# Europe's age of light!

## How photonics will power growth and innovation

Strategic Roadmap
2021–2027

PHOTONICS21

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# Europe's age of light!

## How photonics will power growth and innovation

Strategic Roadmap 2021–2027

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# Contents

# Preface

Light technologies are the key enabler for societal megatrends like digitalization, IoT, big data, artificial intelligence and autonomous transportation. Photonics provides vital components to medical technologies for the instant diagnosis of major diseases and will be essential during the digital transformation and Industry 4.0.

While the global photonics market has reached €600 billion, we estimate that only 20% of the potential power and benefits of light technologies have been unlocked. During the next transition towards digitisation, it is clear that photonic technologies are essential and with further development, we are taking steps towards realising our vision of 'Europe's Age of Light'.

This Multiannual Strategic Roadmap is an essential strategy for European photonics that we have mapped out collaboratively for our journey forward. The roadmap is the next development from the 2018 Vision Paper "Europe's Age of Light", in which more than 3000 members from over 1700 companies in our Photonics21 expert community were consulted. The result is a Photonics Roadmap that is collective, democratic and robust.

In Europe, our acknowledgement of light technologies, and our belief that they will be at the very heart of the digital transformation are so profound that we have already deemed them a Key Enabling Technology. In the recent European Commission and European Investment Bank report on "Financing the Digital Transformation" (2018)[1], photonics technologies are regarded as "one of these essential key enabling building blocks for the digital transformation of Europe".

The European coordination of photonics is exemplary: the Horizon2020 Photonics Public-Private Partnership (PPP) was created to build on the strengths of the European photonics sector and by that reinforce the competitiveness of the European industry. For this purpose, the European Commission joined forces with the photonics industry, represented by Photonics21, and the research community. The result has been a dynamic and productive partnership which has been recognised as the best PPP in Horizon2020 by the Commission's independent evaluators and demonstrated by the PPP's impact on jobs and growth in Europe.

About five thousand European photonics companies and organisations currently hold second place in the world market thanks to the innovation and successful product and application development.

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[1] 2018 European Commission and European Investment Bank report on "Financing the digital transformation: Unlocking the value of photonics and microelectronics", which states that". ..the Photonics sector is an essential key enabling technology and represents an important building block of the next digital revolution, which will be based on deep technologies."

This competitive position was reached in part by the collective efforts of politics, science and industry and the successful networking across Europe.

We are committed to the Horizon Europe Programme and will carry out the digital transformation in close cooperation with other key technologies, end-user industries, scientists and in close contact with citizens and politicians.

In writing this Multiannual Strategic Roadmap, we must acknowledge the European photonics community for their active contribution, for their tireless work as well as their unique and innovative ideas that are shaping the future. Our special thanks go to the European Commission for their support of this photonics strategy process.

Giorgio Anania and Bernd Schulte
Photonics21 Vice-Presidents and spokesmen

# Executive Summary

Photonics technologies are indispensable for powering the future European digital economy and will underpin as yet undiscovered advances in many other sectors such as health, space, mobility and security.[2]

An essential Key Enabling Technology, photonics is a crucial "building block of the next digital revolution"[3] that will happen in Europe in the next few years. Specifically, light technologies will provide the necessary "tools and solutions to every industry in every region in Europe that takes up the challenge to become more competitive"[4].

This Strategic Roadmap outlines the challenges that will be addressed in the new European research and innovation framework programme, FP9 or 'Horizon Europe', to strengthen the digital transformation while simultaneously increasing the well-being and quality of life of European citizens.

Today, the European Photonics industry, comprised of mainly SMEs, is fast-growing and thriving: there are an estimated 5000 companies that have created more than 300,000 highly skilled jobs in this sector alone with an annual turnover in excess of €60 billion. With a compound annual growth rate (CAGR) of 6.2%[5], the European photonics industry is growing four times faster than the European GDP.

Europe is one of the leading players in the global photonics market, ranking only second to China. With strong growth forecast, the photonics market is projected to grow at a CAGR of 8.4%[6] leading up to 2022. This strong position underlines the continuing economic potential of light technologies[7] for the future. Photonics technologies are key enablers for future mega-markets such as Internet of Things (IoT), cybersecurity, quantum technologies, healthcare and additive manufacturing among others.

In the future, with new light technologies entering the market, photonics will increasingly impact all areas of our lives and become ubiquitous: from photonic sensors in wearable devices monitoring our health and in self-driving cars observing their surroundings to LED lighting that acts as a secure communication hub for our wireless devices just to name a few.

In preparation for FP9, the Photonics21 platform developed the new strategy for European photonics and all its associated end-user industries. Responding to the changes in needs and challenges in both the photonics sector and the European priorities, Photonics21 recognised that some technologies matured while new areas are evolving.

Building on the successful, proven, collaborative approach, Photonics21 consulted with its stakeholders, which included over 1,700 companies and research organisations across Europe. In a series of 12 workshops,

***"Europe is one of the leading players in the global photonics market, ranking only second to China."***

*"Highly integrated, accurate and fast photonic sensors with multi-sensor data fusion are the sense organs of the digital society."*

the photonics community developed this Strategic Multiannual Roadmap. In total, our experts established eight thematic roadmaps which are summarised below:

In **information and communication**, a new programmable optical infrastructure will be the 'central nervous system' upon which the digital society, industry and European economy will heavily rely. Photonics communication technologies are the optical lifelines of our modern society and economy, transporting data at an ultrafast pace in millions of extended fibre-optic networks around the globe in every home.

Highly integrated, accurate and fast photonic sensors with multi-sensor data fusion are the sense organs of the digital society. These light-based technologies, therefore, feed new Artificial Intelligence algorithms to enable autonomous driving, smart cities, industry 4.0 as well as a comprehensive understanding of our climate or breakthroughs in medicine and healthcare.

However, a formidable research challenge for the next decade for light technologies in this information and communication sector will be delivering the required performance, resilience and cybersecurity, while satisfying cost, energy efficiency and technological constraints.

The thematic roadmap associated with **industrial manufacturing and quality** addresses the industry 4.0 challenges by planning for a future where a fully digital value chain, from supplier to customer, will introduce new forms of collaboration, customisation, new services and new business models – all of which will strengthen Europe's industrial base. New laser systems and the integrated use of sensor technologies for parameter monitoring will be at the heart of completely digital and connected value chains, allowing companies to move quickly between mass production of identical parts and the manufacture of individualised products.

Significant challenges for Europeans in **life sciences and health** are the ageing society and the related increase of age-related diseases as well as the increasing costs of the healthcare system. The development of mobile, wearable photonic devices (combined with advanced biosensors for instant point-of-care diagnostics and treatment which measure the wearer's medical condition and wellness) will contribute to early diagnosis and subsequent intervention, to reduce healthcare cost and improve well-being.

Affordable photonic-based real-time diagnostics to classify disease status, and to monitor and assess treatment responses will open doors to the practical implementation of precision medicine, improving the effectiveness of treatments. Future light-based developments may help to search for new biomarkers and develop promising treatments for currently incurable diseases, as well as a greater understanding of brain functions.

New technologies in **lighting, electronics and displays** will be the "intelligent backbone" of the Internet of Things (IoT) and enable information and communication technologies to become pervasive and ubiquitous. Micro-Displays in glasses and even contact lenses will offer personalised information via augmented reality, making complex work more accessible. Classical navigation and information systems will be replaced by information which can take into account the preferences and habits of every individual. Lighting, electronics and displays will also play a crucial role when coping with future challenges related to energy efficiency, well-being and food security.

Monitoring the occupation of buildings and the subsequent switching-off of heating, lighting and electrical devices in unoccupied areas through sensor-based lighting control could significantly reduce energy consumption. Such systems will be omnipresent in new buildings and used for retrofitting existing buildings. Developing human-centric lighting that improves our well-being and reduces accidents will become a standard feature in private and public spaces. In farming, the use of artificial light specifically tuned to enhance plant growth combined with light-based sensorics will be essential to increase yields and food quality mainly, for urban farming where space and light are at a premium.

The Internet of Things (IoT) revolution, where machines will sense, operate, decide and communicate without our intervention is transforming our society. With a significant cost of the IoT systems relating to sensor subsystems, the photonics **security, metrology and sensors** community is at the heart of this transformation. Since an increasing number of sensors will need to integrate with the IoT, the future of "embedded photonics" in IoT, smartphones, tablets and other industrial products will be carefully examined.

Underpinning all of the previous areas is the **design and manufacturing of optical components and systems**. While many components and systems need to be tackled, one technology that provides key benefits across all areas is the development of photonic integrated circuits and devices. Success in this area will lead to reduced cost and size, and improved robustness of photonics systems. New, enhanced photonic integrated circuits will enable the full deployment of photonics technologies across many sectors and will play an essential role in the European digital transformation. Demand for integrated photonic devices also comes from the emerging field of quantum technologies, specifically quantum computation and communication, suggesting an urgent need to develop both technologies in parallel.

An important area for the future of photonics is the **education and training** of the next generation of professionals. They will need to be provided with the necessary skills to successfully and innovatively exploit the great potentials that photonics technologies have to offer. In the future, innovative approaches will be needed to attract students towards STEM disciplines and photonics studies. Disruptive fundamental and applied research will continue to be the basis for future technological development that will allow us to tackle problems that currently appear unsolvable. Similarly, the active cooperation between academia and industry needs to continue, which in the past has successfully translated many photonics-based research outputs into the market place and has been a very successful strategy.

Owing to the increased deployment of photonics technologies in the **automotive and transport** sector, a thematic roadmap for this area was produced. The key light technologies that will play an important role here are photonics-based sensors, communication and lighting technologies as well as advanced human-machine interfaces. The advancement of these technologies will contribute to solving four main challenges: improved road safety, cleaner mobility, congestion-free road transport and the digitisation of the automotive industry.

The final thematic roadmap, focusing on **agriculture and food**, addresses the global challenge of food security in the light of climate change and population growth. This roadmap examines the need for food production to be economical, less wasteful and environmentally and socially sustainable. Light technologies have much to offer to this area through monitoring and measuring tools, on farms, in food processing plants and the consumer's hands. While there are already examples of photonics being deployed successfully, the biggest challenge the thematic roadmap addresses are the need to produce solutions that are low cost and easy to implement that address the specific needs of the European agri-food community.

To turn the Photonics Strategic Multiannual Roadmap into a reality more robust cooperation between the European Commission and the European photonics community will be needed. The European photonics community requests that Photonics should become a strategic priority in the new European Framework Programme, Horizon Europe.

