower charging, increased safety risks, and lack of information of remaining battery life. The current lack of battery health monitoring makes it hard to set a resale price of batteries. It is also difficult for the seller to provide a warranty or establish a malfunction cause.

Photonic Integration for Sensors

Key aspects to enable extensive industrialisation are the technologies' scalability, cost, packaging, and integration. Photonic sensors are widely used in industrial fields, effectively used both as a stand-alone system and as embedded sensing elements as in mechanical and structural parts. However, for a larger uptake, they require suitable interrogation systems not currently available, in terms of compactness, weight, power consumption, cost and robustness to harsh temperature and vibration environments. Photonic integration is a key enabler to overcome these and to create embedded sensing systems suitable for compact, robust and cost-effective multi-physical sensing. The silicon on insulator (SOI) and hybrid III-V materials on SOI platforms, combined with mass manufacturing packaging and assembling technologies, can leverage decades of experience from the microelectronics industry, successfully addressing large volume market requirements.

Affordable photonic sensors can be used for the Internet of things (IoT) of various systems, leveraging on the robustness and the ability to embed safely electrical non-conductive connection in various materials and structural parts, to generate the necessary data to enable advanced functions like automated driving, predictive health or maintenance monitoring. These IoT products will enable a stepwise improvement in efficiency through digitisation and integration of smart components with multi-physical sensing capability (like temperature, humidity, pressure, force, or strain).

Research and Innovation challenges:

- Low cost, high-performance photonic integrated circuit (PIC) based on Silicon Photonics, III-V and hybrid III-V – SOI platforms;
- Advanced mass manufacturing packaging and assembling technologies;
- Cost-effective technologies to allow compact PIC systems operating at high temperatures (>100°) with low power consumption (< 1 W), including reliable packaging and assembling for mass production.

Affordable and efficient Adaptive Driving Beam (ADB) for mainstream vehicles

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 tail lights 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.

First generations of the adaptive driving beam are already on the market, and future generations may move further into an always-on matrix headlight with a precise selection of the areas which need to be obscured to avoid glare and blinding of other road users. An example of glare-free illumination is illustrated in following images.

Traditional illumination

Glare-free illumination

Example of glare-free headlights
© Mercedes-Benz AG

- Current ADB technologies, already with a high TRL[75] level will enable the development of cooperative lighting schemes, where optimal use of cameras, exterior illumination, headlamps, and infrastructure information have the potential to significantly increase visibility in darkness or adverse weather conditions;
- V2X and IoT are also likely key enabling technologies for cooperative lighting;
- There is a need for studying the integration and fusion of novel sensors (radar, cameras, lidar) in other vehicle components such as headlights, where cost-effective integration can help address system and maintainability cost. A careful balance of the integration benefits versus the cost of repair and warranty costs of replacing complete modules containing expensive sensing function will be needed to benefit consumers.

[75] Technology Readiness Levels (TRL) is a measurement of estimating technology maturity

Information Projection

New pixelated headlights allow efficient communication with the driver as well as other road users by projecting selected symbols and additional relevant information on the road. Such information may be in different forms, for example, warning symbols and driving path guidance (the following images illustrate example cases). Therefore, advanced lighting functionality will also be required in the most automated vehicles.

Information projection

Example of a driver interface through projected symbols
© Mercedes-Benz AG

- High-resolution matrix-beam headlights can project a variety of information onto the area in front of the vehicle, with the expected benefit to the driver and surrounding road users. Functional requirements for such information projection, and human factors aspects such as distraction potential, need to be carefully investigated. Other elements such as how an automated vehicle should communicate its intentions to other road users will require thorough investigations.

Communication with Light

The development of low-cost, reliable and small components for light-based communication (LiFi[76]) communications, together with the implementation of V2V and V2I communications will enable new capabilities of interaction between various IT devices, machines, vehicles, other road users, and the infrastructure through high-speed, short-range communication.

- Automotive lights enable transparent components which allow the sending and receiving of optical energy for data sensing (embedded sensors in headlamps) or data emission. Such capability provides for integrating additional capabilities into the lighting systems. These novel designs should improve capacity, shape, and maintainability.

Immersive Interaction and Occupant Monitoring

The involvement of photonics technologies in new tasks like communication and passenger entertainment is expected to be significant. Higher levels of automation and new ways for in-vehicle sensing are expected to bring substantial changes in the way humans interact

[76] Li-Fi is a technology for wireless communication between devices using light to transmit data

with the vehicle, not only from the driver and passengers' point of view but also with other road users that may interact with the vehicle. A possible future vehicle driver interface is illustrated in the following image.

Left: Example of possible future vehicle driver interface.

Improved, advanced HMIs are required to cope with the increased amount of information available through digitalisation, enabling safe control of the car. Successful implementation will require cooperation between the photonics industry and human factors specialists[77].

- The automated vehicle is expected to modify the patterns of vehicle use, enabling eyes off-the-road, from short-duration tasks such as email or web interaction to longer duration tasks such as movies, reading, or gaming. Detailed analysis of the physiological effects of lighting under the new forms of vehicle use, which combine different levels of visual performance, together with aesthetics and comfort, will be needed. New strategies for monitoring occupants will be required to sense their readiness to resume control of driving when required;
- A more immersive system interaction experience is expected to be a future trend in next-generation vehicles. Such interaction involves various modalities, including novel displays which involve larger conformal, congruent, frameless displays, enabling multiple levels of three-dimensional engagement such as holographic displays;

[77] Automotive HMI: Present Uses and Future Needs. D. Barat et al., Society for automotive displays. Future of Automotive Displays and HMI. https://onlinelibrary.wiley.com/doi/abs/10.1002/sdtp.11633 retrieved 2020-08-28.

- Interactions with the extended information content should be combined with the priority of safer roads, thus requiring less driver attention with better and faster access to relevant information in semiautonomous modes. 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). The autonomous vehicle cockpit is yet to be defined, and several alternatives are possible, requiring cooperation with display expertise, human factors, and end-users;
- Such new devices and systems need to be well-integrated, reliable, and low-cost, with reduced system unit volume and power consumption. These new devices should be able to be utilised efficiently depending on the task at hand for the vehicle occupants. Such a trend is envisioned by reducing the gap currently existing between the automotive and the consumer market of photonics and electronic devices. As automotive applications will increasingly use more enabling technologies based on photonics from consumer electronics, the costs should decrease, and the integration level should increase.

Micro displays

Information will become personal and ubiquitous – always and everywhere. Such aspects hold in all aspects of life, both in personal as well as in business environments.

Micro displays in glasses and contact lenses will offer personalised information via augmented reality to make complex work easier and life more comfortable. Classical navigation and information systems will be replaced by information which can take into account the preferences and habits of every individual.

Increase productivity by 10%

To increase productivity by 10% means the required energy consumption (and therefore the related CO_2 emissions) could be reduced by 10%. To increase productivity by 10%, the first challenge will be for lighting to become a fully and seamlessly integrated system in buildings, objects and within the structures that surround us. This challenge presents new research problems: material development ('how can lighting be integrated into different materials without reducing its performance or lifetime?'), system architecture ('how can the lighting system communicate with other systems such as the building management, car control, security systems), or component development.

Besides the technical aspect of productivity, light also influences the wellbeing of every individual. New scientific findings show that reaction of the human body on certain spectral light distributions is complex and depends, among other things, on the age, gender, cultural environment, geographical location, mood and health of the individual. Continuous and intensive research will enlighten our understanding of the interaction of light with humans, animals and plants.

"Today we are only beginning to formulate the expertise and knowledge of the mechanisms of plant growth and the means to influence plant health and output."

Truly Circular Economy

The field of Urban Farming is gaining momentum globally. The driving force differs between regions. While in European cities, some of its appeals are based on the surge for 'living in alignment with nature' or avoiding unnecessary transport of vegetables from the surrounding to the end-users, the situation in emerging countries is quite different: agricultural business in the megacities is a pure necessity.

Light, with its features intensity, colour, control mechanisms, is one of the main ingredients to adapt to specific crops. Today we are only beginning to formulate the expertise and knowledge of the mechanisms of plant growth and the means to influence plant health and output. The skills and capabilities will be decisive for future market success and therefore comprise one of the key research challenges in the future.

Considering the growing number of places with water shortages, successful research for optimised plant watering by proper lighting will help billions of people enhance their quality of life.

Another aspect of the 'circular' economy is the saving of resources, particularly energy consumption in production facilities. Here, the light may be considered in different ways.

While intelligent and efficient lighting may lead to a reduction in annual utility costs, photonics technology in quality control, employed across the entire manufacturing chain may also support the reduction of waste material, implicitly enhancing the efficiency of resource input in production.

An additional benefit could be generated via a local generation of electricity (photovoltaics in facades, greenhouses, buildings), reducing the need to transport energy from source to user.

Further research challenges are needed concerning the influence of proper lighting for the reduction of water consumption in plant growth and how photonics components can improve the eco-balance of plants.

Photonics as a flagship science for innovation

An emerging opportunity for Europe where automotive, transportation and aerospace industries are strong is object-integrated (or structure-integrated) photonics, combining traditional microelectronics, flexible, printed & hybrid electronics and mechanical structures together.

This process enables the integration of photonics functionalities (displays or lighting, large-area sensors, user interfaces) inside traditional structures like cars, aeroplanes, trains, trams, elevators, escalators, providing displays inside a laminated glass, switches and user interfaces on the surfaces or within injection-moulded parts.

The technology provides the design freedom, weight and space reduction, functional conformability, durable integration of electronics and mechanics, lean assembly and novel innovative solutions and services.

To keep these markets in Europe evolutionary and revolutionary further action will be essential. An example of next-generation demands is on material and device development for broadband and narrow wavelength emitter and detection systems for the frequency band from 1µm to 12µm, that are compatible to the existing semiconductor and optoelectronic technology. Such devices can be used as sensors for medical, environmental and transportation systems, but also in Human Centric Lighting (HCL).

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 novel concepts being introduced.

While lighting and OPV become more and more connected, the collaboration with other Photonics21 workgroups 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.

In the field of OPV, major collaborations will be regarding new materials with better efficiency and long-term stability.

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 2021–2027

Identified technologies with milestones, challenges and cooperation needs

Mobility

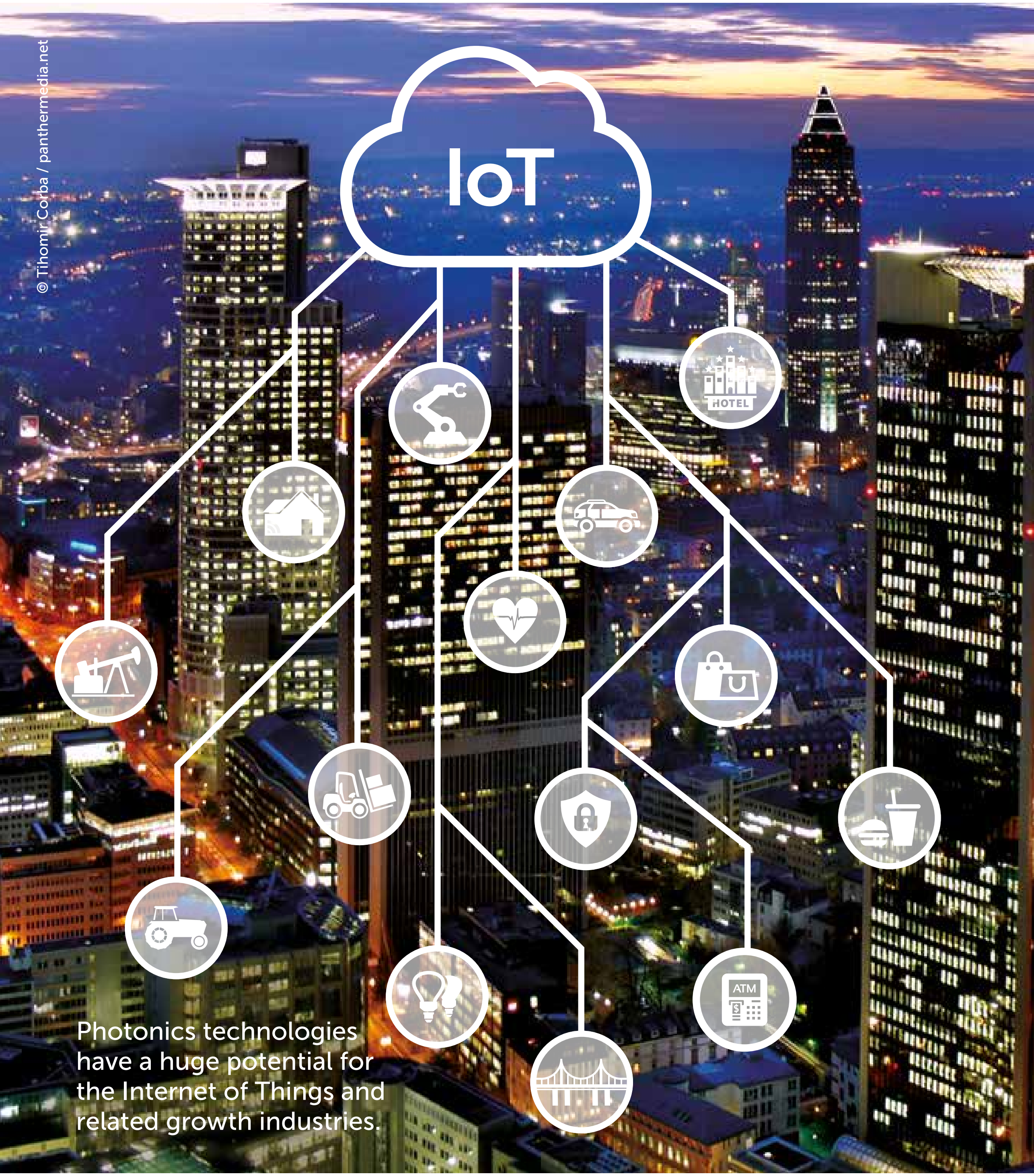
	2021	2022/2023	2024/2025	2026/2027	2028
Overview **Technology Challenges**	• Photonic sensing • Battery health monitoring • Affordable and efficient Adaptive Driving Beam	• Photonic sensing • Battery health monitoring • Affordable and efficient Adaptive Driving Beam • Information projection • Communication with Light (LiFi)	• Photonic Integration for Sensors • Battery health monitoring • Information projection • Communication with Light (LiFi) • Immersive Interaction with displays having new properties • Micro Displays	• Photonic Integration for Sensors • Information projection • Communication with Light (LiFi) • Immersive Interaction with displays having new properties • Micro Displays	• Photonic Integration for Sensors • Communication with Light (LiFi) • Immersive Interaction with displays having new properties • Micro Displays
Critical milestones to move from Science to Market	Sensing sufficient for automated highway driving High-beam always on, except where glare	Sensing and Adaptive Driving Beam adverse weather performance	Daylight vs night-time information projection requirements Distraction and drowsiness monitoring	LiFi range, bandwidth and immunity requirements	Distraction measures
Photonics **Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges**	Sensing range and resolution for highway speed under all relevant weather conditions	Affordable high-resolution matrix headlights and related control abilities Efficient light sources and optical systems with appropriate colour temperature and colour change abilities.		Wavelength selection Communication protocols and interference handling	Virtual displays Augmented reality Congruent displays
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	The proper balance of sensor requirements when fused with other in-vehicle sensors such as radar and cameras	Human factors, such as physiological effects of lighting and human ability to cognitively absorb information projection without causing a distraction		V2X community	Human factors and ergonomics related to immersive interaction