Implementing this roadmap will strengthen the European economy and competitiveness further while the economic performance of the European photonics industry will benefit in a fiercely competitive global market. Furthermore, it will have a positive effect on future R&D investments by private organisations and will contribute to creating one million new jobs in the digital economy in Europe.

Photonics is quite simply indispensable for driving Europe's digital transformation and coping with future most essential issues in the fields of ICT, health, mobility, energy, security. The European photonics community is united, ready and determined to take up the challenges and will continue on its successful course, increasing Europe's competitiveness, well-being and quality of life.

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[2] Letter of Concern of the Nobel Prize Laureates to the European Commission, January 2019.

[3] European Investment Bank (2018): Financing the digital transformation – Unlocking the value of photonics and microelectronics, www.eib.org/en/infocentre/publications/all/financing-the-digital-transformation.htm, p.9.

[4] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): 'Europe's age of light! How photonics will power growth and innovation', Photonics21 Vision Paper, Brussels / Düsseldorf / Berlin / Frankfurt am Main, 2017, p.9.

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

[6] MarketsandMarkets: Photonics Market by Product Type (LED and Lasers, Detectors, Sensors & Imaging Devices), Application (ICT and Production Tech.), End-Use Industry (Media, Broadcasting & Telecommunication and Consumer & Business Automation) – Global Forecast to 2022, Nov 2017.

[7] European Technology Platform Photonics21: Market Research Study Photonics 2017, May 2017, p.26.

# 1. Introduction


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.


*"Almost Everything We Know About The World, We Have Learned Through Light!"* – Prof. Dr. T.W. Hänsch, Nobel Prize Winner

Photonics is an *"essential Key Enabling Technolog[y] and represent[s] [one] important building block of the next digital revolution, which will be based on deep technologies.[8]"* – European Investment Bank, 2018

## 1.1 Europe's future depends on photonics

Photonics technologies contribute significantly to the European economy. In the face of fierce global competition, continued investment in photonics is vital.

Despite being recognised as a key enabling technology and developed for some years, photonics is still a fast-evolving technology. Some industry experts estimate that we have only achieved 10-20% of its full potential[9]. Because light has many properties that can be harnessed and utilised (with some being easy, and others challenging) photonics continues to provide a rich source of technological development and exploitation opportunities, as well as providing a unique route to solving problems in many application areas.

There are two ideas that we will underline in this introduction: that the photonics sector is an essential contributor to the European economy and, that its advancement is vital to the development of other digital technologies and flagship programmes – and indispensable to European security.

**European Photonics Innovation: bold investments needed**
Photonics is a highly dynamic and fiercely competitive market valued at €447 billion in 2015, which continues to grow at an above-average rate compared to other sectors. The photonics market currently has an annual growth rate of 6.2% per year and is expected to continue. Understanding photonics' innovation potential, global economic powers are investing actively in the R&D of light technologies and the competitive advantages they can provide. A key player in this market is Europe, with its highly dynamic photonics industry which is currently "the world's innovation and market leader in many of the products and services that will power the digital economy of the 21st century"[10].

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[8] European Investment Bank (2018): Financing the digital transformation – Unlocking the value of photonics and microelectronics, www.eib.org/en/infocentre/publications/all/financing-the-digital-transformation.htm, p.9.

[9] Survey of photonics experts carried out for the creation of the European multi-annual photonics roadmap, Dec 2018.

[10] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Europe's age of light! How photonics will power growth and innovation", Photonics21 Vision Paper, Brussels / Düsseldorf / Berlin / Frankfurt am Main, 2017, p.11.

## 1.1 Europe's future depends on photonics

Today, as highlighted in figure 1, Europe is in a strong position with a global market share of 15.5%, making it the world's second largest manufacturer of photonics products after China[11]. With rapid development since 2011, most European photonics segments have displayed a growth rate way above that of the average World GDP or the average EU GDP & Industrial Production Index.

"Compared to 2011 – and despite increasing global competition as well as the devaluation of the Euro over the last years – the European Photonics core segments remained strong and could defend a leading world position up to 50% - far beyond the average EU industry share of 15.5%.[12]"

Figure 1 further highlights that the economic performance of the European photonics industry is based on a strong scientific community.

As highlighted in the Photonics PPP Impact Report 2017, "the European photonics industry grew especially strong in its already large segments like Machine Vision / Measurement and Image Processing (CAGR +5.6%), Medical Technology (CAGR +5.3%) and Production Technology (CAGR +4.7%)"[13].

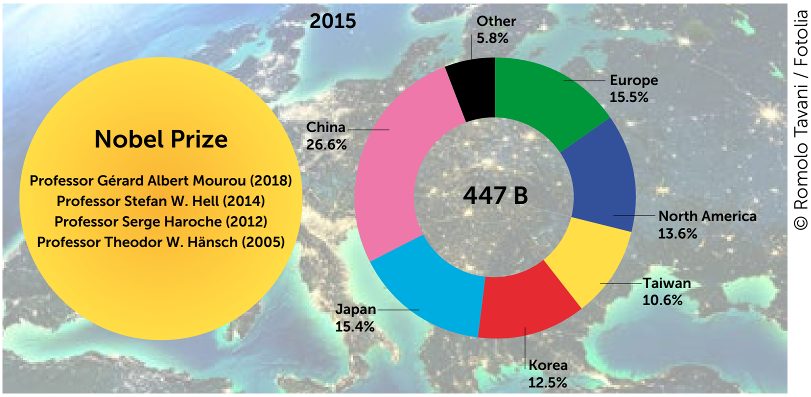


**Figure n°1:** Photonics in Europe connects both sides of the innovation process.

Cutting-edge research – global number 2 leadership position.

Source: Optech Consulting, Market Research Study Photonics 2017.

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

[12] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Jobs and Growth in Europe – Realizing the potential of Photonics, PPP Impact Report 2017, Düsseldorf, p.33–34.

[13] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Jobs and Growth in Europe – Realizing the potential of Photonics, PPP Impact Report 2017, Düsseldorf, p.33.

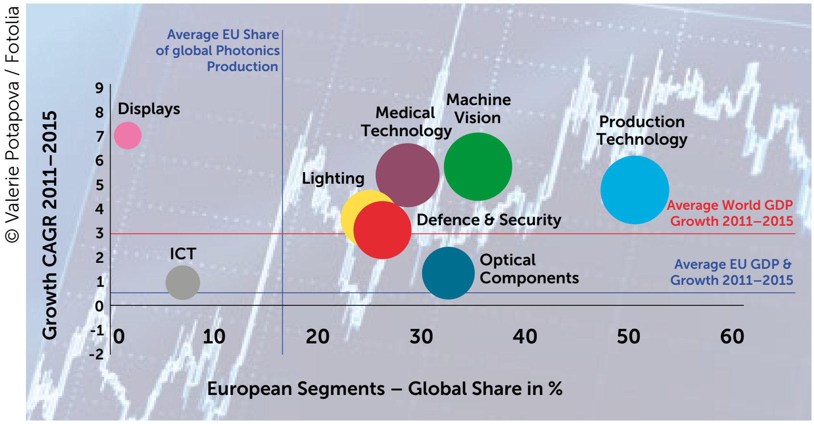


**Figure n°2:** Results of European photonics research funding: global technology and market leadership in European core segments.

Source: Optech Consulting, Market Research Study Photonics 2017

Figure 2 highlights that, today, the European Photonics industry holds high global market share in Photonics for the production technology (50%), Optical measurement & Image Processing (35%), Optical Components and Systems (32%), Photonics based Medical Technology and Life Sciences (28%), as well as in Defence and Security Photonics (26%) and Lighting (25%)[14].

China achieved market dominance through the manufacture of commodity products in high volume and at low added value, such as displays and lighting. Europe, on the other hand, is dominant in high tech sectors and high value-added products as shown in figure 2, for example exporting the laser machines that are being used in China to make the commodity products. However, there is strong evidence that China is investing in higher value technologies to compete in these markets with Europe.

**Funding Photonics: Growth, Opportunity and Prosperity**

European funding plays an essential role in ensuring that the European photonics industry continues to be competitive. Photonics funding has helped de-risk investments in innovation and unlocked significant national and private investment. Industrial photonics R&D spending matched Europe's by fourfold. Having received substantial innovation investment, Europe's photonics industry, doubled over the last ten years and now employs over 300,000 people directly in more than 5,000 photonics companies and organisations, which are mainly comprised of SMEs. Those jobs are, on average, highly skilled and very well paid. How much the European investment in photonics has contributed to its economy is given in the "*European photonics at a*

[14] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Jobs and Growth in Europe – Realizing the potential of Photonics, PPP Impact Report 2017, Düsseldorf, p.33–34.

## Europe is the world's 2nd largest producer of photonics products

European photonics at a glance.

### Investment

Nearly **€10 billion** – In 2015 European Photonics Industry pledged €9.6Bn to Innovation (R&D spending and Capex)

R&D intensity in the Photonics industry amounts to nearly **10%**

Photonics industry is leveraging public investment in the PPP projects by a factor of **4.3**

Industry participation in Horizon 2020 PP projects increased to **45%** compared to 35% in FP7

**7** Prototyping and Pilot Manufacturing services to help end user industry to speed up product development

**€49 million** invested by the EC in the PPP Pilot manufacturing services (Pilot lines)

**67** projects started so far under the frame of Horizon 2020 with a public investment of a total of **€278 million** EC funding over the first 3 years of Horizon 2020: 2014-2016

### Market

The European Photonics market amounts to **€69 billion** per annum

European Photonics Production has increased by over **62%** over the last 10 years

The European Photonics Production has grown with an average CAGR of **5%** since 2005

European Photonics Production Growth rate is more than **3.5** higher than EU GDP Growth rate

**50%** global market share for European Photonics for Production Technology

**35%** global market share for European Photonics for Optical Measurement & Image Processing

**32%** global market share for European Photonics for Optical Components and Systems

Global Photonics Industry grew from **€228 billion** in 2005 to **€447 billion** in 2015

Global Photonics market expected to amount to **€615 billion** in 2020

The photonics sector is **growing twice as fast** as the global GDP

### People

**19,000** new jobs created in the European Photonics Industry

Forecast: **42,000** new jobs could be created by 2020

**9** PPP Projects explicitly devoted to promoting Research, Education & Training in Photonics

More than **1700** Photonics companies and research organisations back the Photonics PPP.

More than **3000** registered personal members in the platform Photonics21

About **1000** attendees in Photonics PPP strategy development workshops and meetings

Around **300,000 people** in Europe are employed directly in the photonics sector

Source: ETP Photonics21: Europe's age of light! How photonics will power growth and innovation, Photonics21 Vision Paper, 2017 *glance*" overview. Importantly, the growth of the European photonics industry will continue provided investment is facilitated, allowing these companies to keep their competitive edge[15]. The following thematic roadmaps were prepared with such a growth in mind.

*"Europe's photonics industry, doubled over the last ten years and now employs over 300,000 people directly in more than 5,000 photonics companies and organisations."*

**Global Investment to secure the Future of Photonics**
Highly skilled and well-paid employment is extremely valuable to society and the overall economy and is sought by many countries. Competing economies are already implementing plans that will help them exploit the significant opportunities that photonics will provide to their economies. Countries that are manufacturers of volume consumer goods wish to keep their industrial base at present. By 2020, the South Korean government has announced that they will have increased investment into photonics by €2.8 billion per year[16]. The Chinese central government is also increasing its annual spending in photonics by 40% to €1 billion by 2020[13] which is complemented by regional investments, often a multiple of central government funding. Other countries which are seeking to keep high-value manufacturing jobs onshore are also investing. In the US, photonics has been classified as a strategic key enabling technology and has identified critical photonics-driven fields critical to the US competitiveness and its national security[17]. One example from the US is the AIMs initiative which provides $610 million of public-private partnership funding into developing US-based integrated photonics manufacturing capabilities.

As a result of these global investments into photonics, Europe's place as a market leader is not guaranteed and requires immediate, active support. However, to Europe's advantage is its dynamic, open, and well-connected community that spans the complete innovation supply and value chains (from research to industry, from components to systems to end-users) placing Europe in a strong position to provide an excellent return of investment.

[15] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Jobs and Growth in Europe – Realizing the potential of Photonics, PPP Impact Report 2017, Düsseldorf.
[16] "Political steering processes in Asia aimed at the photonics industry" 2015, BMBF, VDMA and Spectaris.
[17] National Research Council. 2013. Optics and Photonics: Essential Technologies for Our Nation. Washington, DC: The National Academies Press. https://doi.org/10.17226/13491.

## 1.2 Architects of the Roadmap: the dynamic and innovative European Photonics Community

"The Photonics cPPP has grown from the Photonics21 European Technology Platform, which was launched in 2005 with the aim to be the first European platform to bring together stakeholders from industry, academia, and policy in photonics. Since its establishment, the platform has steadily grown and today includes around 1700 organisations – two-fifths of them being companies – with more than 3300 members[18]."

The rise from a niche technology sector to one of the most important industries for the future of Europe is a remarkable achievement and, in part, the result of a firm commitment from the European photonics industry. The photonics stakeholders have spent years developing and continuously updating the European R&D Photonics strategy in an open, transparent, democratic and participative decision-making process, and have worked tirelessly to promote the implementation of this strategy in Horizon 2020[19].

**Right:** That's what the European photonics community stands for. © Photonics21, VDI Technologiezentrum GmbH.


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[18] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH (2018): Photonics21 – Photonics cPPP – Progress Monitoring Report 2018, Düsseldorf. www.photonics21.org/download/ppp-services/photonics-downloads/cPPP-Progress-Monitoring-Report-2018-final-002.pdf, p.5.

[19] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH (2018): Photonics21 – Photonics cPPP - Progress Monitoring Report 2018, Düsseldorf. www.photonics21.org/download/ppp-services/photonics-downloads/cPPP-Progress-Monitoring-Report-2018-final-002.pdf, p.25.

The European photonics community is well organised and highly effective under the umbrella of Photonics21 as the biggest Technology Platform in Europe and the Photonics PPP (Public Private Partnership). The Photonics PPP has been valued 'best in class' by an independent expert group from the European Commission as part of the Horizon 2020 mid-term evaluation[20]: it was acknowledged as exemplary for well-functioning PPPs, which is a significant achievement considering that the European photonics ecosystem is complex, cross-border and interfaces with many other sectors as a supplier or technology user. With a setup as complex and extensive as this, the need for a multinational, well-connected, and responsive platform was essential. "Since the establishment of the PPP, Photonics21 gained more than 1000 new members to implement the European Photonics strategy further.[21]"

*"The Photonics PPP has been valued 'best in class' by an independent expert group from the European Commission as part of the Horizon 2020 mid-term evaluation[20]."*

The European photonics landscape is built from a base of world-class research groups, a strong SME-based industry and a few larger companies. Together they form the European photonics ecosystem. Most of these photonic players are active in regional photonics clusters, as well as national technology platforms, which is to be expected given the various industrial sectors that photonics supports.

Owing to the multidisciplinary nature of photonics, along with the prolific research and industrial base that Europe has, the sector has naturally evolved into regional innovation clusters and national technology platforms that represent the interests of the photonics community at a local and national level. Given that the sector can create significant employment these innovation clusters play an active part in the regional or national innovation strategies. Given that this close relationship supports the strategic research and innovation directions for photonics at the European level, it is therefore vital that the regional innovation clusters and national technology platforms continue their cooperation and pursue a common European photonics R&I strategy in the close future.

The EU acknowledges the vital role that national technology platforms and regional innovation clusters play in advancing the photonics innovation capacity needed in Europe, and strengthening the innovation value chain. It is essential to continue the link between *Horizon Europe*, national and regional strategies, and European regional development funds to define and implement the photonics strategy and guide R&D funding to innovative European SMEs.

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[20] https://publications.europa.eu/en/publication-detail/-/publication/6de81abe-a71c-11e7-837e-01aa75ed71a1/language-en, last accessed on 2018/09/06.

[21] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH (2018): Photonics21 – Photonics cPPP - Progress Monitoring Report 2018, Düsseldorf. www.photonics21.org/download/ppp-services/photonics-downloads/cPPP-Progress-Monitoring-Report-2018-final-002.pdf, p.23.

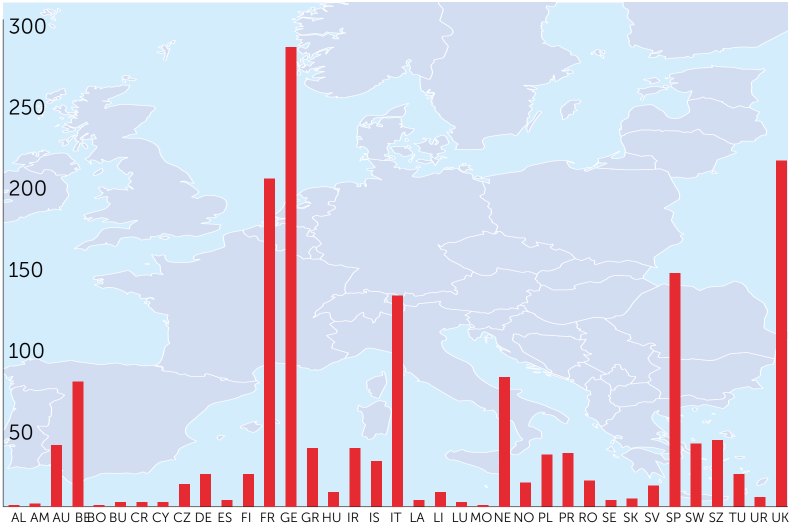
## 1.2 Architects of the Roadmap: the dynamic and innovative European Photonics Community

**Figure n°3:** Photonics – made in Europe.

More than 1700 companies and research organisations form the Photonics21 stakeholders – overview on the geographical representation.

AL – Albania
AM - Armenia
AU – Austria
BE – Belgium
BO – Bosnia
BU – Bulgaria
CO – Croatia
CY – Cyprus
DE – Denmark
ES – Estonia
FI – Finland
FR – France
GE – Germany
GR – Greece
HU – Hungary
IR – Ireland
IT – Italy
IS – Israel
LA – Latvia
LI – Lithuania
LU – Luxenbourg
MO – Moldova
NE – Netherlands
PO – Poland
RO –Romania
SE – Serbia
SK – Slovakia
SN – Slovenia
SP – Spain
SW – Sweden
SZ – Switzerland
TU – Turkey
UR – Ukraine
UK – United Kingdom

Source: Photonics21, VDI Technologiezentrum GmbH




Number of Photonics21 affiliations per country

## 1.3 Roadmap Objectives

The photonics community has worked together to produce this document, the Photonics Multiannual Strategic Roadmap 2021-2027 for the new European Research Framework Programme, Horizon Europe. It was created through an open and transparent community process and was organised by the European Technology Platform, Photonics21 and the acclaimed Photonics Public Private Partnership. As a result, this document provides a long-term strategy for the next seven years that will have wide industrial acceptance. This roadmap outlines future research and innovation that will need to be requested by industry. It is specifically tailored to the vision that Europe has set out for itself and is the follow up to the Photonics21 vision document "Europe's Age of Light! How photonics will power growth and innovation[22]", which started with defining eight goals for major global challenges and how photonics will help to fulfil them (see the following box). Later on, the roadmap lays out the development needed to reach those goals.

> *"This document provides a long-term strategy for the next seven years that will have wide industrial acceptance."*

**What will drive the future of of innovation in 2021 and beyond?**
European leadership in photonics will deliver these benefits by 2030:

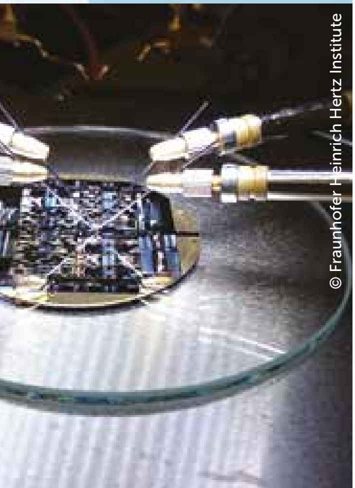


- **Instant diagnosis of major diseases**
- **Quality food from farm to fork**
- **Accident and congestion-free road transport**
- **A truly circular economy**
- **A million new jobs**
- **10% higher productivity**
- **Zero downtime in a terabit economy**
- **Photonics as a flagship science for innovation**

[22] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH, Photonics21 Secretariat (2017): Europe's age of light! How photonics will power growth and innovation", Photonics21 Vision Paper, Brussels / Düsseldorf / Berlin / Frankfurt am Main, 2017.

# 2. Photonics technologies empower every sector and

# our society



In 2011 the European Commission published a report on the photonics leverage effect, a phenomenon created where light technologies are the enabling element of a product or a solution. The study concluded that photonics impacts around 10% of the European economy[23]. At that time, the photonics leverage was identified in multiple markets as diverse as retail, medical and healthcare, manufacture of electronics and vehicles, transport and telecommunications[19]. However, due to the maturation of some elements of the technology, this effect is expected to be much more abundant today.