3.4 Climate, Mobility & Energy

Lighting & organic photovoltaics

	2021	2022/2023	2024/2025	2026/2027
Overview **Technology Challenges**	• Cost-effective VHF and embedding • High-efficiency luminaires and light sources for energy saving • Semiconductor-integration and System in a Package to save resources • Sensing and energy harvesting/ wireless power • Deep UV-LEDs for Corona prevention • IR based sensors • OPV efficiency + stability increase • Next-generation freeform optics for energy-efficient luminaires • LED in X (in cars, textiles,...)	• Multicolour high pixel density dice • New materials for light emitters, detectors, OPV,... for energy saving • Transparent displays, OPV, luminaires • Visible wavelength VCSEL + optics • System in Package for higher power LEDs (resource-saving) • 3D printed optics for resource-saving • Horticultural lighting • Validation and verification of HCL	• Extended 2D materials + integration in optoelectronic devices to save resources • Integration of OPV • Automotive lighting (LED, OLED, laser,...) • LiFi, e.g. in transportation • Enhanced lifetime OPV • Photonic computer simulation models (aligned with experiment) • Lighting for IoT • Horticultural lighting	• New materials (for more energy-efficient light emitters and detectors, OPV,...) • Smart GaN for HF/VHF • In-vivo sensors coupled with AI • Photoelectrochemical devices for water splitting • LIDAR for wind turbines • Low power displays • High-efficiency optical transceivers
Critical milestones to move from Science to Market	• Complex ecosystem • Proof of manufacturability • Proof of business case - Cost for manufacturing low enough - Consumer persuaded of a new concept - Understand the real demand of consumer (as part of HCL) - Seamless product integration	• Scientific and business community able to judge the market/technology • Open source vs. alternative implementations decided • Standardization	• Cost-effective integration of passives with usable performance. • Single-chip-solution/topology for LiFi receivers • Fast phosphors for LiFi	• High-speed detectors • Low voltage photonic detectors • Long lifetime
Photonics **Research (R) & Innovation (I) Challenges**	• Extension of VHF to SELV, higher power, wide output-range • Cost-effective supply for IoT-devices, most probably also based on VHF • Closed-loop solutions for colour-temperature • Sensor fusion • Process improvements • Realistic lifetime models	• Sensorics/camera with hyper-spectrum analysis (IR, UV) => cheap system-approach • Wireless power (electromagnetic-resonance and radio) for sensors and small luminaires	• Single-chip-solution/topology for light-source: GaN transistor on LED • Phosphor with high time-constant and high efficacy for low light-ripple	• Energy-harvesting concepts based on light (IR, visible-light), temperature and radio
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	• Industry 4.0 • IoT • Artificial Intelligence • Big Data • Photonics21 WGs • Photonics to enable AR/VR • Energy monitoring systems • Photonics in 5G • Energy-efficient Building • Medical	• Industry 4.0 • IoT • Artificial Intelligence • Big Data • Photonics21 WGs • Photonics to enable AR/VR • Energy monitoring systems • Photonics in 5G • Energy-efficient Building • Medical	• Industry 4.0 • IoT • Artificial Intelligence • Big Data • Photonics21 WGs • Photonics to enable AR/VR • Energy monitoring systems • Photonics in 5G • Energy-efficient Building • Medical	• Industry 4.0 • IoT • Artificial Intelligence • Big Data • Photonics21 WGs • Photonics to enable AR/VR • Energy monitoring systems • Photonics in 5G • Energy-efficient Building • Medical

3.5 Safety, Security, Space & Defence



Main socio-economic challenges addressed

A key responsibility of government is to keep its citizens protected and to make them feel safe. This can be accomplished on three levels: (1) Civilian empowerment, (2) Law enforcement and public safety and security, (3) Defence and Military.

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, with 1.2 million jobs as an indirect result[78]. In comparison, the European Space industry is much smaller with sales of €8.5b in 2018, and direct employment of approximately 43,450 FTEs[79].

Light technologies will provide a crucial advantage to the defence sector: 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 is particularly true once photonics-enabled quantum-computing technology will become a practical reality.

The flow of information proceeds in four steps:
- Information acquisition through appropriate sensing;
- Information transmission, most often through secure channels;
- Information processing, in the future probably exploiting quantum effects;
- Information display, taking into account also the human factors.

The importance of photonics for current and future development of the defence sector is illustrated by the Defence Advanced Research Projects Agency (DARPA): according to one source, more than 20% of the current DARPA projects (12 out of 58) are based on photonics[80]. Similarly, the importance of photonics for DARPA's Microsystems Technology Office (MTO), one of seven current organizational divisions of DARPA: more than 40% of the MTO's projects (27 out of 67) are based on photonics[81]. Fig. 6 shows the distribution of the photonic technologies employed by MTO.

According to reference[81], the majority of the DARPA-MTO's projects (56%) are concerned with sensing, covering the broad spectral range from TeraHertz radiation to Gamma rays; lasers are the second-most important technology (22%,). It does not come as a surprise that

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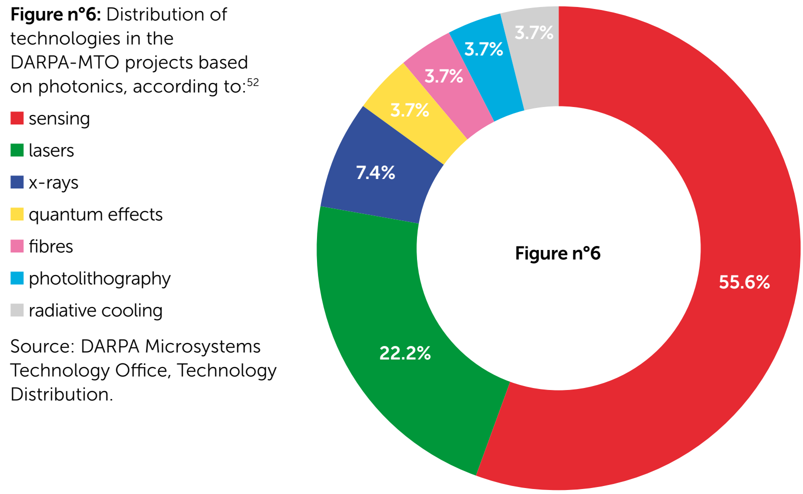
[78] F. Gouardères, "Defence Industry – Fact Sheet on the European Union", European Parliament, April 2020.

[79] Eurospace Space Industry Markets Working Group, "The State of the European Space Industry 2018", Facts and Figures press release, ASD Eurospace, 11 June 2019,

[80] Wikipedia, "DARPA – The US Defense Advanced Research Projects Agency", URL: https://en.wikipedia.org/wiki/DARPA, downloaded on 22 May 2020.

[81] Wikipedia, "The Microsystems Office of the US Defense Advanced Research Projects Agency", URL: https://en.wikipedia.org/wiki/Microsystems_Technology_Office, downloaded on 22 May 2020.

Figure n°6: Distribution of technologies in the DARPA-MTO projects based on photonics, according to:[52]



Source: DARPA Microsystems Technology Office, Technology Distribution.

sensing takes such an important part in the photonic technologies of advanced defence projects at DARPA-MTO.

Our society has embarked on an unprecedented path: the 'Fourth Industrial Revolution', epitomised by the Internet of Things (IoT) transformation. Machines will sense, operate, decide and communicate without our intervention, becoming truly autonomous. This is also true for space and defence markets, where smart, connected and autonomous systems are seen as one of the dominant fields of the future.

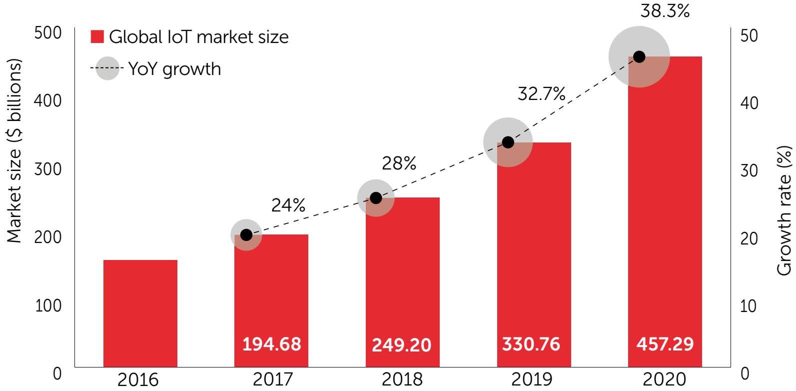
The IoT revolution has huge economic potential, with the number of installed IoT devices forecast to grow to more than 75 billion by 2025[82]. While the worldwide IoT market will be substantial, there are some discrepancies in estimates[83]. One extreme forecast expects the IoT market to grow to almost $9 trillion by 2020, while a more conservative estimate predicts growth to $457 billion by 2020 with a CAGR (Compound Aggregate Growth Rate) of 28.5% for the period 2016-2020[84], as shown in Fig. 7.

With a profound impact on most human activities and markets, the IoT revolution has great potential to support a number of sectors. Fig. 9 shows the top ten IoT growth industries[56], illustrating how IoT solutions will provide key components for the Digital Transformation, significantly changing our society.

By 2022, many expect pressure sensors, temperature sensors and photodetectors to account for almost 80% of all globally enabled IoT

[82] Statista, "Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025", November 2016.
[83] L. Columbus, "2017 Roundup of Internet of Things Forecast", Forbes Media, December 2017.
[84] GrowthEnabler, "Market Pulse Report, Internet of Things (IoT)", April 2017.

Figure n°7: Market size and growth rate of the global IoT market for the period 2016–2020[56]



Source: Growth Enabler IoT Report, April 2017.

sensors. Surprisingly, photodetectors are predicted to contribute only 17.3%[85], as illustrated in Fig. 8. Although the IoT market may dominate the sensing field, there are other markets where products make use of embedded-sensor systems. Smartphones and tablets, for example, are the main drivers for the global image sensor market, which is expected to reach $24.8b by 2023, growing at a CAGR of 9.75% between 2017 and 2023[86]. These numbers illustrate the differences that arise when

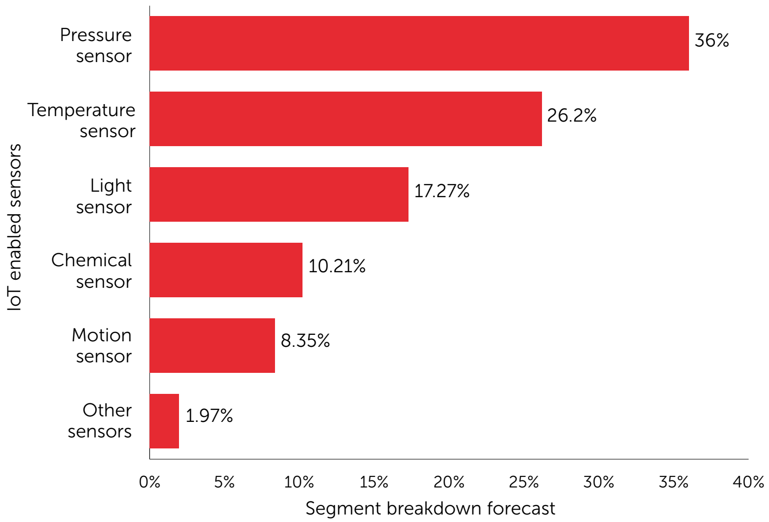


Figure n°8: Global IoT enabled sensors market in 2022 by segment:[57]

Source: Statista website: www.statista.com/statistics/480114/global-internet-of-things-enabled-sensors-market-size-by-segment/

[85] Statista, "Projected global Internet of Things enabled sensors market in 2022, by segment", 2017.

[86] Research And Markets, "Image Sensor Market by Technology... Global Forecast to 2023", January 2018.

The Top IoT Growth Industries

Figure n°9: Top IoT growth industries with key market figures[56], perfectly aligned with the proposed Missions of Photonics21

Source: Growth Enabler IoT Report, April 2017.

Manufacturing
35% of manufacturers use smart sensors. This number will grow to 53% by 2020. Particular benefits include: significant increase in capacity utilisation, lower unit costs and improved safety.

Agriculture
By 2020, 75 millon IoT devices will be shipped for agricultural uses such as tracking soil temperature, acidity levels, and other metrics to help farmers increase crop yeilds. Benefits include: real-time monitoring of livestock health, improved irrigation methods, remote soil monitoring, reduced water consumption and streamlining of farming processes.

Retail
Beacons, paired with mobile apps, are being used in stores to monitor customer behaviour and push relevant advertisments to customers. Particular benefits include: greater customer intimacy, more targeted customer offerings and enhanced profitability.

Logistics
Tracking sensors placed on parcels and shipping containers will further reduce costs associated with lost or damaged goods and increase the speed of order processing. In addition, robots such as the Amazon Kiva, will help reduce labour costs in warehouses. Particular benefits include: Accurate real-time shipment, tracking, monitored & optimised fleet management, and efficient warehouse inventory management.

Utilities
By 2020, energy providers throughout the world will measure and manage rising energy demand using nearly 1 billion smart meters. Particular benefits include: energy savings for cost optimisation, usage-based energy management to minimise energy transmission losses and power outages due to excessive demand.

Infrastructure
Municipalities worldwide will increase their spending on IoT systems at a 30% CAGR (Compound Annual Growth Rate), from $36 billion in 2014 to $133 billion in 2019. Particular benefits include: increased productivity, improved safety, predictive maintenance, reduced asset loss – self diagnosing devices will identify product issues early, from temperature and environmental changes to predicting machine failures.

Banking, Financial Services & Insurance (BFSI)
74% of insurance executives said they believe the IoT will disrupt the insurance industry within the next five years, and 74% plan to invest in developing and implementing IoT strategies by 2016. Particular benefits include: customer personalisation, targeted cross-selling opportunites, improved risk management and operational efftiencies.

Healthcare
646 million IoT devices are estimated to be used in the healthcare industry by 2020. Connected healthcare devices can collect data, automate processes, provide actionable insights including workout routines and much more. Particular benefits include: enhanced medical workflow automation, better analytics for disease management and improved out-patient health monitoring.

Oil & Gas Mining
By 2020, 5.4. million IoT sensors, devices & systems will be used on oil extraction sites to track and measure environmental performance and productivity metrics. Particular benefits include: predictive maintenance & monitoring of drilling equipment and the distribution pipeline network, to ensure safe & efficient midstream operations and workflow automation.

Transportation
By 2020, the automobile and transport sectors, will witness over 220 million connected cars on the road. Particular benefits include: better automotive analytics, improved traffic conditions, optimised fuel usage and travel routes. IoT will be a key enabler in the driver-less cars and trucks industry, being pioneered by Tesla, Uber and Otto trucks.

Hospitality
With 31% of hotels using next generation door locks, and 33% having room control devices, 16% having connected TVs, and 15% using beacons throughout the hotel, IoT has become a symbolic link between consumers and local hotel providers. Particular benefits include: increased personalisation and proactive room replenishment, enabling automatic reordering and improved forecasting and staff management.

Food Services
By 2020, an estimated 301 million IoT devices will be deployed by food service providers including digital signs connected throughout grocery stores and fast-food outlets. Particular benefits include: enhanced workflow efficiency, improved financial and inventory management at store fronts and faster-delivery to customers.

Defence
Future battles will be won or lost using real-time reconnaissance data from sensors connected to military assets on land, air or water. Consequently, spend estimates on drones are expected to reach $58.7 billion by 2020. Particular benefits include: providing battlefield situational awareness, proactive equipment maintenance, remote training and efficient inventory management.

Connected Buildings & Smart Homes
By 2030, the majority of home devices will connect to the Internet. 43% of building managers in the US believe that IoT will significantly affect overall building operations within the next three years. Particular benefits include: Energy savings, ease of access control, intelligent surveillance and monitoring improved building operations and support for sustainability efforts.

Above: Photonics technologies empower smart glasses and augmented reality.

markets are analysed in terms of pieces sold or in terms of turnover, whereby high-volume applications will not necessarily generate the highest revenues.

In conclusion, photonics is a fundamental enabling technology, powering IoT applications in all markets, especially those relating to Safety, Security, Space and Defence. Since "*EU research funding is aimed mainly at civilian objectives" and "the civilian EU programme for research and innovation … has been opened more widely to 'dual-use' projects*"[78], photonics-empowered IoT devices are the perfect vehicle for dual-use technologies with an enormous impact on almost any kind of civilian or non-civilian application. As a consequence, this roadmap focusses on **photonics-empowered, autonomous and resilient dual-use IoT microsystems**.

Additionally, according to Reference[87], there were approximately 6,300 globally active IoT startup companies with an average valuation of $5m at the end of May 2020, therefore many creative and innovative individuals from across the world are working in this promising area.

[87] Web resource: Global IoT startups and investments: https://angel.co/internet-of-things, downloaded on 27 May 2020.

"An image sensor with 10 Megapixels acquiring 100 frames per second produces the staggering data rate of 1 billion data points per second."

Major photonic research and innovation challenges

The predictions for IoT sensing usage illustrated in Fig. 8 are somewhat disconcerting: what could possibly be the reason for a mere 17% forecast uptake photonics in 2022 for the Global IoT enabled sensors market?