This leverage effect also holds for the emerging digital economy. The recent publication of the European Investment Bank "Financing the digital transformation" underlines the strategic means and high economic leverage factor of photonics technologies estimated at 10% of the European economy "with leverage ratios that may go up to 50 between the photonics market size and the total market size impacted.[24]"

"Photonics related projects [...] cover all high relevance application markets for tomorrow's society and economy" from personalised healthcare, industry 4.0, smart cities to securing the digital society, connected mobility – to name but a few. "Photonics as Key Enabling Technology for providing solutions to tomorrow's major societal challenges is of the utmost importance.[25]"

Photonics technologies will become increasingly embedded in future products and services because they are often the only means of achieving specific performance requirements; but even where there are competing technologies, the photonics solutions tend to be faster, more accurate or precise and use radically less energy. The advantages of photonic solutions mean that they are used to drive innovation in other sectors such as healthcare and life sciences, security and safety, mobility and IT, industrial manufacturing, farming and food production. The research and innovation activities that are laid out in the following thematic roadmaps highlight the enabling effect of the technologies.

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[23] European Commission's study SMART 2009/0066: The leverage effect of photonics technology: the Europeanperspective.

[24] European Investment Bank: Innovation Finance Advisory Studies "Financing the digital transformation – Unlocking the value of photonics and microelectronics", prepared for DG Research and Innovation and DG Connect, European Commission, 2018, p.11.

[25] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH (2018): Photonics – a critical Key Enabling Technology for Europe – Role and impact of Photonics in H2020, Düsseldorf, 2018, p.9.

*“Photonics is at the core of a transition in computing technology that will see ever more traditional silicon circuits make way for optical computing.”*

## 2.1 Photonics: Key Enabler for Europe’s Digital Transformation

Unsurprisingly, photonics technologies and their advancements are underpinning emerging technologies essential to the European digital transformation. Without photonics, these technologies will struggle to grow or may not even develop at all. It is crucial to recognise the interconnection of technologies and the skills needed to understand them. How this might be done with photonics will be explained using a few examples below.

**Artificial Intelligence**

Within smart cities, Artificial Intelligence (AI) will be used to manage traffic flow. But for AI to be useful, software solutions and computers will not be practical on their own: they will need to connect to the physical world through sensors and communication links. Many of the sensors that will be deployed in smart cities depend on photonics, such as cameras, or LiDAR for example, because they provide detailed information at an affordable cost that a safe and deployable transport system requires.

Data will need to flow to the computing unit or units that run the AI algorithms, and at present, this information is carried via fibre optic cables. However, as sensing and measurement technology are increasing in their capabilities and deployment, higher communication bandwidths will be required to transport that data. In some applications, such as autonomous vehicles, the communications need to work in real-time, and latency is a real issue. This means that some of the wireless links will have to use free-space optical solutions since radio-frequency technology is not capable of meeting the bandwidth needs. Here, because there are no other means of achieving the requirements, the successful deployment of AI will depend on photonics technologies for delivery.

Finally, computing will also change. IBM predicts that future computing hardware will not be based on CMOS systems but a new, more complex type of processing unit. These new units may as well be based on photonics or photonics-enabled quantum computers. Today, photonics is at the core of a transition in computing technology that will see ever more traditional silicon circuits make way for optical computing, whereby photons replace electrons in running our digital machines. Light-transmitting circuits will enable significant advances in computing speed, creating entirely new digital services.

### IoT

At present, the Internet of Things benefits from photonics, and indeed it could be argued that in the future, without photonics the IoT would not be possible, considering that most of the communication will eventually be transported by photons, as part of a fibre-based core network. However, there are also photonics-based sensors such as cameras, infrared sensors, hyperspectral imagers that will also become IoT enabled.

In the future, more data will be generated and transferred as a result of more devices being connected. Requirements on data capacity, speed and security of data will increase, putting additional requests on an optical communication system. The photonics community is already planning for this future as we can see in the thematic optical communications roadmap.

As a result, the photonic sensing community is preparing for an IoT-driven future which has been addressed in the corresponding roadmap. This requires R&D efforts to produce energy efficient devices capable of arranging data so that only essential information is transferred and can easily interface with other devices. The expected high volume of sensors will drive the need for low-cost devices, which, in turn, will call for the development of new photonics sensors that are cheaper while maintaining the same performance.

The predicted rollout of Industry 4.0 will drive innovation in the manufacturing sector. The laser processing community will utilise IoT to connect their machines to sensors to enable them to control their processes more accurately. For many advanced laser processes such as additive laser manufacturing, it is necessary to achieve consistent quality. The final example, and likely to be the "last hop" in IoT is the opportunity available to the lighting community: by integrating Li-Fi technology (similar to Wi-Fi but using light), with LED light they can act as a communication hub between many IoT enabled devices.

A coordinated and systematic work programme, based on solid roadmaps, will allow the photonics community to reap the most significant benefit from the IoT revolution. Relying on industry to fund this work, without support, will delay the benefits being felt by society and likely to affect the economic growth of Europe.

### Cybersecurity

Security is key to the European digital transformation. With the proliferation of smart devices and the increased deployment of IoT-enabled devices, we will be more vulnerable to security attacks. Many photonics technologies are in development aiming to increase cybersecurity.

Li-Fi has many advantages over Wi-Fi, and perhaps the most significant in this context is that wireless communication is contained within a room. With Li-Fi, one cannot access a data network from outside a building. Because the light is directional, specific areas could be allocated within a room that has access to Li-Fi hubs, creating high-security areas. This could be useful when vulnerable IoT devices may need to be protected.

Another area discussed in connection with cybersecurity is quantum secure communication. Quantum secure communication is almost entirely photonics based. At present, we rely on encryption codes that are based on mathematical algorithms. However, with the advent of quantum computers, the computing power will become strong enough to break codes in a short space of time. This time is called the "post-quantum" era by the data security community, and in anticipation of this event, photonics-based hardware solutions are being developed for the quantum secure communications community. The solutions are based on the generation and detection of single photon pairs that are entangled. Since it is challenging to create devices that can efficiently produce these deterministic photons and to bring quantum secure communication to market, further photonics technologies need to be developed.

**Quantum Technologies**

The emerging field of quantum technologies depends heavily on photonics technologies, even if photons are not the central quantum element under interrogation. Photons are often used to probe the quantum device: within quantum clocks, quantum-based probes for brain scans or quantum computing, usually lasers and detectors are involved. Of course, many quantum technologies directly use photons such as in quantum communication. To bring these applications to market needs the development of photonics technologies ranging from single-photon detectors and sources to amplifiers for quantum communication. Quantum computation based on photonics builds on integrated photonic devices and systems. Equally, atom-based quantum gravimeters that are at present slightly smaller than a bedside table could be miniaturised and the cost reduced by utilising integrated photonics. Another issue for quantum technologies is the need for specific lasers which are at present mainly scientific lasers and too expensive for an extensive rollout. To bring quantum technology to the market requires the parallel development of photonics technologies. If the research and innovation investment in light technologies are well coordinated, other photonics areas could benefit from these advances. These could have an impact on communications, healthcare and life-sciences and sensors for example.

## 2.2 Game-Changing Photonic Trends

There are already many photonic solutions that improve European competitiveness in different sectors. However, there are some significant barriers which impede a photonic-based approach: there are often issues with the cost, size, efficiency, output power, or sensitivity that prevent photonic solutions from being widely deployed. These drivers tend to be common across many sectors and respond to 'market pull'.

Light has, however, several properties that are extremely desirable, for example for quantum effects used in the quantum technology sector. Creating products based on these advantages, by seeking problems that utilise the approach best, is often described as a 'technology push'. The resulting products often solve problems that have appeared impossible by other procedures.

Support for both market pull and technology push is essential to ensure that Europe makes the most of the transformational impact that photonics offers. To undertake this, it is vital that we understand the trends that are common across all photonics areas. Solving them will enable a number of the challenges highlighted in the following thematic roadmaps. These key trends are:

- Integration: making systems smaller and more robust, dealing with large number interfaces that can be bulky;
- Modularisation and Platforms: developing photonics modules to be used as plug-and-play which requires the development of common standards;
- Increasingly interdisciplinary R&D;
- Cross-fertilisation from one photonics application area to another.

The continuous search for new materials that are more suitable, pushing boundaries on performance and operation across multiple wavebands, has been a trend for a long time. More specific trends are discussed in chapters later on.

With increasing co-dependence on the advancement of the different photonics areas, the photonics community needs to continue and expand its coordination. Only then will we maximise the speed of development and exploitation of the opportunities that arise from new photonics solutions for the European digital transformation. This requires efficient facilitation which has been currently provided by Photonics21 and through the European Photonics PPP.

***"The continuous search for new materials that are more suitable, pushing boundaries on performance and operation across multiple wavebands, has been a trend for a long time."***

### Four Photonics Technology States

When trying to classify how photonics technologies will evolve in future and what they will enable, the picture is very complicated. Even areas that appear to be mature still have the potential to grow, along with technologies that are successful in one area and could be translated into another. Some technologies are about to enter the market, and some areas are still primary active only in the research laboratory.

This complex picture of photonics technologies can be summarised into four general categories:

### Established in the market but with room to develop

Displays, lighting and photovoltaics are established technologies, which are still in active development into other markets. Display technology, for example, is being miniaturised, along with more stringent environmental conditions, and moved into automotive dashboards or VR/AR headsets. Another example is lighting: low power LED lighting has already made an impact on electricity consumption across Europe, and this is the first generation to benefit from the technology. While device-level manufacturing is well established in the Far East, there is still a role for Europe to take the lead in setting the direction of new developments such as the emerging trend of digitisation of lighting through the integration of sensors and light-based communication (Li-Fi).

### Operating in a developing market – requires a broad strategy to drive competitiveness

In this category, photonics-based products are already established in a beach-head marketplace and making a difference; however, the market has not yet reached maturity. The current lead that Europe has is at risk if no strategic co-ordination of R&D directions is put in place. High power lasers, for example, are already up and running in machine shops and enabling new methods for cutting, joining and surface treating. These machines allow for new design freedoms and make new engineering choices possible. However, the systematic development of these machines has not been completed, and many opportunities to do more exist: there is a driving need to reduce the cost, increase power and improve beam quality, and open up new application areas. Developing these tools and techniques has the effect of coincidentally increasing European manufacturing performance in other sectors. However, some of the developments are such a fundamental and high risk, that research is still carried out at universities. The limited individual R&D per company warrants owning at the EU level to stave off competition, primarily from other geographies.