One possible answer is obvious at first: price. Compared to temperature and pressure sensors, the integration of photonic subsystems into IoT solutions faces two problems: first, the complexity (and therefore the price) of temperature and pressure sensors are much lower than those involving photosensors. Photonic solutions often require additional components such as lenses, filters, mirrors, gratings, optomechanical parts or even MOEMS[i]. Second, the data rate of an imaging system is significantly higher than that of any temperature or pressure sensor. To illustrate this point, consider a temperature sensor providing one temperature reading every second. An image sensor with 10 Megapixels acquiring 100 frames per second produces the staggering data rate of 1 billion data points per second.

A good example for the IoT Photonics conundrum is LIDAR[ii], the acquisition of three-dimensional imagery (or "distance maps") of the environment, making use of modulated light sources and in-pixel demodulation techniques. In its simplest form, LIDAR is employed to measure the distance of a person's ear to their smartphone – while LIDAR's most demanding application is the continuous high-precision measurement of the distance between earth and moon.

LIDAR would be ideal, therefore, in all cases where the relative distance between autonomously moving systems (robots, cars, UGV[iii], trains, drones, missiles, planes, satellites...) and/or living beings need to be measured quickly, continuously and with high precision. LIDAR would be particularly ideal for the autonomously driving cars, UGVs and drones of the future, given that it is capable of acquiring complete 3D maps at distances of several 100 meters, with a precision of a few centimetres, pixel counts of many million and repetition rates exceeding 100 Hz. However, Ultrasound and RADAR solutions are often preferred for affordability reasons.

As stated in Reference[88], while production costs are reducing, a high-end LIDAR for autonomous driving can easily cost more than $80,000, and for low-speed applications, a suitable unit can be purchased for around $4,000.

The enormous amounts of multi-dimensional data generated by photonic solutions pose another problem: it is impossible to transmit this avalanche of data through existing communication channels.

[i] MOEMS = Micro-Opto-Electro-Mechanical System
[ii] LIDAR = Light Detection and Ranging
[iii] UGV = Unmanned Ground Vehicle

[88] S. Liu and J-L Gaudiot, "Autonomous Vehicles Lite", IEEE Spectrum, March 2020.

© epyMetrics AG, Switzerland

Left: Photonics-empowered wearables drive autonomous IoT products in sports, medicine and our daily life.

By necessity, a new IT paradigm is therefore emerging: "Data at the edge"[89], implying that the data torrent acquired by IoT devices must be pre-processed and analysed in the devices themselves. IoT devices must, therefore, become "intelligent". They will have to be capable of "understanding" the captured data, delivering insight and not increasingly huge streams of raw data.

The solution is already around the corner: smartphones have started to employ Artificial Intelligence (AI) engines to interpret the acquired data and to reduce power consumption[90]. Our IoT devices and photonic sub-systems of the future must also follow suit to become AI-empowered.

In conclusion, the major research and innovation challenges for photonics-empowered, autonomous and resilient dual-use IoT microsystems include:

1. **Systems, not components:** integration of the photonic parts into full products must be made as easy as possible, calling for complete, self-contained photonic sub-system modules with a suitable digital bus, control and communication (e.g. the industry-standard i2C or SPI bus systems, or the military MIL-STD-1773 serial data bus).
2. **Miniaturisation:** the form factor of any photonic sub-system is of utmost importance for its integration into the cramped space of an IoT microsystem product. Consequentially, photonic measurement methods must be selected allowing ultimate miniaturisation and

[89] H.A. Peter and D. Krick, "Data at the Edge – Watson Down to Earth. IBM Global Technology Outlook", CIO Club of Excellence, IBM 2015.
[90] F. Agomuoh, "AI-powered smartphones and the features that will make you want to buy them", Business Insider UK, January 2018.

integration levels. Optical gas sensing, for example, should not be implemented with the conventional long gas-light interaction tubes, but rather with innovative, compact multi-path cells or with optical cavities, significantly reducing the space requirements.

3. **Cost-effectiveness:** to achieve the lowest fabrication cost of photonic sub-systems, maximum use of manufacturing techniques related to semiconductor production should be made. Since photonic solutions usually require highly complex MOEMS fabrication technologies (possibly including thermo-electric cooling components), specialized PIC[iv] fabs will be required and should be encouraged.

4. **Platforms, not individual solutions:** for utmost cost-efficiency, minimum NRE[v] is mandatory. NRE can be achieved by developing widely-usable photonic platforms that can either be configured by firmware adaptations, or be customised by simple wafer-scale post-processing steps (i.e. application-specific coating, physicochemical surface functionalization, or mechanical combination with different passive/active optical components). This will enable cost-effective high-volume production, taking full advantage of the scaling effects that are well-known in semiconductor manufacturing.

5. **AI-empowerment:** analysis and interpretation of the acquired data must occur within the photonic subsystem extremely to reduce the external bandwidth requirement. Only insights, and not raw data, should be communicated. The goal is to leverage Photonics with the forthcoming IoT and AI disruptions[91].

6. **Multi-parameter sensing:** today's IoT solutions are typically restricted to single-channel detectors with limited bandwidth (for example, pressure, temperature, light intensity, magnetic field-strength, acceleration, colour, chemical analyte concentration). Future solutions will lie in the simultaneous acquisition of data, in the form of massively parallel multi-parameter/multi-analyte sensor systems, capable of simultaneously acquiring, processing and interpreting huge amounts of data, while only communicating the essential "insights" to the outside world.

7. **Maintenance-free:** for hassle-free user experience, in civilian as well as in defence applications, two properties of a photonic subsystem are essential:

   a) No maintenance is necessary during long periods, or even during the full life-time of the system. To make life easier, no initial calibration should be required during the system setup, and – if

[iv] PIC = Photonic Integrated Circuit

[v] NRE = Non-Recurring Engineering (a one-time cost to research, design, develop and test a new product)

[91] PWC, "Leveraging the Upcoming Disruptions from AI and IoT", February 2017.

necessary – the photonic IoT device should carry out self-calibration without user intervention.

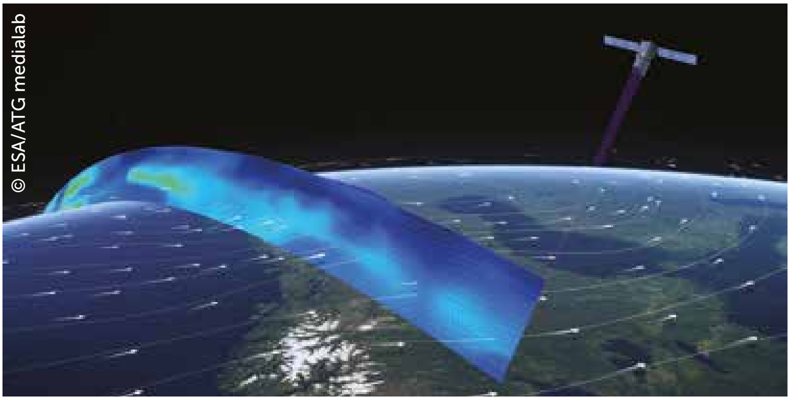
b) The integrity and accuracy of the provided data must be assured, for example through regular self-analysis of the photonic IoT device. The delivery of inaccurate data or erroneous interpretations of data cannot be tolerated.

8. **Resilience/robustness:** the photonic IoT device must be resilient, for instance, fault-tolerant, exhibiting "graceful degradation". This implies that suitable interpolation mechanisms are included (for example to fill in failing pixels), and the sub-system must properly communicate its impending degradation and life-time.

9. **Low Power:** Photonic measurement methods and components must be selected making the greatest possible use of the information in each photon. No photon should be wasted, by employing high-efficiency light sources (LEDs, lasers), low-noise/high-QE photodetectors, and, by avoiding the use of absorptive components such as optical absorption filters.

Below: Photonics-empowered smartwatches monitor our personal well-being and health.

Right: Profiling the world's winds by photonics technologies.



10. **Eco-Friendliness:** in full compliance with the European Green Deal[92], all photonic sub-systems and IoT devices should be constructed and operated for pronounced longevity; they should have the potential for re-use, that recycling of its components and materials is facilitated, and that RoHS and REACH norms are respected.

11. **Focus on high-growth/high-value markets:** by 2025, it is estimated that more than 75 billion connected IoT devices with their embedded sensors will have been installed[82]. The future lies not in the "simple" sensor sub-system already available today but, rather, Europe should concentrate on becoming the leader in advanced, high-performance, AI-empowered, autonomous, resilient dual-use photonic IoT devices of tomorrow[86]. Europe should focus on the large, rapidly growing and high-value markets of the future, demanding the highest performance of their embedded sensor sub-systems. The values in Fig. 9 are very clear[84]: these markets are related to healthcare ("4P Medicine"), environmental sensing (smart homes/cities, mining, "green" utilities, transportation), manufacturing (Industry 4.0), agriculture and food ("Precision Agriculture", "safe and healthy food with reduced waste"), as well as to military & defence.

"Essentially, for the 2021-2027 Roadmap, these key requirements imply that Europe should focus ***on photonics-empowered, AI-supported, autonomous, connected and resilient dual-use IoT microsystems*** *to provide enhanced safety and security for all EU citizens and to improve their quality of life"*

These requirements are translated into the following key target figures (**R&I challenges**) to be achieved by 2028, for resounding market success in a wide range of civilian as well as defence applications:

[92] European Commission, "The European Green Deal", 11 Dec 2019.

- Photonic sub-systems with the highest integration level (including standard digital interfaces and maximum ease of system integration) on-package solutions;
- Platform solutions with high-volume production: more than 1 million pieces per year;
- High-revenue products: more than €10 Million annual turnover;
- Sub-systems with wide application: more than 100 business opportunities or design-ins per year;
- Stabilised, narrow-line light sources for the 3-12 μm spectral range: under €10 per piece in large quantities;
- Stabilised, broad-band VISNIR light sources for 0.3-2 μm: under €2 in large quantities;
- Uncooled point and line photodetectors for 0.3-12 μm: under €10 in large quantities;
- Image sensors with >100×100 pixels for the 0.3-2 μm spectral range: under €10 in large quantities;
- Low-cost, high-reliability and calibration-free physicochemical, wafer-scale surface functionalisation for low-cost, multi-analyte biosensing, as a key technology for combating biohazards such as pandemics as well as biological warfare;
- Micro-spectroscopy subsystems for gaseous and liquids samples: suitable form factor for integration into IoT, smartphone or tablet products.

Collaborative Cooperation

Photonics is a fundamental, cross-cutting technology affecting a large number of applications, particularly if they involve sensing. Many EU-supported activities, therefore, have strong links with photonics and could profit from intense exchanges of ideas and concepts, as well as strategic collaborations[93]:

Health (Pillar II – Cluster 1): photonic technologies play a key role in the future development of multi-analyte biosensing systems (surface-plasmon-resonance, grating-coupled-waveguide approaches), wearable solutions for the Precision Medicine paradigm change (photo-plethysmography, miniaturised NIR/MIR/THz and Raman spectroscopy, OCT and NIROT 3D imaging techniques).

Civil Security (Pillar II – Cluster 3): in all aspects of the Secure Society Challenge[94], photonics offers unique technologies due to its non-invasive, high-speed, high-sensitivity, high-specificity and low-cost

[93] European Commission, "Orientations towards the first Strategic Plan for Horizon Europe", April 2019.

[94] Protection and Security Advisory Group (PASAG), "Horizon 2020 – Societal Challenge 7: Secure Societies – protecting freedom and security of Europe and its citizens", July 2016.

nature of its solutions. These properties are particularly useful for developing technological solutions to terrorism, crime, cyber-attacks (including identity thefts), mitigation of disasters (man-made and natural, including infectious pandemics), food security, migration and environmental threats (including climate change).

Digital, Industry and Space (Pillar II – Cluster 4): the convergence of photonics-empowered IoT and Artificial Intelligence (AI) leads to a new value proposition for the acquisition of data, including three types of analytics: (1) Predictive ("what will happen"), (2) Prescriptive ("what should be done") and (3) Adaptive ("how can we adapt to recent changes")[63]. The convergence of IoT and AI is much more disruptive and profound: to be useful in an application, data must be actionable (reliable, interpretable and useable), and must be complemented with context and field-specific creativity/intuition. This can only be provided by profound knowledge and understanding of the respective field, where the "smart sensor" solution should be employed – the deeper meaning of the term "connected intelligence"[63]. Strategic collaborations between developers of novel AI methods and the developers of novel AI-supported IoT solutions must therefore be encouraged.

EDA CapTech Optronics: 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[95]. Close collaboration with the EDA CapTech Optronics (also called EOST – Elecro-Optical Sensors Technologies) would be highly beneficial given the importance placed on dual-use technologies by this CapTech. A major task of this CapTech is to elaborate SRA[vi] 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...*"[95]. The joint elaboration of SRAs involving dual-use optical IoT technologies is therefore highly beneficial.

EDRP: the European Commission intends to establish a dedicated European Defence Research Programme (EDRP) under the forthcoming EU multi-annual financial framework 2021-2027, with an estimated budget of €500m per year[78]. As concluded from a review of DARPA activities, photonic technologies will play a major role in many areas of EDRP. 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.

vi. SRA = Strategic Research Agenda

95 European Defence Agency, "CapTech Optronics Activities", 6 December 2019, URL: www.eda.europa.eu/what-we-do/activities/activities-search/captech-optronics.

Proposed roadmap for 2021–027

	2021	2022/2023	2024/2025	2026/2027
Overview **Technology Challenges**	• AI empower ment of photonic IoT solutions • New materials and fabrication processes for NIR/MIR/FIR IoT components and sub-systems	Integration of cost-effective, low-power, miniaturized multi-sensor IoT platforms. Demonstration with cloud-based AI/ML engines	Novel concepts for "smart" multi-sensor photonic IoT systems with built-in AI data interpretation: Data at the edge, i.e. cloud-free autonomous IoT solutions	Successful demonstrations of maintenance-free, self-calibrating, fault-tolerant, self-diagnosing, "smart" multi-sensor photonic dual-use IoT solutions
Critical milestones to move from Science to Market	Alliances created between partners in Photonics, AI/ML, security/ safety and defence	PoC studies and demonstrations in selected high-potential dual-use applications and markets	Field tests in selected high-potential dual-use applications and markets	International market penetration with first dual-use IoT components and systems
Photonics **Research (R) & Innovation (I) Challenges**	• Lower costs of NIR/MIR/FIR IoT components and sub-systems. • Value creation through AI/ML empowerment of photonic IoT solutions • Identification: High-value dual-use applications	• Miniaturize multi-sensor PIC-based photonic sensing platforms • Select most promising applications for cloud-based dual-use proof-of-concept demonstrations	• Make IoT devices "smart" by embedding AI/ML engines • Fabricate/ demonstrate cost-effective, autonomous high-value IoT solutions without cloud-computing	• Optimize user value through robust, self-calibrating "smart" IoT solutions • Focus on "green" products, including recyclable or biodegradable consumables
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	Creation of tools and platforms for "smart" photonic IoT sub-systems. Creation of joint roadmaps with experts from safety/security and defence domains	Joint elaboration of specifications of high-impact dual-use IoT solutions in relevant markets: Health, Food, Industry 4.0, Secure Society, military&defence	Joint elaboration of test benches, field test environments and KPIs for dual-use IoT solutions. Joint generation of understanding of the requirements of typical dual-use applications	1. Joint field tests and insight generation of dual-use IoT solutions 2. Joint investi-gation of regulatory aspects and novel photonic IoT industry standards

3.6 Agriculture & Food

Main socio-economic challenges addressed

As photonics technologies advance, the European Photonics Industry is reaching out to understand the technology needs from the agro-food sector. The Agriculture and Food workshop contribution builds on the Photonics21 vision paper 'Europe's Age of Light' (see pages 26-29).

The Agriculture and Food work group 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 agro-food industries. Considering these visions, we ask: in what applications will light technologies play a role and how will this interface with other technologies such as microelectronics and robotics? This may be at the point where discovery-driven research meets industry needs.

By 2030, the technology to feed a world population of 10 billion, push back food-borne illness, and reduce the environmental footprint of agriculture, fisheries and aquaculture needs to be in place. Photonics has already contributed to the supply of safe, nutritious and affordable food and established a sustainable value chain from farm to fork. The access to data is of the highest priority and is necessary for a gradual approach for when the Internet of Things is fully established.