**Ready to make an impact – investment support needed to reach the market**

Many photonics-based technologies form vital parts of future technology markets, but which are not yet at commercial readiness levels, for example, LiDAR, the optical equivalent of radar but with much quicker response times and substantially higher resolution. LiDAR has been in use for research and high-end technology applications for many years, but recently LiDAR systems have fulfilled a vital real-time 3D sensing need for autonomous and semi-autonomous vehicles. Venturing beyond the research applications and into affordable mass deployment will call for more R&D. Systems need to meet all the usual smaller, faster, cheaper requirements; however, they will also need to reach new levels of reliability that are maintenance free. Defining standards and community investment will be required to reduce the size and improve affordability. European investment in these areas, where products tend to be high value and often built on automated production lines make it highly likely that production will stay co-located to knowledge.

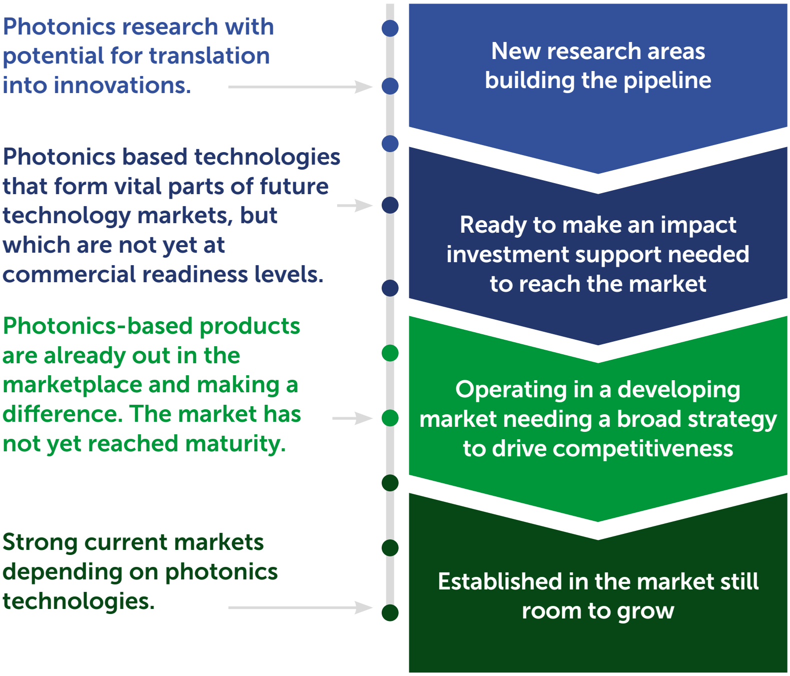


**Figure n°4:** Photonics research on all levels will provide important solutions for Europe's future. Source: Photonics21, VDI Technologiezentrum GmbH.

**New research areas – building the pipeline**

The visible light elements of photonics tend to be mature technologies. As we move away from the visible light, new markets and new challenges are available. Photonics devices already exploit applications at the Infrared spectrum, but moving further towards Mid Infrared and beyond, and down to UV and X-ray wavelengths will create many new opportunities for new products. If we consider the very promising developments of nano-engineered materials as well as the different quantum effects then many new sensing applications, including medical measurement and therapeutics, can be expected.

## 2.3 The Future is Photonics

The subsequent thematic roadmaps explain more in detail about how important photonics technologies are for the European digital transformation:

- Information & Communication
- Industrial Manufacturing & Quality
- Life Sciences & Health
- Emerging Lighting, Electronics & Displays
- Security, Metrology & Sensors
- Design & Manufacturing of Components & Systems
- Photonics Research, Education & Training
- Automotive & Transport
- Agriculture & Food

They underline that Europe's digital program, as well as any other missions that will be undertaken under the next European Framework, are unlikely to achieve their full potential without supporting and funding photonics. Photonics research and innovations take place in parallel with those in other areas and, create synergies from each other. The future innovation potential of established photonics technologies, or those under development, is significant for our digital economy and society in the 21st century.

To implement the European photonics roadmap for the future well-being of Europe, the European Commission and the European photonics community need to join forces to stay on top of the latest developments in the global competition[26].

[26] European Technology Platform Photonics21 c/o VDI Technologiezentrum GmbH (2018): Photonics21 – Photonics cPPP – Progress Monitoring Report 2018, Düsseldorf. www.photonics21.org/download/ppp-services/photonics-downloads/cPPP-Progress-Monitoring-Report-2018-final-002.pdf, p.6.

# 3.1 Information & Communication

## Main socio-economic challenges addressed

Within the next decade, European citizens will enjoy a new quality of life, industrial productivity will flourish, and digital value chains will create a vibrant economy while addressing inequalities in education, labour market, wealth creation and civil rights.

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 the industrial production and the working environment are expected to initiate momentum for a million new jobs in Europe.

We will enter a new era in which trillions of connected objects and billions of human users will not only deliver 10% higher productivity but also improve the quality of life, at home in families and together in communities. Smart connectivity will be the foundation of this new digital world: always available, intrinsically secure, and flexible scaling is the pre-requisite for zero-downtime in a terabit economy.

A new programmable network infrastructure will be the 'central nervous' system that the digital society, industry and economy will heavily rely upon. Delivering the required performance, resilience and security levels, while satisfying cost and energy efficiency, as well as technology constraints, presents a formidable research challenge for the next decade.

The information infrastructure and the communication infrastructure will stop co-existing side-by-side and pervasively merge into a single infrastructure, performing more and richer functions autonomously with minimal human intervention. It 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", e.g. robots, cars, connected objects, interfaces with users) to enable the "automation of everything".

Large data-centres (central cloud) will be used to perform very complex decisions, but are remote and therefore not compliant with the growing need for time-sensitive services, e.g. robot control in digitised factory floors.

Distributed, interconnected smaller datacentres (edge clouds and cloudlets) 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 and will propel the creation of services and applications that have not yet been envisaged.

Photonics technologies are an indispensable pillar of this new secure and resilient ICT infrastructure. Meeting the targets for demanding capacity, energy efficiency and latency 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 essential milestone in 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 in work group 6 (WG6) to provide 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.

The added value of the ICT sector to the European economy was €593 billion in 2014[27] (€686 billion in 2016[28]), representing more than 4% of Europe's gross domestic product (GDP). More than 6.2 million people were employed in the ICT industry in 2014[27]. 40% of ICT market size, 28% of ICT employment, and 49% of the R&D expenditure of €29.4 billion in Europe can be attributed to the communication equipment and services sector[29], demonstrating that it is an essential driving force and a key enabler for the services and applications running alongside.

*"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[30]. It is undisputed that optical communication and network technologies are essential to accommodate this growth in a sustainable way.

In 2017, the global optical component market exceeded $8 billion (Lightcounting[31]), the optical networking equipment hardware markets was in excess of $15.5 billion (Ovum[32]) and the optical router and switch market surpassed $12.5 billion in size (IDC[33]), and the passive optical networking (PON) market exceeded $6 billion (CIR[34]), yielding a total addressable market in excess of $42 billion.

The optical component market alone exhibited a CAGR of 13% from 2010 to 2017[30], reflecting that despite continuous efforts to lower cost-per-bits, the global capacity increase leads to a healthy increase in market volume.

R&D intensity in the optical communication sector is much higher than in the communication sector overall and typically exceeds 10% of revenue[35], 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. Concerning revenue, they represent more than 30% of the global optical equipment market[36]. Two of the three largest component

[27] EU Commission: Digital Agenda Scoreboard – The EU ICT Sector and its R&D Performance, 2017.
[28] EITO: ICT Market Report 2016/17.
[29] Networld2020 analysis, based on EU Commission: Digital Agenda Scoreboard – The EU ICT Sector and its R&D Performance. 2017.
[30] P. Winzer, D.T. Nelson, "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade", J. Lightw. Tech., Vol. 35, No. 5, 03/2017, online at https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7839935
[31] www.lightcounting.com/News_103117.cfm
[32] https://ovum.informa.com/analysts-and-events/event-listing-page/sitecore/shell/~/media/informa-shop-window/tmt/events/ofc-2018/stateoftheindustry-donfrey-ofc2018.pdf
[33] According to IDC, the global router and switch market was >$47 billion. With the assumption that 40% of this market are optical routers and switches this leads to >$18.8 billion.
[34] https://cir-inc.com/reports/current-and-future-markets-for-pon-2017-2026/
[35] Aggregated information from company & analyst reports.
[36] Ovum Informa: Global Optical Networking Market, Market Share Report, 2017.

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 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 a smart information and communication infrastructure. Photonic communication and networking technologies are an essential pillar of this infrastructure. From a user and application point of view, the following technical 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 are cumbersome and relies on unnecessary paperwork, manual processes and redundant interfaces. Artificial-intelligence based automation is vital to achieve 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, the reliance on the network and its service guarantees are increasing. Differentiated services are necessary which deliver a perceived instant 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 impede 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 permanently 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 massive data streams on-the-move, be it by quantum-safe encryption or by delivering a robust and secure infrastructure.


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

**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. Substantial investment and photonic innovations are required to tackle Moore's law and Shannon's limit.

**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 an excellent position to keep its leadership if it continues to innovate at a fast pace. It can be assumed that 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 an 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 mostly 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 support ultra-dynamic reconfigurations working at orders of magnitude faster than anything seen before (from minutes to sub-seconds, and even microsecond response times), for lasers, cross-connects, optical amplifiers, for on-chip or stand-alone components. Digitisation of networks requires devices to be programmable and controllable by artificial intelligence tools, leveraging network analytics collected by real-time optical network monitoring.

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.

**2) Instantaneous response**
**Low and deterministic latency in the optical network connections**
In future communication networks, data exchanges between devices 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 more significant 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.

Networks of robots will be developed in the European manufacturing industry, along with a massive transformation effort, to leverage digital technologies in the design, manufacture, operation and service of manufacturing systems and products. Manufacturing industry (excluding mining, construction and energy) is essential to the European economy[37], with 2 million companies, 33 million jobs and over 80% of exports.

Time-deterministic and time-sensitive networks, therefore, need to be developed, with photonics a 'keystone', key enabling technology ideally placed for the task. This includes studies on the hybrid use of electronic

[37] Ron Davies, "Industry 4.0, Digitalisation for productivity and growth", European Parliament Research Service, PE 568.337, September 2015.

and optical switching and new switching paradigms, 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.