Market outlook 2021-2030 and potential for change:

- Feeding a global population estimated to reach 10 billion by 2050 will require dramatic increases in food production. With agriculture already responsible for 70% of global water use[96], 24% of greenhouse gas emissions[97] and environmental degradation on a planetary scale, boosting food production using current practices is unsustainable.
- Consumers are placing much greater emphasis on food safety, quality and value chain transparency. Food waste is a growing concern: one-third of all food produced is wasted during production, processing, distribution or at the point of consumption.
- Europe is the world's largest exporter of agricultural and food products, with the sector responsible for 7% of all jobs and 6% of European GDP. Export of food processing machinery is vital to several European economies.
- Europe is in the vanguard of high-tech precision farming, where photonics is central to a significant technological shift in the way farmers grow food.
- Photonics technologies provide a powerful toolbox for solving these challenges: 'agri-photonics' is already established as a fast-growing discipline in precision farming and environmental management.

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[96] http://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture
[97] www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector

"To make food processing safer, more efficient and less wasteful photonics technologies such as optical sensors, imaging and labelling play an important role."

- Relevant tools include lasers and lidar (light detection and ranging), hyperspectral imaging and many other kinds of sensors, as well as energy-efficient LEDs. These technologies 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, and screen for contaminants in produce.
- With the development of precision farming, optical technologies can provide information for individualised, more efficient food production, for example by controlling sectoral irrigation, the use of fertilisers, the application of selective plant protection (in farming or supervising livestock) and initiating timely and targeted treatments at the onset of diseases in individual animals.
- To make food processing safer, more efficient and less wasteful photonics technologies such as optical sensors, imaging and labelling play an important role. At the point of sale and consumption, the broader use of scanning and spectrometry will enable food content, spoilage or potential toxins to be identified with far greater accuracy.
- The global market for precision farming equipment and services is expected to grow from $3.3 billion in 2016 to $ 5.9 billion in 2021, with an annual growth rate of 12.4%[98].

Pioneering solution: safe and transparent food production

In a future of efficient high-tech farming, vertical farming, aquaculture and food processing, photonics will play an increasingly important role in raising supply, lowering resource use, curbing environmental degradation and reducing waste throughout the value chain.

In pushing back food-borne disease and contamination – and as consumers become increasingly concerned about the provenance, quality and safety of their food – photonics will be crucial for creating a system that securely monitors the entire value chain from farm to fork and certifies the origin and content of what is served on our tables in order to achieve full transparency and traceability of the complete food chain.

- On a farm, sensitive imaging can detect the earliest onset of fungus, mildew, pests and disease, reducing the need for agricultural chemicals. Spectrometry and laser scanning can detect product ripeness and determine the optimum time to harvest and ship food. In food processing, hyperspectral imaging combined with intelligent software makes it possible to identify and remove defects and foreign matter that traditional cameras and laser sorting machines have missed.

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[98] www.bccresearch.com/market-research/instrumentation-and-sensors/precision-farming-markets-report-ias111a.html

Right: Phenovator at Wageningen University & Research. Automated data collection of the performance of plants (phenotyping) in a growth room using Chlorophyll Fluorescence Imaging. By using active LED lighting the photosynthetic capabilities of a plant is measured.

- Fluorescence spectroscopy can monitor amino acids, vitamins, allergens and other components in foods.
- At a retail and consumer level, spectrometers connected via smartphones have already appeared on the market but are still limited in their functionality. With the next generation of sensors, retailers and consumers will be able to pinpoint the likely origin of produce based on a unique "fingerprint" of parameters such as sugars, phenols, amino acids and anti-oxidants without taking a sample or breaking the package. Photonics will, therefore, guarantee a high-quality European food production, increase trust between producers and consumers, and empower citizens to make better food and nutrition choices. Photonics will enable a leap forward in protecting the European Union's 'Guarantee of Origin' system against cheap substitutes and counterfeit products[99].
- Food and farming, including hydroponics and aquaculture, are a vast and complex area where photonics technology has already been widely deployed across many areas along the value chain.

Some major benefits of agri-photonics:
New lighting and sensing technology will be indispensable in improving vertical farming. With the demand for shorter farm-to-table distances, the economic benefits of indoor and urban farming in warehouses or

[99] European Commission, "The EU's common agricultural policy (CAP): For our food, for our countryside, for our environment", EU publication, 2014 7

underground spaces are becoming increasingly attractive. Vertical farms will develop to produce food on multiple levels, conserving space and water in comparison with conventional greenhouses and carefully controlled environments will also improve produce taste. Research into specialised LEDs and lighting algorithms will optimise growth and yield in a greenhouse or indoor environment. Ultraviolet LEDs will combine light with adequate control of plant diseases such as fungus and mildew.

Photonics for safe, nutritious and affordable food
The development and widespread deployment of sensor technology will allow individualised "sell-by" dates that replace the hypothetical risk of spoilage with the actual risk. A significant cause of food waste at the retail and consumer level will, therefore, be eliminated. Photonic sensing has a crucial role to play in fish, shellfish and algae farming as the sector increasingly shifts towards more complex land-based and indoor systems to minimise the destructive environmental footprint of traditional aquaculture.

Small, cheap sensors – including photonic devices - will 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.

Major Photonics Research and Innovation Challenges

Top-Level Innovation Challenges

Image-based systems: innovation drivers in agriculture and food
Compared to automotive and industry, agricultural machines navigate, communicate and work under several varying conditions and "noise" sources (such as crop and weed, weather, soil conditions, dust, rain, vibrations, sun, wind, for example). As a consequence, the demands for robust photonic systems under outdoor conditions are high.

To combine economic and ecological improvements, data with high spatial and temporal resolution will have to be available for interpretation and instructions. Examples are weed detection and control, selective fertilisation or harvesting. As a consequence robust imaging has become an innovation driver for agriculture (as well as food). Having a look at the worldwide largest fair for agricultural technology (the "Agritechnica", Hanover) about 15% of all awards since 2015 belong to imaging applications. "Imaging" includes a broad range of (dominantly) optical sensors, such as colour/greyscale cameras, shadow imaging (light curtains), 3D-Imaging (laser, stereo, time-of-flight), multi/hyperspectral and thermal imaging. The corresponding

Left: Photonic sensors aboard automated drones are used for field and soil monitoring.

imaging concepts – needed for robust solutions – include (classical) image processing, machine learning, sensor data fusion, smart sensors, simulations, human-machine-interfaces, remote and satellite imaging as well as low-cost imaging. “Digital twins” has become one of the most practice-oriented tools: by simulating sensors in their environment the most promising results – for navigation and processing - are evaluated on the field, whereas the software can be directly transferred from the simulation tool to the machinery.

As a consequence, imaging systems strongly support process automation: the evaluation of the sensor interpretation is crucial for the admission of autonomy (field robotics).

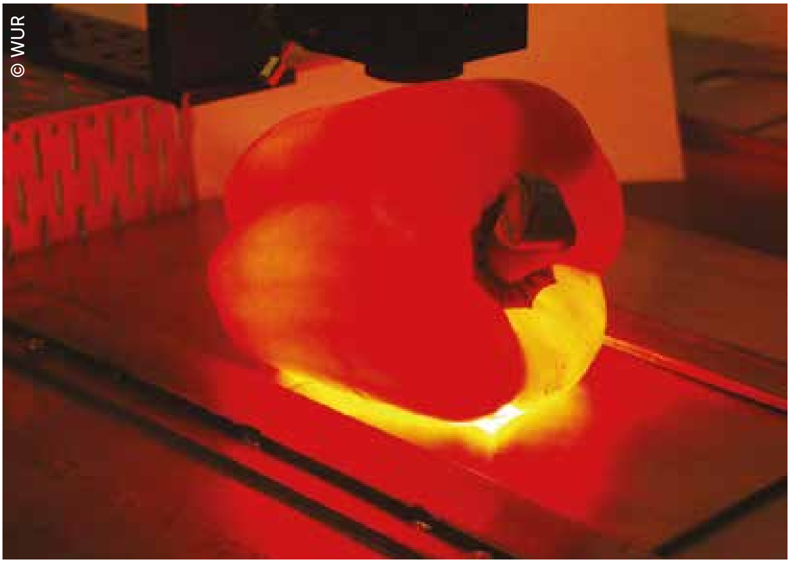
The agriculture and food sectors have unique characteristics that both raise barriers to investment and slow down the adoption of new technology.

- **Spread technology via agricultural extension systems**. Low margins and fluctuating food prices limit farmers’ willingness to invest in new technology. Many players along the entire food value chain tend to rely on traditional knowledge instead of state-of-the-art precision methods. To support the uptake of new technologies by farmers, and to assist them with investment decisions, policymakers and industry associations should collaborate to develop affordable photonics-based systems that fulfil a clear market need. On the other hand, the success of the agri-food sector is determined by the supply chain: the primary food producers, such as Unilever, together with the major supermarket retailers have the power over prices and sales, making the implementation of innovations in the value chain difficult.

- **Strike a smart balance with regulations and standards.** Regulations protect consumers and ensure the safety of food. However, regulations can also hinder the introduction of new processing technology and farming techniques. This balance has not always been adequately achieved in the past: member state governments and the Commission must be careful to find the right balance.
- **Support technology uptake by 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. Europe still has a large and vibrant sector of small farms and food processors not only as a legacy of the past but also due to increasing demand for regional, organic and speciality produce. Solutions include technology-focused support for cooperative associations and the leasing or sharing of equipment by farms and processors. This will require a unique approach by the industry, and specific policy support would help make investments viable in smaller niche markets. There are examples of inter-regional projects where this has already started.

Integrated Photonics Technologies for Agrofood

- Low margins and fluctuating food prices limit farmers' willingness and ability to invest in new technology. Many players along the entire food value chain tend to rely on traditional knowledge instead of state-of-the-art precision methods. Business owners are only interested in technologies that meet their low-price expectations. Size is not an essential criterion: if a device to detect the level of decay in stored farm produce is the size of a shoebox, this is not a problem.



Right: Bell pepper inspected by VIS/ NIR spectrometers on sugar content, early disease developments, etc. Transmitted light through the product is analysed, based on large set of sample predictive models. Prototype developed at Wageningen University & Research.

Long-term (2021 onwards)

- The long-term markets for systems-on-a-chip are more promising. Agrofood has an opportunity to benefit from integrated photonics developments in IoT devices, infrastructure monitoring, zero-latency lidar, secure big data and AI. Small low-cost solutions are especially important for retailers and consumers.

"Photonics sensors can monitor tree growth with high precision, identify which species are present and spot the first signs of disease."

1. Fibre Optic Sensing

Fibre optic sensing is a rapidly growing application field for Photonics Integrated Circuits (PIC) technology. In the Netherlands, an Alkmaar-based photonics engineering company Technobis responded to a challenge from the aerospace industry. Technobis was asked to build a fibre-optic sensing system for new aircraft which was designed to replace traditional sensors (connected by up to 18,000 copper wires) with a couple of optical fibres. Technobis has succeeded in placing 1500 sensors into one fibre and developed architecture to poll the data from all these sensors down the same fibre. The weight and power consumption, as well as the cost of the parts, are much lower than the classical system. Technobis has made use of wholly ruggedised solid-state chips, so there are no moving parts. The system has been extensively tested and validated. So far, many Application-Specific Photonics Integrated Circuits (ASPIC) interrogator systems have been realised as operational system-on-chip devices. These demonstrators have shown that all essential building blocks are working and complete interrogator on-chip solutions can be produced.

Technobis sees this architecture as interesting to satellite and drone-based earth monitoring systems. However, while the current focus is still on Fibre Bragg Grating (FBG) devices, other sensing principles are gaining attention: new innovative sensing functionality requires less non-recurring engineering and development activities and resources than conventional systems.

The next important step in making this technology available in the market is to secure high TRL maturity: not only should the optical chip be reliable and able to perform to specification, but the production and its implementation through PIC packaging services (and subsequently their integration in avionics systems) also needs to mature. Scaling up sub-assembly, series production and operational functions of these products will, therefore, be imperative.

2. Developing sensors in Finland for forestry

Juha Purmonen, Executive Director of Photonics Finland, explains that optical technologies are becoming increasingly important, not only to manage the growth of Finnish forests but also to monitor the progress of international environmental targets that

"Light sources and especially laser technology can be applied for direct intervention and manipulation in the agrifood sector."

have been agreed. Photonic sensors aboard aircraft, satellites and automated drones do more than watching out for fires or illegal logging. Photonics sensors can monitor tree growth with high precision, identify which species are present and spot the first signs of disease. Light-based technologies help forestry managers 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, so the lumber yard can monitor its incoming material and plan production accordingly. The efficient use of raw materials and the employment of side streams, as well as the recyclability of products, are basic bio-economy principles: a 50% reduction in landfill waste has been recorded over the past five years.

Currently, there are a little over 200 photonics companies in Finland, generating annual revenues of around €1 billion and employment for over 4,000 highly-skilled professionals. Around 50% of the companies are focused on serving the domestic forestry industry, while the other half exports its technology. The Finnish photonics sector is currently experiencing an annual growth of 15 to 20 per cent.

3. The most accurate Laser-on-a-chip

Breakthrough applications in datacom, RF signal processing, biosensing, and driverless technologies (lidar) increasingly rely on the functionality of integrated photonics. For photonic chips to function as efficiently as possible, it is essential to be able to control the light signals accurately. All light particles being transmitted should have the same wavelength and therefore the same colour.

In 2017, University of Twente researchers developed a minuscule laser on a chip with a maximum linewidth (the maximum uncertainty in frequency) of just 290 Hertz, deeming it the most accurate laser on a chip that has ever been created. The laser is tunable so that users can specify the colour of the laser themselves, within a broad-spectrum range.

LioniX International has developed the narrow-linewidth tunable laser based on a hybrid-integrated external cavity laser. The commercial version uses state-of-the-art Photonic Integrated Circuit technology and has distinct advantages including, high-power capability, ultra-narrow line width, as well as broadband tuning and is all fitted into a compact design. LioniX International is already selling a commercial version of this laser on a chip. Currently, laser linewidth for this product is <100 kHz, typically 10-20 kHz.

It will be possible to manufacture smaller yet very high-power lasers inside the TriPleX platform. Industry enquiries suggest this laser-on-a-chip technology is essential for the accuracy in many applications, including Optical Beam Forming Networks, and RF analogue links for the new 5G networks. Next-generation lasers-on-a-chip will be crucial in making lidar navigation units smaller, more accurate and less expensive. Applications include next-generation driverless tractors.

4. Building new sophisticated applications cheaper and faster
Members of the European Photonics Alliance have identified a Europe-wide industry need to develop hybrid lasers that operate at wavelengths beyond 1505 nm by using other gain material.

Developing these tunable lasers will require adapted chip design and different approaches to packaging the chip into functional modules. However, this parallel approach will yield manufacturable products much quicker than if each company were to develop their lasers individually.

Lasers and lighting devices: tailored light for agrifood applications
The use of lasers and lighting technologies as active agents has considerable application perspective in the agrifood sector.

- LED lighting concepts have been investigated, proposed and realised in greenhouses and will play an important role in vertical farming and aquaculture of photosynthetic organisms such as algae and seaweed. Solutions for spectral tailoring of the lighting conditions and intelligent lighting solutions are already available and support individualised lighting. Lighting concepts are also relevant for indoor livestock farming.
- Optical sensors – point sensors and imaging devices alike – often benefit from excitation by lasers and irradiation by LEDs tailored to the needs of the sensor concept. Further development of versatile, robust, and adapted sources will be needed to support and improve sensor solutions.
- Light sources and especially laser technology can be applied for direct intervention and manipulation in the agrifood sector. The spectral dose-response of the targeted effect plays a major role in the selective induction of effects and in many fields, basic research to elucidate the spectral dose-response is still missing. The complexity of the biological mechanisms and matrix makes the identification and well-defined description of the response mechanisms difficult. So, in this field, both basic research to identify and quantify the parameters influencing effects and effectiveness are necessary as well as application-oriented research tackling a well-defined application in a realistic environment. Applications include, but are not limited to:
  - plant protection (lethal treatment of weed and herbivorous insects)
  - laser biostimulation for seed germination and seedling growth, production of secondary metabolites relevant for plant protection but also functional food and nutrition

– decrease of microbial and virus load on food products
– laser marking of food (fruit, carcasses) to improve traceability and reduce labelling cost and waste
– light-induced manipulation of food products, for example, reducing allergens

The laser and LED industries are increasingly interested in extending their market towards the agrifood sector, so both considerable interest and activity in research projects as well as a positive price development for hardware components can be expected and should be fostered.