*"Photonics will not only fill the gaps of the current technologies but will also open the door to completely new applications."*

Some applications require network resources only for a short time. Consequently, approaches enabling a faster reconfiguration (of less than one 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 an industrial environment, 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.

Due to the impact on industry and telco operator businesses, photonic devices able to work in a harsh environment (such as within a wide temperature operating range, or in high humidity, etc.), will be an active research field in the upcoming years.

Photonics will not only fill the gaps of the current technologies but will also open the door to entirely new applications, such as the use of LiDAR (Light Imaging, Detection, And Ranging) to increase the manufacturing accuracy and monitor the robots in a factory.
A new communication network based on 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).

It needs to be agile, programmable, and capable of transmitting large amounts of data quickly as well as allocating and configuring bandwidth resources accordingly.

While the success of internet technologies can mostly 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.

Digitising industrial processes requires reliable and low latency communication with guaranteed service quality.

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. This has a considerable impact on the creation of new jobs: an increase in digitisation by 10% results in a decrease in the unemployment rate by 0.84%. Moreover, a 10% increase in digitisation produces a 6% increase in the country's score on the Global Innovation Index.

**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 many 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.

Those applications create an entirely new working environment and renew the quality of urban life. They always require 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 big cities.

**Below:** Photonics technologies contribute to a secure transmission of data.

Beyond providing communications across an increasingly complete optical fibre network, photonic technologies are expanding into specific wireless use-cases. LiFi becomes an alternative for more secure indoor communications, satellite communications are using laser light as a “fibre in the sky” technology, free space optics provide a high capacity line of sight connectivity, and optical subsystems could be used for beam forming, 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 apparent benefits concerning 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 advantageous however it comes with as yet unseen challenges regarding the quality of service and security.

Trusted services will be carried over a single IT and telecom infrastructure while being immune to the rest of 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, they 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 giving 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 fibre can be easily tapped, once the physical access to the optical fibre is available. This 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 can be summarised as reducing the product of power efficiency x capacity (pJ/bit x capacity).

The increasing use of optical technologies within the ICT industry is an opportunity to limit the rising 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, or 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 bigger and more efficient switches that flatten network and datacentre architectures.

Extrapolations from today's traffic predict rates of 10 terabits per second for optoelectronic interfaces and over 1 Petabit per second for optical fibre systems by 2024[38], 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 a 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. This will linearly increase cost and threaten future capacity growth.

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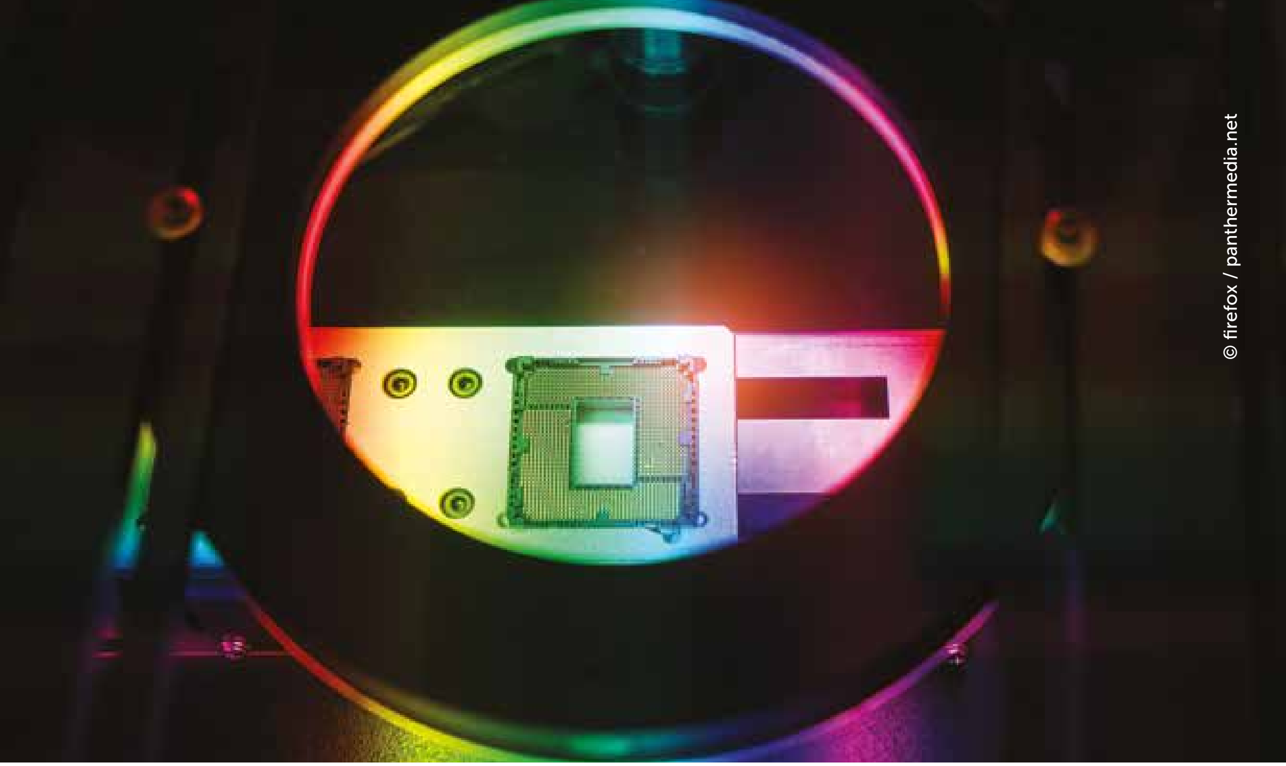
[38] P. Winzer, D.T. Nelson, „ From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade", J. Lightw. Tech., Vol. 35, No. 5, 03/2017, online at https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7839935





**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 many 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, along with the new fibre types, will be needed.

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.

*"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."*

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

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. Ultimately these advances will pave the way for 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 many European Commission initiatives to increase the quality of life through innovation across Europe.

Optical networks offer unprecedented capabilities regarding aggregate capacity, service transparency and operational simplicity. These networks are a key enabler for the deployment of the next generation 5G mobile network, as currently addressed by the 5G PPP, and also provide a 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 critical photonic technologies there are: optical transceivers providing higher capacity at a reduced cost, footprint and power consumption for 5G fronthauling 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 come 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 robust 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 new 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 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 vital 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 WG1 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 to drive electro-photonic integration, and with the robotics field 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 technology 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 WG6, to turn the WG1 roadmap and vision into practice.

Topics to be addressed in WG6 are:

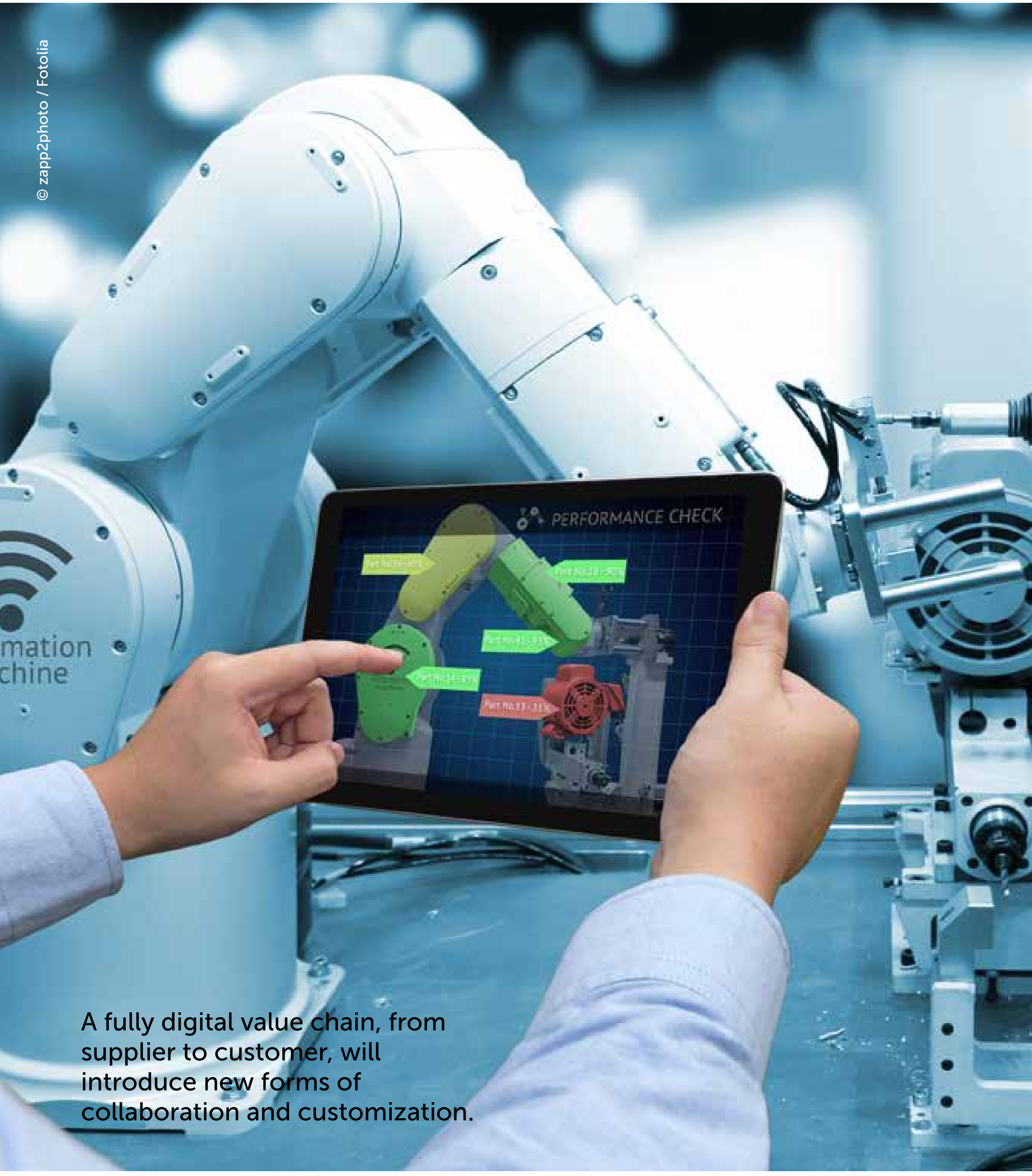
- Multi-chip module technologies combining digital electronic dies with optical 'chiplets';
- Solutions for optical chip-to-chip connectivity and on-chip networks;
- Electro-photonic integration;
- III-V and Silicon integration (uncooled, non-hermetic);
- Integration of new materials into Silicon platforms 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).

## Proposed roadmap for 2021–2027

| | 2021 | 2022/2023 |
|---|---|---|
| **Overview**<br><br>**Technology Challenges *(user view)*** | Zero-touch operation | Instantaneous response |
| **Critical milestones to move from Science to Market** | Open platforms, open interfaces & APIs | The growth of latency critical applications |
| **Photonics**<br><br>**Research (R) & Innovation (I) Challenges** | **AI-enabled optical networks:**<br>• Interoperable optical network nodes based on open HW and SW (white boxes)<br>• Dynamically self-configuring optical network technologies based on AI/ML for control, optimisation, and fault detection<br>• Optical devices enabling energy-efficient telemetry and analytics in optical networks | **Deterministic latency comms:**<br>• Optical networking technologies<br>• Latency-optimised optical interconnects<br>• Optical precision timing solutions<br>• Integrated optical comms for demanding sensor/actuator systems (e.g. 3D machine vision)<br>• Optical robot and sensor networks<br><br>**Ultra-dynamic networks**<br>• Optical solutions for industrial internet applications<br>• Optical spectrum and Ethernet services with hard service guarantees<br>• Large scale, fast optical and hybrid e/o switches<br>• Ultra-dynamic photonic devices (laser, cross-connects) |
| **Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)** | Artificial intelligence | Factories of the Future, robotics |

| 2024 | 2025/2026 | 2027 |
|---|---|---|
| Access anywhere | Intrinsic security | Sustainable capacity growth |
| The rise of cloud & fog computing | Standards, certification, integration | Cost-per-bit & power-per-bit reduction |
| **Fibre in the sky:**<br>• Optical wireless access including LiFi and VLC<br>• Free-space optics (FSO) for backhaul, SatCom and aerial vehicles<br><br>**Deep fibre access:**<br>• Coherent PONs<br>• New Radio-over-fiber solutions for fixed wireless access (FWA)<br>• Colourless transceivers, high output power PICs<br><br>**Optical radios:**<br>• Optical subsystems for beam forming and steering<br>• Optical concepts to generate and receive radio frequencies in the 100GHz-1THz domain | **Quantum safe comms**<br>• Chipscale quantum RNGs and QKD engines<br>• Pluggable quantum optics<br>• Quantum repeater<br>• Photonic devices for trust & security<br><br>**Critical infrastructure protection and resilience**<br>• Resilient optical network architectures<br>• Hardened optical infrastructures<br>• New methods for intrusion detection<br>• Hard slice-ability and service isolation | **More than Shannon & Moore optics:**<br>• Multi-band WDM systems<br>• System & subsystem technologies for space division multiplexing<br>• Petabit integrated energy efficient transceivers (<pJ/bit/s)<br>• Optical ASICs and FPGAs<br><br>**Towards optical computing:**<br>• From electronic to optical IT<br>• All-optical data centres<br>• High-speed photonics neural networks<br>• Optical compute functions<br>• Neuromorphic photonics |
| Human-centric internet | Quantum Flagship, cyber-security | Microelectronics, Graphene Flagship |

# 3.2 Industrial Manufacturing & Quality






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

## Main socio-economic challenges addressed

### Empowering Industry 4.0 with tailored light

The *Grand Challenges* facing European research are well-documented. In line with these overreaching 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;
- Realise highly efficient and zero emission manufacturing in urban environments;
- 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.

Europe is particularly well-placed 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 most significant manufacturing category for photonics – was worth €11.7 billion in 2016, a 9.3% increase upon the previous year[39]. European photonics companies control roughly one-third of this market.

These machine tools 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 should 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, it is imperative that the main technological challenges listed below are addressed.

| Fast | Green | Flexible |
|---|---|---|
| • High speed materials processing<br>• Short product development cycles<br>• Rapid manufacturing of complex products<br>• Connected production processes | • $CO_2$ emission reduction<br>• Weight reduction<br>• Material savings<br>• Product lifecycle and sustainability | • Agile manufacturing<br>• The digitalisation of the process chain<br>• Manufacturing of affordable individualised products |

[39] Laser Market Data 2017, Optech Consulting, http://optech-consulting.com/html/laser_market_data.html

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

Results from the above technological challenges will contribute directly to achieving the missions:

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

More than just simple, versatile manufacturing tools, new laser systems will address these challenges. They will be at the heart of fully digital and connected value chains, allowing companies to move between mass production of identical parts and the manufacture of individualised products. Quality control of manufactured parts will become an on-line capability, driven by the integrated use of sensor technology for parameter monitoring.

Similar sensor technology will provide rapid feedback, to enable full process control during manufacturing, thereby reducing scrap parts. The industrial production of micro, and nano, materials 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 laser itself, and the way the beam is delivered, (to the interaction point with the material being processed) when combined with its ease of digitisation, will deliver the most versatile and flexible machine tools, ready for the next generation of manufacturing.

## Major photonics research & innovation challenges

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

**Laser beam sources**: due to the increasing demands on process speed and quality, an increase in system performance - and at the same time an increase in the quality of optical fibres - coatings and laser components will be necessary. First, laser beam sources with high efficiency and adaptable beam parameters are necessary to follow industrial needs. Higher beam intensities and process-adapted beam distributions are required for challenging applications on high-temperature materials and fibre composites.

This 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, with which continuous, and digital, photonic process chains can be realized.

Starting from today's 100W class lasers, entirely 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 basis for these new high-energy beam sources, with ideal beam quality, will be compact and efficient high-performance diode lasers, which must be provided for pumping both solid-state lasers, with a broad spectrum of wavelengths (depending on the active medium) and for direct applications.

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

Also, flexibly switchable laser beam sources with selectable or adjustable pulse durations, wavelengths, polarisation or wavefront profiles adapted to the absorption conditions of the different materials being processed, will be necessary.

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

This requires powerful frequency conversion technologies and advanced system technologies. Wavelengths in the mid, too far, infrared and novel coherent beam sources down to the X-ray range, will create additional areas of application in manufacturing and metrology with entirely 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 transmission of laser radiation without loss or distortion, even in the mid and far infrared range. For further integration into machine technology, ultra-fast scanning systems will be needed for flexible production systems, enabling process speeds beyond 1000 m/s, with simultaneous high positioning accuracy and flexibility for manageable processes in production lines.

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

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

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 an 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 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 functionalization or multi-function in the same process.

*"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."*

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 complex multiscale 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 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 correctly 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. A simple 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 intended for power transmission, on the one hand, and used for signal transmission from the interaction zone on the other, pose significant challenges concerning the wavelengths to be transmitted.

To enable a production with high throughput, massive parallelisation could be a 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 the drawing to the finished component, 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 methods within the data and process chain. Methods like digital twins could achieve this close connection between processes, devices and systems.

**Quality Control and NDT:** for the future, the major challenge is to ensure high product yield while 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 apply mainly 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.

Also, the final quality must also be 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 able to be used online and in real time. In this area, the combining of optical methods with the laser processing head will be a particular 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 the use of artificial intelligence processes. Here, reduced metamodels will allow real-time evaluations and early prediction of product quality, going up to lifetime predictions. The generated information will flow into comprehensive databases, with the help of which, process development costs might be significantly reduced.

**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. In 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


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


**Left:** Laser cutting of coated and uncoated electrode foil.

be needed and applied to components employing ink jet printing to allow functionalization 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 achieve optimised processes.

**Skilled people and flexible infrastructure:** with its close links to research institutes in the fields of optics and manufacturing technology, photonics play 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 photonic-based production.

Lifelong learning is a significant 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.

The future establishment of photonic science hubs is intended to 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 environments 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 collaborative projects, research networks and clusters, providing novel and innovative solutions to manufacturing problems.

Within the photonic sector, a close cooperation between corresponding work groups is necessary: with WG 5, as sensors will play a significant role in the digitalization of manufacturing process information; with WG 6, as components and integrated systems will be used in complex process monitoring systems; with WG 3, as industrial manufacturing touches the realms of production of food and health products (for example, in Process Industries or Additive Manufacturing); to the automotive and transport sector, which acts as a "customer" of production systems, towards the end of the process chain.

For the implementation of laser-based manufacturing solutions in Industry 4.0, close cooperation with the PPP Factories of the Future (EFFRA) has already been established, and this should be continued on multiple levels. The same applies to the PPP Robotics and towards the sector of data analysis, artificial intelligence and machine learning.

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

**Right:** Efficient manufacturing processes by the use of the laser.

## Proposed roadmap for 2021–027

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

# 3.3 Life Sciences & Health



Photonics technologies drive the digital revolution in healthcare.

## Main socio-economic challenges addressed

Focusing on the mission within the core competence of "Life Science and Health", Work Group 3 examined *instant diagnosis of major diseases*[40].

The European population ages increasingly: the number of people older than 65, relative to those in the working age, is assumed to increase by a factor of two by 2045. Since age is one major factor for an increased probability of becoming ill, a significant 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[41], dementia and macular degeneration are concomitant effects.

However, age is, unfortunately, only one factor for death by disease: worldwide the number of similar 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 essential and represent persistent challenges that need to be tackled.

This 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. In this context, a major trend is P4 medicine (Predictive, Preventive, Personalized and Participatory), for which instant diagnosis of major diseases is imperative.

However, not only will the patients' burdens have to be decreased: our healthcare systems already struggle to keep up with the ever-increasing costs, a fight that will become increasingly harder due to our ageing society. Healthcare spending already accounts for nearly 10% of our GDP, amounting to roughly one trillion € per annum[42]. In an ageing society, there will also be a decrease in workforce, a trend that will soon lead to near full deployment, 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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[40] 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.

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

[42] https://ec.europa.eu/health/sites/health/files/state/docs/health_glance_2016_rep_en.pdf


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

Another non-age-related challenge is increasing mobility. High mobility leads to the spreading of infectious diseases in large areas in short amounts of time. In many developing countries, healthcare is still underdeveloped with affordable methods yet to be found to increase the health and wellbeing of their respective citizens. While it should be self-evident to help, there are also significant markets linked outside of Europe, which could also be served by European industry and lead to increased growth.

European industry is already among the global leaders in the healthcare market, which is growing with double-digits[43]. The total market volume of the segment in 2015 was €33.8 billion[44]. Photonics for Healthcare is assumed to reach around €50 billion worldwide by 2021. Accordingly, it is not only one of the largest markets among photonics, but also one of the more rapidly expanding sectors. 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.