Cooperation needs with other disciplines or fields

Aside from much closer cooperation with experts from the agricultural domain such as farmers, crop production scientists and animal health experts, cross-technological cooperation is needed.

Photonic sensors need to become "smart" through AI-empowerment. Close collaboration with all fields related to machine learning, big data analytics and AI is imperative: the convergence of IoT and AI leads to a new value proposition for the acquisition of data, including three types of analytics: (1) Predictive ("what will happen"), (2) Prescriptive ("what should be done") and (3) Adaptive ("how can we adapt to recent changes").

However, the convergence of IoT and AI is much more disruptive and profound: for data to be useful in an application, it must be actionable (reliable, interpretable and useable). So for this purpose, data must be complemented with context, field-specific creativity and intuition (which can only be provided by profound knowledge and understanding of the respective field, where the "smart sensor" solution should be employed) and therefore gives a deeper meaning to the term "connected intelligence."

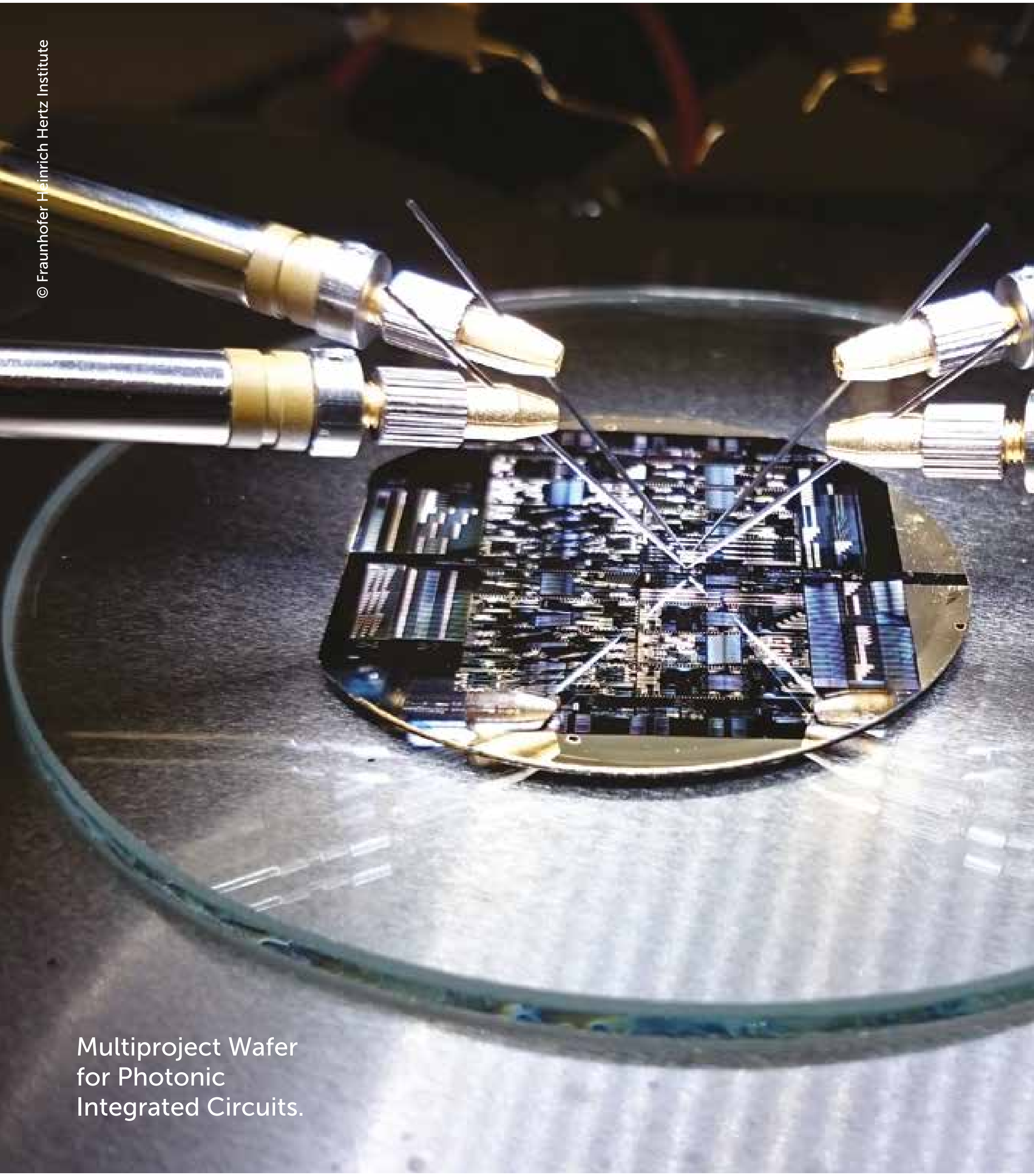
As a consequence, the convergence that will transform business is not restricted to IoT, and AI: sincere cooperation and partial convergence with the respective application fields will be critical for the success in our future IoT-enabled world. The cooperation consortia that will be vital for leveraging the full range of benefits of multi-analyte AI-supported photonic biosensors must therefore include:

- All work groups of Photonics21
- All domains relating to AI, Machine Learning and Big Data Analytics
- All disciplines for which novel photonic solutions with "connected intelligence" should be provided in particular Connected Buildings, Green Utilities, Transportation, Agriculture and Food, as well as Manufacturing.

Proposed roadmap for 2021–027

	2021	2022/2023	2024/2025	2026/2027
Overview **Technology Challenges**	Mapping and gapping: • AI & photonic solutions • Identify powerful applications	Mapping & gapping: • Continuous alignment of crossover research agendas • Powerful applications identified	• Fingerprinting of plants/food products with novel concepts for "smart" multi-analytic photonic systems with built-in AI/ML data interpretation	• Novel concepts for maintenance-free, self-calibrating, fault-tolerant, self-diagnosing "smart" multi-analytic photonic sensor (IoT) systems
Critical milestones to move from Science to Market	• Report & new alliances / projects launched in crossover Photonics & AgTech	• Report & prototype demonstrations in projects	• A clear increase in photonic industry sales in AgTech	• International market penetration with benefits of novel products/ services
Photonics **Research (R) & Innovation (I) Challenges**	• Precision agriculture and novel sensors: User benefits • Vertical Farms & autonomous systems through AI/ML empowerment of photonics solutions: User benefits	• Miniaturisation/ featherweight sensor developments • Select most promising applications for cloud-based proof-of-concept demonstrations	• Make sensor systems "smart" by embedding AI/ ML engines • Fabricate/ demonstrate cost-effective sensors aimed for a large number of sales (> 1000)	• Optimise user value through robust, self-calibrating "smart" products • Focus on "green" products, including recyclable or biodegradable consumables
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	• Workshop: AI & Photonics Sensors for field Robotics for autonomous navigation • Exploit crossover calls	• Workshops on: Identify high-impact applications in relevant markets: Health, Food/ Agriculture, Transport, Industry 4.0 • Exploit crossover calls	• Workshops on joint spec creation, demonstrations and insight generation in relevant markets and applications • Exploit crossover calls	• Joint field tests and insight generation • Mutual investigation of regulatory aspects and novel industry standards

3.7 Sovereignty in Core Photonics Technology Platforms



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Multiproject Wafer for Photonic Integrated Circuits.

Main socio-economic challenges addressed

As noted in the Photonics21 strategy document "Europe's Age of Light", photonics will play a vital role in addressing the key socio-economic challenges facing Europe in the 21st century. As examples, we may note the following:

- Facilitating healthcare through the instant diagnosis of major diseases
- Promoting healthy living while preserving the environment
- Facilitating accident and congestion-free transport
- Enabling 21st-century manufacturing using photonic tools and photonics-enabled digital infrastructure to create a million new jobs
- Promoting a high quality of urban life through smart homes and cities
- Ensuring that our digital infrastructure keeps pace with the integration of billions of new Internet-enabled devices, fulfilling our needs for information, business, finance and home infrastructure
- Maintaining the pace of research, innovation and education needed to keep Europe in first place for economic success and quality of life

In other chapters of this Strategic Research and Innovation Agenda, Photonics21 work groups have set out their vision for how these objectives will be achieved and the research and innovation agenda that needs to be addressed. The role of the Core Photonics activity is to ensure that the fundamental technological developments are in place to underpin these application-specific developments and thereby provide the solutions to the socio-economic challenges that we face.

During the last frameworks, a consistent and coherent vision for the enabling technologies was established and carried through by the Photonics PPP. A central element of this vision has been photonic integration, i.e. the realisation of high-functionality optical subsystems on a single chip or a small number of chips, as well as the establishment of sustainable technology platforms – manufacturing pilot lines – for selected technologies. These approaches have already paid significant dividends in providing the basis for the multi-hundred Gigabit per second communications systems on which the internet depends, opening up a wealth of opportunities in other fields and bringing ground-breaking technologies within reach of entrepreneurial SMEs. These themes will continue but should now be developed to embrace a number of distinct objectives:

- Enhanced functionality and spectral coverage, to facilitate new applications in biomedical, environmental, industrial and sensing fields
- Continuous development in performance to address the increasingly sophisticated requirements of communications, sensing and control systems, while enabling new applications based on quantum technologies and new computing architectures such as neural networks

- Emphasis on photonic circuits and systems, building on photonic integration technology in combination with other photonic devices such as imaging sensors, microelectro-mechanical systems (MEMS), microelectronics and advanced assembly techniques to realise complete systems in the most effective way
- Continued investment in platforms and pilot lines, to match evolving performance expectations, close gaps in supply chains and strengthen the transition to volume manufacturing.

Major photonics research and innovation challenges

As noted above, we should build on our strengths to develop the integrated photonic technology that is required. We see significant challenges in providing the technical basis for the full range of applications that we envisage, including 3D sensing, automotive LIDAR, communications above 1Tbit/s per wavelength and the myriad of opportunities to improve quality of life through improved healthcare. We emphasise a unified approach wherever possible to manage the costs of developing advanced technologies that are relevant in all of the key fields.

Many of the considerations noted in chapter 3.5, Safety, Security, Space & Defence, apply to all of our targeted application areas. In particular, we wish to emphasise the following underlying themes:

- Systems, not just components: we must provide effective means for the combination of technologies to achieve overall systems goals
- Miniaturisation: Many applications require subsystems that are very small so that they can be integrated into other devices such as sensor elements and smartphones
- Cost-effectiveness: The power of photonic integration to achieve high performance at minimum cost will continue to provide major opportunities for innovative products
- Platforms, rather than individual solutions: This is the key to achieving maximum return on investment and reach the largest number of market sectors in the shortest possible time
- Robustness and reliability: Many photonic systems will be embedded in safety-critical systems where reliability and resilience are mandatory
- Power efficiency, to mitigate the environmental impact of large-scale electronic systems deployment and allow new applications which are self- or battery-powered
- Eco-friendliness, in line with European priorities, to preserve and improve the environment
- Accessibility: Key platform technologies should be made available to the broadest possible user base through measures such as sustainable manufacturing pilot lines.

In the following paragraphs, we identify four major technical themes for research and innovation, one organisational development, which we have named the 'Innovation Factory', and one supporting activity, which is to develop and maintain international roadmaps for key photonics technologies, in order to facilitate investment decisions by funding bodies and companies alike.

"Photonic monitoring/ sensor systems will be vital for the quality of life of all EU citizens and will be required to solve the major societal challenges of the next decade."

Photonic integrated circuits (PICs) for monitoring/sensing systems

Rationale

Photonic monitoring/sensor systems will be vital for the quality of life of all EU citizens and will be required to solve the major societal challenges of the next decade. These include healthcare/life sciences (real-time multi-analyte diagnostics, physiological treatment, interventional augmented reality (AR) assisted guidance, personalised medicine), environmental sensing (Internet of Things (IoT), smart homes/cities, mining, water, green utilities, transportation), manufacturing (IoT, Industry 4.0) and agriculture and food (precision agriculture, safe and healthy food with reduced waste).

For all of the above applications, the focus will lie on approaches that permit the measurement of multiple parameters at the same time, combined in many cases with access to the outside world or the sample being analysed or treated (organ-on-chip, microfluidics). This requires a systems approach at sufficient TRL level, with high chip integration levels (hybrid, heterogeneous or homogeneous), determined by the specific market application. The focus should also be put on widely usable photonic platforms that can either be configured by firmware adaptations (software-defined-photonics), or that can be customised cost-effectively. Furthermore, integration of the photonics PICs into full products must be made as easy as possible, calling for complete, self-contained photonic sub-system modules with suitable digital bus, control and communication interfaces. Finally, focus is put on the "chiplet" approach, currently being pioneered in the microelectronics industry, where highly developed individual PICs are combined on a standardised substrate through a highly efficient and cost-effective assembly procedure.

Research and Innovation Challenges.

- Compact (coherent or incoherent) imaging monitor and sensor systems (Optical Coherence Tomography (OCT), spectroscopy, lidar, etc.)
- Compact non-imaging monitor and sensor systems (Point of Care (POC) diagnostics, environmental scanners, etc.)
- Photonics for augmented reality (not only for displays)
- Semiconductor lasers and photonic integration platforms for all required wavelength ranges, from the visible to the mid-infrared
- Multi-technology integration

Pervasive Photonics in Next-Generation Electronic Systems

Rationale

One of the major challenges of innovative applications is the handling of big data. Data has not only to be collected and processed, it also has to be transferred. Today, a significant bottleneck for all big-and secure-data applications and industries, including System-in-Package and System-on-Chip based solutions, is the lack of interconnects addressing communications off-chip (chip-to-chip, between modules) or on-chip (between cores) with low latency, low power, high bandwidth and high density.

The most promising approach to overcome these challenges is the use of photonics. This will be key to the introduction of disruptive computing technologies and new system architectures, leading to faster, cheaper, power-efficient, secure, denser solutions for industrial applications. Furthermore, generic co-integration with other essential building-blocks of computing technology will be possible, as photonic-based standard interfaces between building blocks are introduced and implemented.

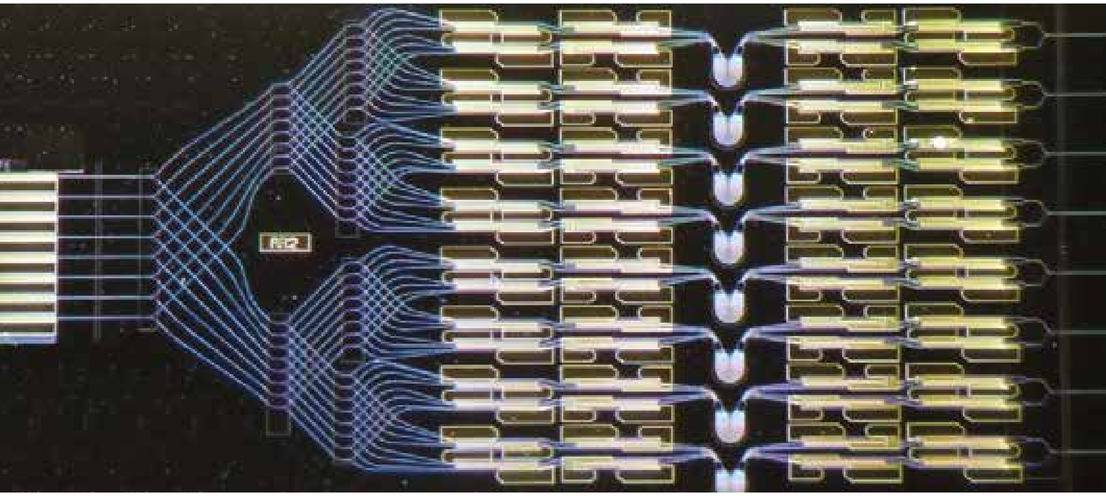
Research and Innovation challenges

The impact of photonics on next-generation electronic, communication (5G) and computing systems or networks will be twofold:

- By solving efficiency and capacity issues in data centres, high-performance computing (HPC) and electronic systems

The increasing use of optical technologies within the ICT industry provides a key opportunity to limit energy consumption while enabling massive growth of overall data capacity. Achieving integration between electronics and optics on a single die or on a single multi-chip module

Below: Photonics systems lay the foundation for future innovation.



or chipset will make a significant contribution to the development of lower power and more efficient systems, both at network and data centre level and board, module and chip level.

- The co-integration of photonics and electronics will enable large and efficient switches and high bandwidth density/low power transceivers. These are essential components for solving **I/O and cross-connect bottlenecks** encountered in communication networks, data centres and computing system based on von Neumann architectures.
- **The Chiplet approach** (i.e. integration of different Photonic and Electronic Integrated Circuits on an interposer) will reduce manufacturing costs while allowing the most appropriate technology to be adopted for each specific purpose. Targeting high-performance, compact, low-cost and low-energy components across the entire interconnect hierarchy level cannot rely on a single technology platform. The objective here is to create the optimal synergies between different technologies, streamlining their deployment beyond Tb/s-scale to create high-performance, low-cost and low-energy optical interconnect components and sub-systems. A "Mix & Match" of components or building blocks will deliver the optimal heterogeneous integration and align their synergistic deployment towards the specific needs of individual functions. The Multi-Chip-Module concept, familiar from microelectronics, can be extended to photonic interposers to interconnect a large number of processing/IP cores.
- **A manufacturing pilot line approach** will be appropriate to bring heterogeneous/chiplet integration to the necessary TRL levels and facilitate the adoption of this new technology in production systems. We note that there will be a critical need for standardisation of all interfaces in such an initiative.

• By enabling new computing paradigms

Conventional digital computers based on von Neumann architectures are now reaching computation efficiency limits. New standards are needed to breach the energy efficiency wall by orders of magnitude. New disruptive technologies (quantum computing, neuromorphic computing, spintronic and optical computing) will pave the way for new applications driven by cyber-physical systems and Artificial Intelligence (AI). These trends challenge computing technologies with:

- Increasing performance at acceptable costs for High-Performance Computing (HPC) and low power and ultra-low power computing,
- Making computing systems more integrated into the real world,
- Making "intelligent" machines, and
- Developing new disruptive technologies.

- **Analogue and Neuromorphic photonic computing** provide a way to surpass the performance limitations inherent in traditional von Neumann architectures. Photonic integration technology, with high switching speeds, high communication bandwidth and low crosstalk offers an opportunity for ultrafast neuromorphic processing that can complement conventional or neuromorphic microelectronics (e.g. optical hardware accelerators).
- **Quantum computing** promises a much more efficient way of computation than its classical counterpart. Building a scalable optical quantum computer requires hundreds of thousands of components integrated on silicon wafers that meet modern requirements of performance, scaling, and yield. A dramatic evolution of current integration platforms is needed.

Photonic Integration for Communications

Rationale

As noted in the introduction, photonic integration has been and will continue to be a key enabler for communications functions, ranging in scale from major internet backbone links spanning continents to short-reach interconnects in computing systems, data centres, industrial installations and even consumer equipment. It is vital that progress is maintained in this field, which is pivotal for all kinds of systems in every application field.

Research and Innovation challenges

We note many specific RIA challenges:

- Microwave photonics and mixed analogue-digital integration technologies for wireless systems, 5G telecom and beyond
- Low cost, high-performance PICs for transmission over all distances at data rates above 1Tbit/s, embracing coherent and advanced modulation formats
- Photonic interconnect integration and advanced packaging at the level of printed circuit boards, including low-loss waveguide technology on thin glass and polymer-based materials as well as high channel-count, standard optical interfaces for PIC and MCM/chiplet-based on-board optical engines
- Photonic interposer substrates with integrated optical waveguides and coupling interfaces, high electrical routing capacity and fine-pitch interconnection density as a platform for large-scale chiplet assembly and integration
- Solutions for optical chip-to-chip connectivity and on-chip networks
- Technology for free-space-optical communication, supplementing conventional RF wireless techniques for office, industrial and outdoor (e.g. automotive) applications

Right: Hybrid Y-branch dual-wavelength master oscillator power amplifier suited, eg., for nonlinear up-conversion and hyperspectral imaging.

- Components supporting very wide bandwidth in the fibre (e.g. 120-200 nm), complementing the development of new fibre technologies offering lower latency, high phase stability and low loss
- Synergistic design of communications subsystems incorporating both photonic and high-performance microelectronic circuits, e.g. using the ''chiplet'' approach to integration.

Enabling Components for Future Systems

Rationale

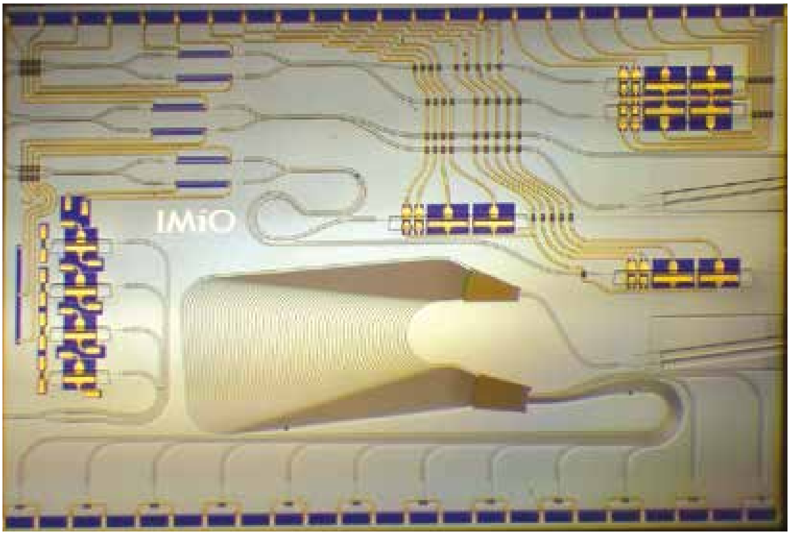
To serve our chosen application areas, our integration platforms need to be augmented with new functions and performance enhancements, requiring in many cases the development of new semiconductor materials and innovative device structures. We also emphasise the need for developments in the fabrication technology for photonic devices, including epitaxy, lithography, patterning, die fabrication and assembly.

Research and Innovation challenges

We note the following key challenges for photonic device technology throughout the next research and innovation framework, all of which should be addressed by RIA activities:

- Broadband ("white") light sources for sensing
- High sensitivity avalanche photodetectors (including arrays) for low-light detection and imaging
- High-efficiency semiconductor lasers operating at high temperatures (>85°C) and high efficiency across all wavelength bands
- Incorporation of new building blocks such as magneto-optic elements for non-reciprocal functionality (e.g. optical isolation), polarisation handling and nonlinear functions

Right: Fiber sensor interrogator.



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- Epitaxial growth of efficient light-emitting structures on silicon, e.g. III-V semiconductors and SiGe nanostructures, and their integration into comprehensive photonic integration platforms
- Developments in heterogeneous and hybrid technologies combining key benefits of diverse materials, e.g. silicon, III-V semiconductors, electro-optic polymers, ferroelectrics, magnetic materials and nanostructures and plasmonic structures
- Electronic-photonic integration
- Scalable, robust and cost-effective packaging and assembly technologies.

For the process challenges, we particularly note the need to master epitaxial material growth and processing on large wafers with improved quality, uniformity and very low defect densities.
In addition to research and innovation activities to establish and prove new device and materials concepts, it will be valuable to establish programmes in which new equipment and processes can be trialled and assessed in a real manufacturing environment.

Innovation Factory Photonics

Rationale

A key element of our strategy to facilitate the commercialisation of research results, and thus reap the economic and social benefits mentioned above, is to lower the entry threshold for photonics in general and photonic integration technologies in particular. An Innovation Factory is a virtual institution offering solutions for the complete photonics value chain from chips to packages and systems.

It combines multiple sites, multiple technologies, and addresses a multitude of different applications. Along each value chain, there will be pre-competitive research and development activity leading to TRL5-6 maturity. Each value chain will also be connected to a pilot line and pre-series production facilities. In this way potential customers, including SMEs, will be able to take advantage of a seamless pathway from initial concept through to production, employing scalable manufacturing methods appropriate to the market and without having to worry about manufacturing investments before the market is proven.

"An Innovation Factory is a virtual institution offering solutions for the complete photonics value chain from chips to packages and systems."

Funding should be equally shared between the contributing institutions (e.g. developing value chains with many members) and the customer institutions.

This new form of cooperation will make a significant contribution to strengthening European photonics and photonics user industry competitiveness internationally. It may also constitute an evolution path for pilot lines and projects conducted in the Horizon 2020 programme.

Research and Innovation challenges
The Innovation Factory should both close gaps in European photonic value chains and set up easy and effective access mechanisms for all relevant target markets. This involves two steps:

- Close gaps in photonic value chains, bringing photonic processes whose functionality has already been demonstrated (TRL3-4) to a maturity high enough for implementation in factory services.
- Setup the Virtual Factory. Key steps here will be to identify the most critical value chains, develop appropriate interfaces between the individual elements in the chain (value steps), implement logistics between these value steps and define design languages and protocols, so as to realise an effective and vibrant **virtual factory** with a flexible and open structure, allowing for a multiplicity of competitive and pre-competitive actors and services.

International Photonic Road-Mapping activity

Rationale
Investments in photonic technology need to be informed by the technical requirements and specifications that will need to be met and the timeline on which they can be delivered. This information is vital for the pervasive application of photonics across all fields of business. Consensus across the industry concerning goals and objectives will provide a solid, reliable basis on which to plan and to invest.

The International Photonic Roadmap should be the reference for our industry, informing not only all of the participants in the photonics value chain but also client industries who will build their success on the adoption of photonic technology. A robust roadmap will provide the basis for confidence across the entire ecosystem needed to meet our aggressive growth expectations. The roadmap should cover short, medium and long-term strategic goals, to inform research, product development and infrastructure developments throughout the next Research Framework and beyond.

The international photonic road-mapping activity envisaged here will facilitate the same exponential growth as has been experienced in microelectronics since the 1970s, which has been dramatically helped by the availability of a clear roadmap adopted across the entire industry (International Technology Roadmap for Semiconductors, ITRS).

Coordination and Support challenges

The International Photonic Roadmap should address both of the following aspects:

- International road-mapping activity addressing Photonic Integrated Circuits and Systems, concerning the integration of research results in various scientific and technological disciplines, and applications including data centres, telecom, aerospace, automotive, healthcare, defence, agro/food, industrial manufacturing, Internet of Things (IoT), nanotechnology, biomedicine and cognitive sciences.
- Support for research coordination and strategy/policy for European photonic integration activities.

Right: Ultra-compact high-power pulse light source providing pulse widths from 3-15 ns and a pulse power up to 100 W, suited for lidar applications.

Cooperation with other disciplines and fields

Since the mission of the Core Photonics activity is to provide the component and systems technology which underpins all of the specific application areas, our priority is to maintain the closest possible coordination with the application work groups, so that maximum synergy is achieved and platforms are developed which are truly advantageous for all of the desired areas.

We note that many of the application areas require a combination of technologies (photonics with microelectronics, MEMS, microfluidics, etc.). It is therefore essential that we make appropriate connections to the research and innovation programmes in these fields and ensure that the optimum solutions to multi-technology integration are identified and adopted. Specific examples will include the Quantum Flagship and the Key Digital Technologies partnership.

Proposed roadmap for 2021–2027

	2021	2022/2023	2024/2025	2026/2027
Overview **(Technology) Challenges**	Photonic Components and Systems Enhanced functionality, spectral coverage, performance to enable new applications New organizational frameworks to facilitate route to market			
Critical milestones to move from Science to Market	Horizon 2020 pilot lines successful and sustained	Innovation Factory established	Enhanced production technologies	>50 products in market through Innovation Factory
Photonics **Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges**	Photonic Systems Integration → PICs for sensing; PICs for communications → Pervasive Photonics in Next-Generation Electronic Systems → Enabling component technologies →			
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	Microelectronics, microfluidics, imaging sensors, MEMS → Production equipment, techniques, materials → Roadmapping, international liaison →			

3.8 Photonics Research, Education & Training

The photonics experts of the future will drive the European knowledge society.

Main socio-economic challenges addressed

In a knowledge-based society, Photonics is a major driver for innovation and a flagship science playing an instrumental role in the creation and dissemination of knowledge and ideas.

To fully exploit its disruptive potential, governments, companies, educators, students, and ordinary citizens across all disciplines need to be increasingly aware of the opportunities inherent in utilising light for sustainable development, Green Deal economic growth and for the benefit of humankind.

Although important results have been achieved during Horizon 2020, and several successful projects have increased the general awareness of the pervasiveness of Photonics and its potential impact as a driver for digital innovation, industrial competitiveness, technological sovereignty, economic growth, and citizens' well-being, there is plenty of work still to be done.

Attracting the next generation to STEM disciplines, and in particular to Photonics, as well as encouraging students who are completing their studies to continue their professional development in Photonics (both in academia and in industry), are crucial challenges. Retaining these young minds needs not only focused but also sustained efforts and innovative approaches.

A knowledge-based society with high-tech industries requires a skilled workforce. Adequate and specific curricula at all levels of education and lifelong learning programs are the basis for future knowledge creation, technological sovereignty, and industrial competitiveness.

Photonics education and exploitation should not be confined to science and technology. Indeed, light and light-based technologies offer incredible opportunities in social sciences, art and humanities, with a great impact on everyday life. The need to approach different and unexplored areas of applications requires, on one hand, the exploitation of available good practice and existing instruments, and on the other, the development of new languages and schemes.

Many photonic technologies and their applications are mature. They enable design, realisation and market exploitation of many innovative products that tackle the major societal challenges that we are facing. They have a considerable leveraging effect on economic growth in many fields. However, new areas are still to be explored, new knowledge to be created, existing technologies need to be developed further and new challenges should be addressed. Disruptive fundamental and applied research will be the basis for future technological development that will allow us to answer problems that today seem to be without any possible solution.

Strong and continuous cooperation between academia and industry has characterised advances in photonics over the past years and has proven to be a successful strategy. The capability of sharing the research agenda and priorities will be the key to future success. Indeed, there are many disruptive ideas that photonics can realise and new fields that it can explore. The creation of photonics innovation hubs to implement the full value chain – from knowledge creation to market exploitation through education, research and innovation – will allow us to maintain and strengthen the European competitiveness and leadership in photonics and photonics-enabled technologies. The impact of Photonics will be critical in creating new jobs.

Major photonics research & innovation and education & training challenges

Major photonics research & innovation challenges

Disruptive research has proven to play a major role in supporting long term innovation. Topics that have seen breakthroughs, and likely to have a major impact in the future, can be divided into three areas:

- the capability of both extending the functionalities and customising optical components through new materials and new design and fabrication techniques (for example, 2D-materials, nonlinear materials, Micro- and Nano-engineered materials, freeform optics, adaptive optics, laser-based advanced manufacturing and material processing);
- the use of extended light characteristics (wider wavelength range from X-rays to THz and beyond, extremely high or low powers, ultrashort laser pulses down to a few optical cycles) and the exploration of radiation-matter interaction in extreme conditions;
- the use of new approaches, typically moving from classical interactions to quantum-based processes in light generation, manipulation, and detection.

However, the main challenge is to translate the new knowledge coming from fundamental research into real innovation potential, thereby making it disruptive, which requires a two-fold approach. On one hand, it requires a change of mindset: fundamental research should no longer be considered as a standalone priority, but rather, should be directed towards the technological needs and challenges that the photonics industry – as well as industries that are enabled by or can benefit from, photonics – is facing. Research should be directed towards the application-driven missions where discoveries make the change, thus initiating and establishing the value chain.

On the other hand, there is the need to create a suitable ecosystem that allows new ideas to be feasibly tested and brought to a TRL level of interest for further research to be taken up by industry. To achieve this aim, a network of flexible and versatile facilities – to be integrated into Photonics Innovation Hubs and databases – should be established across Europe, thus closing the value chain.

Ideally, building on existing excellence and nodes, Photonics Innovation Hubs should be realised covering the whole value chain, from disruptive research and low TRL facilities, through SME incubators to pilot lines for pre-commercial exploitation. Education and training programs, together with the suitable facilities, should be an important part of the Hubs for each country and its communities.

Major photonics education & training challenges

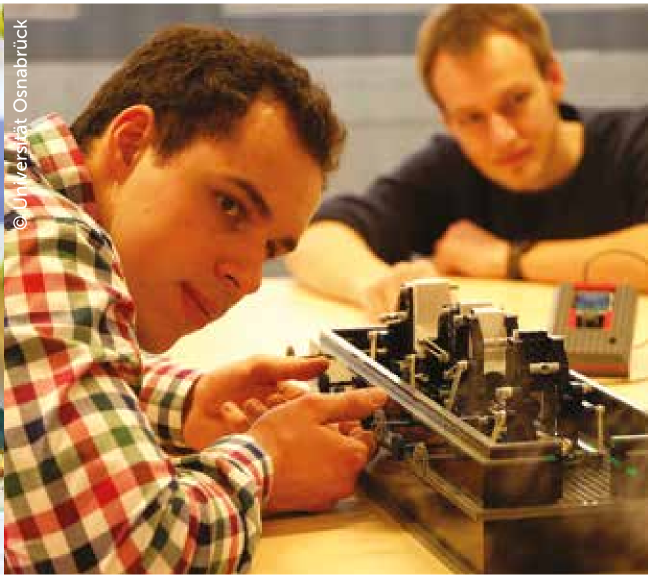
Photonics needs to become a pervasive discipline at all levels of education and professional training: it has to be brought to the attention of the whole population and that of policymakers through correct information and communication. Indeed, awareness and skills are vital for the successful exploitation of the great potential of Photonics technologies in a digital society. Suitable communication, educational instruments and content should be developed depending on the target population.

New challenges ahead

The skills for a future photonics workforce have to be defined and appropriate training must be given. Action must be taken at different levels with a Pan-European approach:

- academic and vocational training in photonics must be a priority both in STEM curricula and in other educational fields addressing Higher Education (HE) and Vocational Education and Professional Training (VET) alike;

Left: Encouraging young students to study photonics is important to drive the digital revolution of Europe.



Above left: The early fascination for photonics technologies and related experiments leads to a bright future for Europe.

Above right: Photonics experiments with the lego laser demonstrate the fascination for light among students.

- skills development and implementation with a European focus, ensuring a roll-out of the necessary training, both at HE or VET level, at national and regional levels;
- development of International Qualifications in Photonics, supported by a Quality Assurance System to ensure the quality of the delivered training;
- mobility of students and workforce have to be stimulated, since the required skillset is highly specialised, with educational and industrial needs not often aligned geographically.
- lifelong learning programs should be set-up by academia and VET, but ensuring a connection between training, Research and Technological Development (RTD) and industry, to target industry needs, mainly in the case of SMEs, since they often lack internal resources for training: the need for photonics programs suitable for companies that are non-specialists that may benefit from the uptake of photonics technologies should be targeted;
- digital skills should be part of all programs to allow full exploitation of photonics potential in digital innovation;
- entrepreneurial and innovation mindsets should be stimulated to maximise the impact of newly discovered technologies;
- the need for an interdisciplinary cross-KET approach should be adequately addressed and valued, for example, by enhancing the visibility of photonics in related curricula, such as chemistry, electrical engineering and biomedical engineering.

Outreach towards young minds and students, non-photonics professionals and the general public needs to capitalise on the successful programs set in place during Horizon 2020 and scale-up to a Pan-European dimension. Adequate infrastructures should be realised, best-practice should be shared, and educational and training material should be continuously upgraded and disseminated. To enable this in a sustainable way it is necessary to establish a Pan-European network of institutions specifically devoted to photonics outreach to all areas of society, including students, citizens and industry.

A further key challenge is to actively reach out to digital industry initiatives in support of digitisation of photonics (and non-photonics) SMEs; the contribution of Photonics to the digital transformation of traditional jobs should be validated appropriately.

"Photonics is at the very core of many new emerging disciplines and an integral technology to developments such as artificial intelligence, robotics and quantum technologies."

Cooperation needs with other disciplines or fields

Photonics is a Key Enabling Technology and a science that can foster innovation in a future digital society that supports sustainable development for both a better, safer society and for the well-being of our citizens. It needs to cooperate with other disciplines and fields, in particular with other previously established KETs, namely, micro-and nanoelectronics, advanced materials, advanced manufacturing, nanotechnology, and biotechnology.

Photonics is at the very core of many new emerging disciplines and an integral technology to developments such as artificial intelligence, robotics and quantum technologies. Indeed, only combining the disruptive potential of all these disciplines, breakthroughs can be achieved and all challenges can be fully addressed. Cross-discipline work programs and actions should be foreseen to foster transversal knowledge creation and effective cooperation. Strengthening links with excellent science and education programs (ERC and MSCA actions) and FET-Flagship actions to favour the transfer of new, potentially disruptive ideas into the technological value chain is vital to any future developments.

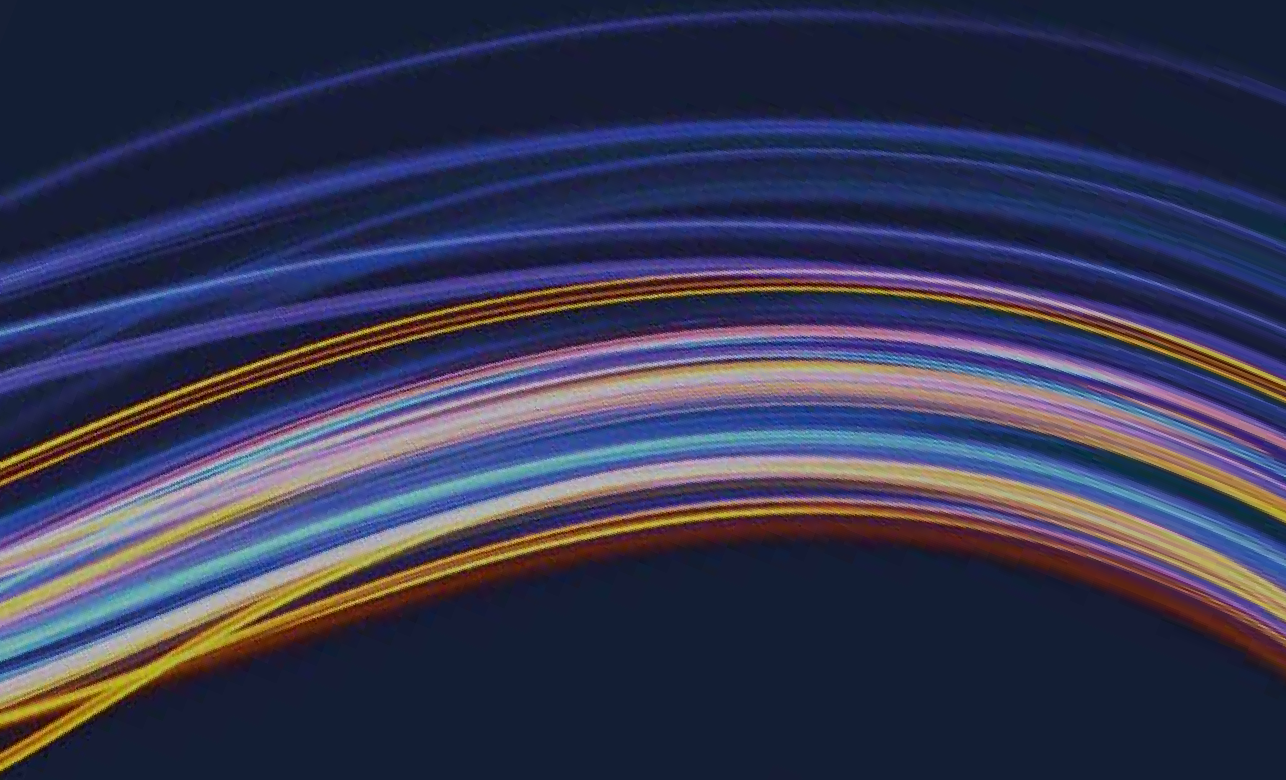
A strong partnership should be created with the stakeholders and policymakers setting the priorities for societal challenges. Indeed, focusing on specific medium to long-term targets and mega market trends will foster real innovation, and stimulate the development of new technologies and products.

Beyond the target applications where photonics has traditionally exhibited a major role (ICT, industrial production, life science, lighting), new emerging fields have to be approached such as automotive and connected mobility, agrifood, clean and sustainable environment, cultural heritage preservation and fruition, smart homes, high-quality urban life and circular economy. Such a broad approach will help to direct technology developments and maximise their overall impact, thus fostering optimal exploitation of a cross-KET approach.

3.8 Photonics Research, Education & Training

Proposed roadmap for 2021–2027

	2021	2022/2023	2024/2025	2026/2027
Overview **(Technology) Challenges**	Define skills for a future workforce and create the future European photonics workforce Outreach towards young minds and students, photonics and non-photonics professionals and the general public. Ensuring at the same time that reskilling and upskilling of the existing workforce is also addressed.	Develop new approaches to Education & Training at the European level Take up disruptive research in the Photonics Innovation Hubs and across the value chain Support the creation of Photonics innovation hubs Support the creation of a network of European training providers, supported by a European Framework, in Photonics	Actively reach out to digital industry initiatives in support of digitisation of photonics (and non-photonics) SMEs	Valorise the contribution of Photonics to the digital transformation of traditional jobs
Critical milestones to move from Science to Market	Create alliances with excellent science and education programs (ERC, MSCA, FET-Flagship) on one side and with programs focusing on applications and societal challenges Identify favourable and unfavourable conditions in terms of awareness and presence of Photonics hotspots	Act at the level of all policymakers to raise awareness and understanding of the potential highly positive impact of Photonics Connect isolated Regions to Photonics hotspots Expand the role of Photonics in STEM and social sciences/humanities education and training programs	Bring Photonics technologies as key enablers in non-photonics Innovation Hubs	Expand the presence and role of Photonics in all products and technologies for the digital society
Photonics **Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges**	R&I: Develop new knowledge through strong cooperation between academia and industry at lower TRLs E&T: team-up with industry for better tailored E&T programs, including life-long learning E&T: set up a pan-European network of institutions committed to outreach that makes possible sustained efforts to nurture future European workforce, promotes entrepreneurship and reaches new industry sectors	Identify the disruptive research nodes and integrate them into the value chain for R&I and in the E&T programs E&T: Train researchers towards an entrepreneurial mindset Develop innovative platforms and tools for teaching and training Continue to strengthen the presence of Photonics technologies in the FabLabs	R&I: Increase the number of flexible facilities for closing the gap between new knowledge creation and industrial research Increase the number of pilot lines E&T: expand the use of photonics instruments and platforms in non-photonics E&T programs; Set-up new initiatives and structures, and team-up with the existing ones, to bring photonics to the citizens and the citizens to photonics	R&I: Expand the role of Photonics in SMEs' incubators E&T: Set-up specific actions to widen the audience for photonics and strengthen the impact on adults Team-up with Science & Technology Museums for the uptake of Photonics as flagship science
Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)	Identify high-impact fields and applications where new knowledge in Photonics is more likely to give future breakthroughs Set-up interdisciplinary E&T programs including Photonics as a flagship science for digital innovation Team-up with experts in education and communication to include new instruments and approaches in Photonics E&T programs (e.g. gamification, Virtual Reality and Digital training, apprenticeships, work-based training)	Create photonics-based tools and platforms with an interdisciplinary approach: on one side team-up with traditional KETs for multi-purpose tools and platforms, on the other side approach new emerging disciplines (e.g. Artificial Intelligence) and fields (e.g. Robotics) to evidence the potential of Photonics to expand functionalities	Set-up a pan-European network of flexible facilities and infrastructures for the fabrication and characterisation of low TRL demonstrators based on a multidisciplinary approach and combining different enabling technologies	Set-up a pan-European network of pilot lines combining different enabling technologies for a more efficient approach to the development of innovative products and systems for new markets and new societal needs



For Europe's key industries to remain competitive in the global marketplace, they need to upgrade their products and services with digital technologies like photonics much faster than previous attempts.

Strategic Research and Innovation Agenda

4. Additional activities

Next to the research and innovation activities as outlined in the previous chapters, the private partner of the new European Partnership for Photonics will also commit to undertaking the following additional activities and investments:

'Additional activities' planned in the *Additional Activities Plan* and agreed by the Governing Board, within the scope of the Strategic Research and Innovation Agenda are necessary to achieve the objectives of the European Partnership. The Additional Activities Plan may also include actions related to mobility, skills, communication and dissemination, or early consideration of relevant standardisation, regulatory and certification issues. The additional activities also include exploring funding sources in addition to Horizon Europe to help a European Partnership achieve its objectives.

For Europe's key industries to remain competitive in the global marketplace, they need to upgrade their products and services with digital technologies like photonics much faster than previous attempts. The European Partnership for Photonics will seek access to these end-user industry communities and jointly develop 'photonics enabled' industry strategies and roadmaps. In contrast to the 'core photonics technology platform roadmaps' (technology push), the end-user roadmaps will follow the needs of end-user markets and societal challenges (market pull). This fundamentally new approach will lead to the establishment of new strategic value chains between Photonics and end-user industries in Europe that will guarantee Europe's sovereignty in the development and manufacturing of strategically relevant digital products. Cooperation agreements with end-user community stakeholder associations are currently being prepared. Roadmaps could cover topics like Photonics4 Medical Diagnostics, Photonics4 Digital Manufacturing, Photonics4 Space and Photonics4 Smart Green Farming, for example. The 'photonics enabled' end-user industry technology roadmaps will contain information pertaining to the market Technology Readiness Levels from 5-8.

Additionally, the European Partnership for Photonics will launch a series of workshops at a regional level called 'Photonics4 - ...' addressing different regionally relevant end-user sectors. These workshops will bring together photonics technology providers and end-user companies to trigger concrete business-to-business or research-to-business collaborations on a short-term basis.

The European Partnership for Photonics will cooperate with the National and Regional Advisory Group composed of relevant public authorities for preparing joint calls between member states and associated states. It will make sure that the member state representation in the National and Regional Advisory Group will grow from its current level of seven to twelve member states and that joint calls with a funding volume of at least ten million Euros will be initiated. The partnership will also create a platform for photonics regions to network, discuss and agree on joint cross-regional investment projects. Photonics21 will also serve as a secretariat for the regions, such as regional ministries, to prepare for joint activities and make the link to the European Photonics Partnership. This way, dedicated funding activities by the European Partnership (for example, Pilot Lines) can be closely coordinated with the regions. Furthermore, Photonics21 will promote the 'EU Interregional Innovation Investment Instrument' (currently prepared as part of the next multiannual financial framework 2021-27) to the regional authorities to commence joint activities. A 'Thematic Photonics Platform' has already been established under the Smart Specialisation Platform of the EU Commission[100], in which seventeen regions are currently participating.

In terms of communication, the partnership will establish the central communication platform and switchboard on Photonics Research and Innovation in Europe. This includes the broad communication about Horizon Europe Photonics Partnership project achievements towards the end-user industry as well as photonic-related stories in opinion-forming media.

Towards the photonics community, the partnership will provide all information about the strategy development approach, processes, decision making to ensure a broad, open and transparent strategy development and implementation process via the website, regular newsletters, and communications via Twitter and LinkedIn. Furthermore, information about financing opportunities provided by the European Investment Bank and the European Photonics Venture Forum and Entrepreneurship contests will be circulated to the community via newsletter, webinars and workshops. To increase the deployment of photonics in end-user industry and to start a new collaboration, the partnership will provide a central public relations service to the Horizon Europe Photonics Partnership projects helping them to communicate about the impact of the projects to the end-user industry. In coordination with the project coordinator and the Photonics Unit of the European Commission, the partnership will issue press releases, contact media and follow up on press coverage. The focus will be on those projects that have the highest impact and offer the highest chances of success to be taken up by end-user trade media or international media. Articles about successful photonics projects have been published by the project and featured in top-class international media such as global Tier-1 National and International media operating throughout Europe. Finally, the partnership will educate and advocate for photonics and the way it contributes to

[100] https://s3platform.jrc.ec.europa.eu/photonics

solving societal challenges like tackling the green deal, digitising European industry or safe food from farm to fork towards the political level with a focus on the European Parliament and member state national authorities. A specific communication action will be started towards venture capital investors by issuing and distributing "Photonics Investment Reports" on major markets like Smart Farming, Industry 4.0 or alike to promote photonics as a high-value investment area. All information will be widely communicated as soon as they are available from the start of the project to the respective target groups.

For a comprehensive industrial strategy, skill shortages need to be addressed, as competition for talent is fierce in high-growth technology sectors like photonics. To raise awareness for photonics as a key enabling technology for innovation across diverse application areas, and to support the skills supply in Europe, the partnership will create a networking platform for sharing best practices on educational and training materials as well as educational courses for school children in photonics.

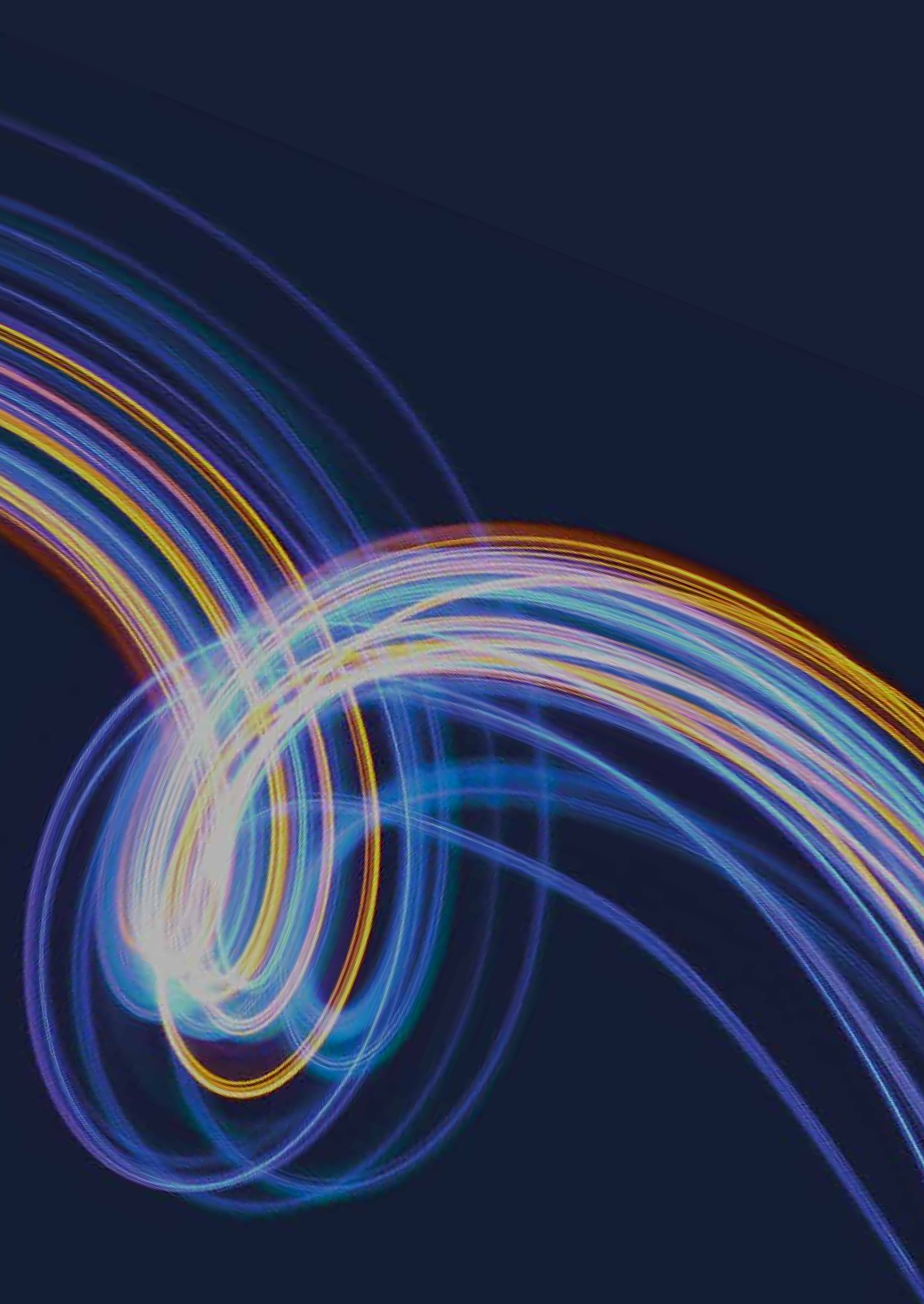
The platform will leverage the extensive materials and activities that exist today across the consortium and our partners and will address the missing activity - the sharing of best practise and knowledge. This will have two elements: first the sharing of materials that are created across European and national projects, to ensure that there is a continuous evolution of these resources. At the same time, the network of outreach officers will discuss best practise for the accessibility of the material on the platform. These will be published on a website, along with their associated materials, such as feedback forms, in a categorised structure to make the material easily accessible. Second, the partnership will build a network for individuals who co-ordinate photonics-focused outreach activities across Europe and organise five webinars or workshops where they can share best practise and training for those who wish to participate in outreach and co-ordinate cross-European activities such as the International Day of Light. This group will also provide input to the materials catalogue and feedback on website accessibility and hereby help to develop training.

4. Additional activities

Area of Activity / Investment Area	**Activities (high level scoping exercise)**	2021		2022		2023		2024		2025		2026		2027	
		HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY
Broaden Stakeholder Basis / Committment	Organize for an effective Photonics21 membership management under the light of broadening stakeholder basis														
Broaden Stakeholder Basis / Cross Cutting Acitivites / Community / Ecosystem	Photonics21 work group workshops with members, 6 application work groups and 1 core photonics work group														
Broaden Stakeholder Basis / Cross Cutting Acitivites / Community / Ecosystem	Joint workshops with external stakeholders such as other partnerships in relevant thematic areas														
Broaden Stakeholder Basis / Cross Cutting Acitivites / Community / Ecosystem	Matchmaking activities such as the organisation of webinars and workshop to facilitate matchmaking														
Broaden Stakeholder Basis / Cross Cutting Acitivites / Community / Ecosystem	Systematically coordinate / seek collaboration activities with other communities and partnerships														
Broaden Stakeholder Basis / enlarge Strategic Value Chains / Knowledge Sharing / Ecosystem	Prepare strategic photonics technology enabled value chain road-maps with strategic value chain partners														
Broaden Stakeholder Basis / enlarge Strategic Value Chains / Knowledge Sharing / Ecosystem	Photonics-related and photonics value chain related webinars with various targets groups such as investors, reserachers, end-users														
Financing Growth / Provide Risk Capital	Prepare and distribute Photonics and Photonics related strategic value chains investment papers	x						x				x			
Foster Growth and Research Excellence / Research and Innovation	Trigger co-investment (ind. pilots and demonstrators) activities between EU member states and regions incl. associated states														
Foster SMEs and Entrepreneurship	Facilitating access to growth financing for photonics SMEs and Start-ups: Running dedicated photonics financing boot camps with the European Investment Bank														
Impact / Research Excellence / Research and Innovation	Strengthen entrepreneurship in photonics and strategic value chain innovations by awards, investment opportunities together with VCs, EIB, Business Angels and national agencies														
Impact / Research Excellence / Research and Innovation	Collaboration with end-user communities on the various regional,national, European and international level to secure synergy utiliziation and deployment of future oriented EU photonics technologies in strategic value chains														
Impact / Research Excellence / Research and Innovation	Collaboration with other Partnerships on research and innovation topics (alignment, synergies, etc)														
Impact / Research Excellence / Research and Innovation	Provide strategic value chain research and innovation priorities as input to Horizon Europe work programmes														
Impact / Research Excellence / Research and Innovation	Provide input to research and innovation policies by each strategic value chain and application work group (ie. position papers)														
Impact / Time to Market / Strategic Value Chains	Fostering founding and promotion of utilizing European photonics pilot lines for strategic value chains														
Impact / Time to Market / Strategic Value Chains	Promote access to (blended) innovation financing for photonics start-ups and SMEs – Establishing a strategic partnership with the European Innovation Council														

4. Additional activities

Area of Activity / Investment Area	Activities (high level scoping exercise)	2021		2022		2023		2024		2025		2026		2027	
		HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY	HY
Monitoring	Activity and Progress monitoring report of the Photonics Partnership – plus mid-term and final report	X		X		X		XX	XX	X		X		XX	XX
Monitoring and Market update	Development and publication of global and European photonics market studies and value chain analysis	X						X							X
Monitoring and Market update	Specific activities to support photonics start-ups such as a European photonics start-up radar and the support of the European Photonics Venture Forum														
Research Excellence / Education and Life-long learning	Raise the awareness for photonics as key enabling technolgy for its strategic value chains and ensure the skills supply in Europe, create a networking platform for sharing best practice on educational and training material and educational courses for school children in photonics														
Strategic Value Chains / Cross Cutting Budgeting and Committment	Engage with regional authorities to trigger cross regional / national photonics and photonics strategic value chain related investment initiatives and networks														
Strategic Value Chains / Cross Cutting Budgeting and Committment	Cooperation activities to align with national, regional and photonics/photonics strategic value chain related roadmaps														
Strategy development and Goverment	Consultations with partners and other programs to prepare for 2-page terms sheets for MoU														
Strategy development and Goverment	Work Group Meetings (A-WGs and Core WGs): Coordinate and steer Horizon Europe photonics partnership projects	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strategy development and Goverment	Core Programme Steering Board Meetings to coordinate cross cutting and synergy using strategic value chain activities		X		X		X		X		X		X		X
Strategy development and Goverment	Association Board / Partnership Board Meetings	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strategy development and Goverment	Executive Board Meetings	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strategy development and Goverment	Board of Stakeholder and Executive Board meetings	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Strategy development and Goverment	General Assembly meetings	X		X		X		X		X		X		X	
Visibility / Communication / Community / Ecosystem	Develop a European Photonics Communication Strategy / (definition, implementation and updates) in close cooperation with strategic value chain partners														
Visibility / Communication / Community / Ecosystem	Regular update the photonics communication channels (such as website, social media, newsletter, etc.)														
Visibility / Communication / Community / Ecosystem	Generate interesting European Photonics Partnership related and funded project news releases for b2b and corporate messages														
Visibility / Communication / Community / Ecosystem	Develop and conduct European photonics events in the form of online meetings, hybrid events or physical events when the overall situations allows														
Visibility / Communication / Community / Ecosystem	Develop and foster National/local photonics communication activities by project partners such as the organisation of thematic Photonics4 end-user workshops														
Visibility / Communication / Community / Ecosystem	Organisation of Photonics Partnership specific events such as the Photonics Partnership Annual Meeting, webinars, etc.														



5. Appendix

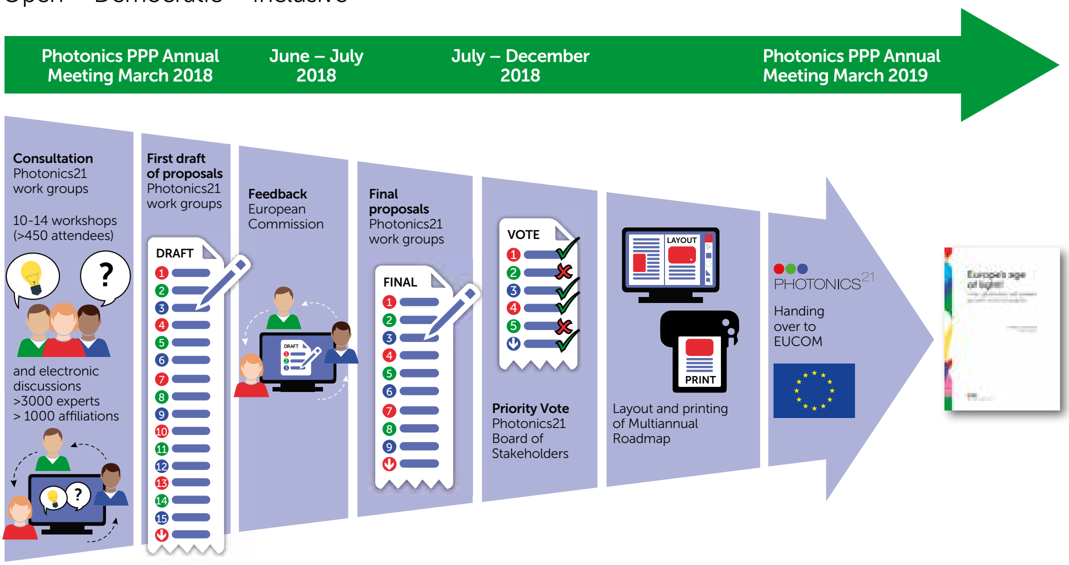
The Photonics Strategic Roadmap 2021-2027 was developed and adopted by the members of the European Technology Platform Photonics21, which represents the photonics community in Europe. The launch of the photonics roadmapping process took place alongside the Photonics PPP Annual Meeting 2018 on 8th and 9th March 2018 in Brussels. The process continued throughout the year through additional workshops and feedback consultation among the Photonics21 workgroups, as well as an open consultation on the Photonics21 website. The final photonics roadmap was published in March 2019. An update of the Photonics Strategic Research and Innovation Agenda was prepared in the course of 2020, the updated version was published in November 2020.

Each Photonics21 work group provided a dedicated section to this document outlining their roadmap for future photonics research and innovation challenges in the different application fields.

More than 300 photonics experts from all over Europe have discussed and selected the future photonics research and innovation challenges during the eight workshops alongside the Photonics PPP Annual Meeting 2018. Four additional Photonics21 follow-up workshops with photonics experts as well as representatives of the end-user industry took place between June and September 2018 to elaborate and finalize the roadmap.

Photonics21 Agenda Process towards FP9

Open – Democratic – Inclusive



Above: Overview on the Photonics Roadmap Process © Photonics21

Roadmap Process Communication

The Photonics21 Secretariat performed the planning and coordination of the European photonics roadmap process towards *Horizon Europe* and was responsible for the workshop preparation in cooperation with the Photonics21 work group chairs.

Through the Photonics21 newsletter, the Photonics21 website **www.photonics21.org** and the Photonics21 twitter account **https://twitter.com/Photonics21** the Photonics21 secretariat communicated all aspects of the photonics roadmap process and provided workshop information to the European photonics community.

Interactive Workshops and Roadmapping Process

Each Photonics21 workshop operated democratically and interactively, with the participants invited to provide their input and views. These were then discussed with all workshop participants to conclude with the respective photonics research and innovation challenges.

Prior to the current workshop arrangement, the Photonics21 secretariat was responsible for both the preparation and the workshop concept, coordinating the latter with the Photonics21 work group and work area chairs.

The first workshops in March 2018 started with a short review on the identified roadmap 2014 – 2020. Following this, the participants were asked to identify the most critical three missions for their respective workgroup as outlined in the Photonics21 vision document *Europe's Age of Light! How photonics will power growth and innovation*.

Having identified the most relevant missions, the participants were asked to develop sub-mission/targets for their chosen themes. The workshop participants were then asked to identify relevant photonic R&I challenges to reach the defined sub-missions and objectives. Finally, the workshop participants were tasked with identifying boundary conditions and additional measures needed for market success in 2030.

The collected workshop input was taken into consideration for the subsequent editing of the respective thematic chapters of the photonics roadmap.

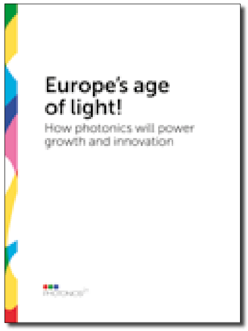
Writing the Photonics Roadmap

Following the Photonics21 workshops, each workgroup chair set up an editorial team that was responsible for providing a first draft of the specific roadmap chapter. These draft chapters were then circulated to the individual Photonics21 work group members for further comments and feedback.

Additionally, the Photonics21 secretariat uploaded all relevant materials for the photonics roadmap process onto the members' area on the Photonics21 website. This area is accessible to all Photonics21 members, thereby ensuring an open, transparent and democratic process for defining the new photonics roadmap.

The development of the photonics roadmap was based on the Photonics21 vision document *Europe's Age of Light! How photonics will power growth and innovation* which outlines eight missions, to which photonics will provide, bespoke solutions in the future.

The Photonics Strategic Multiannual Roadmap builds on this document to identify research and innovation challenges for the coming years. It will serve as the strategic reference document for defining the photonics research and innovation priorities for the new Framework Programme, *Horizon Europe*.



Above: Photonics21 publication Europe's age of light! How photonics will power growth and innovation in preparation for Horizon Europe. © Photonics21.

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