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[43] 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

[44] 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:

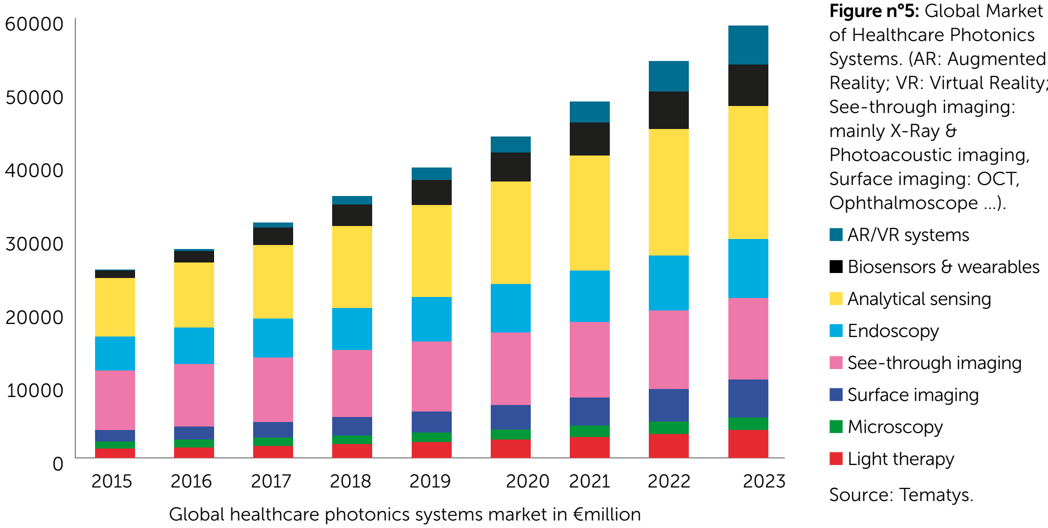



**Figure n°5:** Global Market of Healthcare Photonics Systems. (AR: Augmented Reality; VR: Virtual Reality; See-through imaging: mainly X-Ray & Photoacoustic imaging, Surface imaging: OCT, Ophthalmoscope ...).

Source: Tematys.

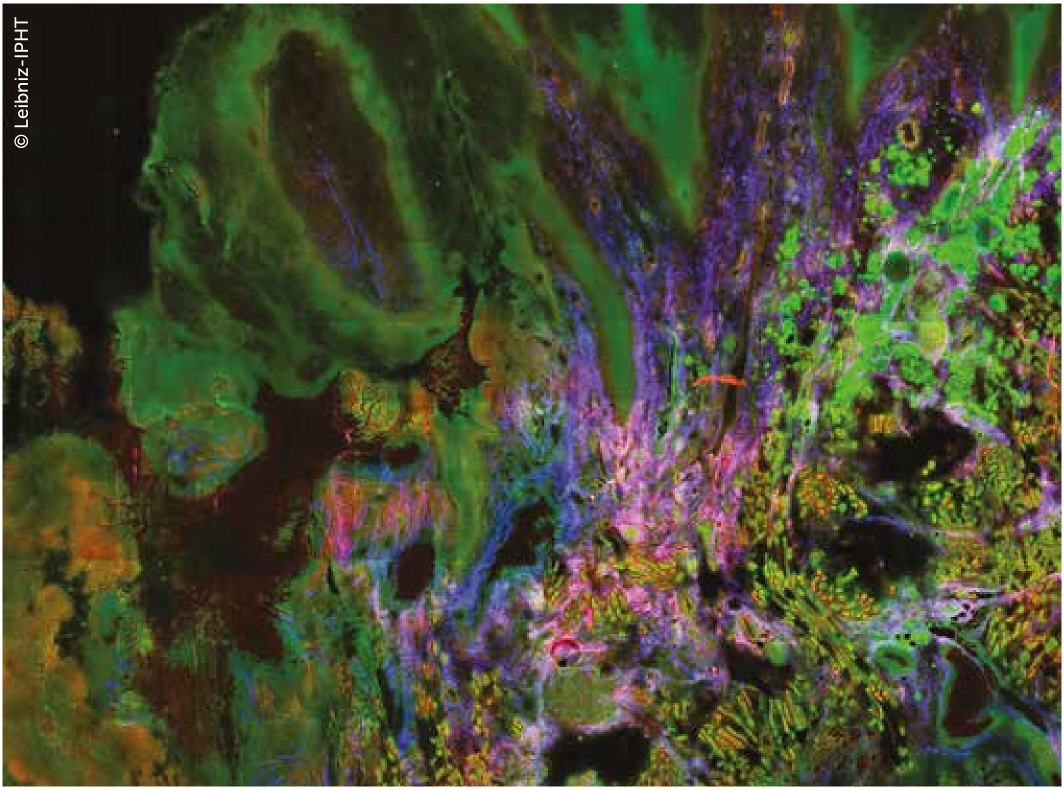
## Major photonics research & innovation challenges

Focusing on *instant diagnosis of major diseases*, Work Group 3 identified three sub-missions which will be pursued in *Horizon Europe*:

1. Advanced Photonic tools for life science industry as well as end-users (e.g. medical doctors, research):
   - Photonic tools for real-time proteomics, genomics, metabolomics;
   - Accelerating and enabling photonic tools for 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).

   In general, these photonic tools should be extremely reliable with high sensitivity and specificity, both exceeding 90%. The cost of the devices remains an important issue however, it is less significant in case of mobile photonics devices. The instruments and tools should be easy to operate with self-explanatory measurement procedures, operator independent results and advanced chemometrics evaluation schemes (e.g. AI-based) combined with an easy to grasp data presentation so that it could be operated by a non-specialist user.

   For imaging-based methods, an increase of both sampling volume (in contrast to point-of-care (POC) methods where decreasing the sampling volume and the limit of detection is commonplace), as well as depth (> 1 cm), will be key targets. Future, potentially multimodal,




**Above:** Multimodal optical imaging of larynx cancer tissue.

methods and tools need to improve against the current state-of-the-art approaches significantly.

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. Also, these tools could find the first application in metabolomics-guided treatment or rehabilitation.

"Photonic tools for pharmaceutical industry, and regenerative medicine..." will be developed to stages where they allow toxicity testing of new drugs in a preclinical phase with both high throughput and the ability to not only monitor over months but also for 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 with the aim of creating 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 many 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.

*"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, cancer, etc.) are emerging 3D imaging methods, which will in future be capable of combining subcellular resolution with a systemic field of view, encompassing entire organs, small animal models or even the complete human body.

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 create new therapeutic protocols.

The challenges for photonics research and innovation are very diverse depending on the particular method or combination of methods applied.

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

More sensitive detectors for all spectral ranges and components like filters and beam shapers need to be developed. The development of affordable pulsed sources and detectors covering 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 the brain, heart diseases etc.; 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 full (organ level), deep view (> 1 cm) and high resolution will enable a 3D label-free[45] histopathology in combination with an AI-based identification of conspicuous tissue

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

areas and volumes. Imaging will be possible down to the cell level (diffraction limited), also by combining different photonics modalities. This will allow precision surgery with real-time discrimination and selection of surgery targets as well as targeted treatment. In the corresponding surgical microscope, photonics sensing and augmented reality, e.g. by light-weight near-eye visual displays with very high resolution and vast 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 what happens with current ultrasonic imaging devices. 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 for example breast cancer (e.g. chemotherapy monitoring), Alzheimer (glymphatic system monitoring) or infectious diseases (pathogen identification and antibiotics resistance determination). Also, instruments and algorithms for the analysis of tissue composition (e.g. water, lipids, collagen content) or detection of newly identified biomarkers will contribute. Overall, they will enable to monitor label-free pathophysiological conditions and the wellness and health of patients.

Optogenetics methods will be developed further to enable neural re-wiring, e.g. for deaf or blind patients, prosthetics or even the functional recovery of cells and determining brain oxygenation to a level accurate enough (i.e. tenfold in comparison with today). Depending on the application, the corresponding systems have to be robust, accurate and allow real-time measurements with proof and highly reliable design, allowing them to be long-term stable even under harsh environmental conditions. Adapted photonic components such as light sources and detectors have to be developed to enable new biophotonic systems, which have to be configured to operate them under standard procedures that have yet to be determined. Advanced computing methods will be required to manage and evaluate the vast 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 and wellness, transportable photonic devices for monitoring environmental parameters

Applications for mobile photonic devices could potentially be quantitatively assessing the blood sugar for diabetes, vital sign monitoring such as pulse, blood pressure, blood oxygenation, evaluating the quantity of new specific and local biomarkers, as well as controlling the pharmacokinetics of pharmaceuticals and the progression of pathologies.

Such photonic devices could be carried on or even within the body. In the latter case, the volume of the device should not exceed 1 $cm^3$, and, correspondingly, the weight should be limited to a few grams. Ideally, the device should have a low power consumption connected with self-charging abilities, and have a manageable heat loss. Generally, materials must be fully biocompatible.

Mobile photonics devices could additionally be used for pathogen identification and support doctors on visits to enable fast medication. In general, the mobile device should produce reliable results accurate enough for their purpose, but much quicker and cheaper than conventional analysis tools. Specialised devices should be able to continuously record (or at low time intervals) the wearer's vital signs, which should be analysed on a daily basis to allow the early detection of diseases related to age or lifestyle or for the prediction of severe 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. On-body 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 handhelds for imaging applications, which enables the building of personalised services based on the available data.

For these portable biosensors to become a reality, new miniaturised light sources are needed, able to cover multiple wavelengths or large wavelength ranges, e.g. 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 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 or safely stored or transferred where necessary.

*"In addition to market access and market acceptance, adherence to standards where they exist needs to be taken properly into account."*

Data evaluation must be performed by objective means, e.g. 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 fit to pass clinical trials, but also fits into the doctor's workflow and is able to gain their acceptance, otherwise the corresponding procedure will fail to be reimbursed. All these steps must also be considered in the face of potentially competing technologies.

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

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

## Cooperation needs with other disciplines or fields

Developmental impediments always accompany healthcare along the way from basic research to a marketable product, (such as regulatory hurdles, standardisation reimbursement issues, and standard protocols) therefore, cooperation with all healthcare stakeholders is essential.

Given that 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.

One of the initiatives that should be of significant note in this context is "Emerging Smart Technologies for Healthcare" (ESTHER) and the similar ETPs (in addition to Photonics) of Nanomedicine, EU Robotics and BIG DATA Europe.

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" and a "holistic concept based on the inclusion and consent of all stakeholders". They aim to provide "integrated, innovative and smart healthcare solutions for all European patients by promoting an innovative European Health Technology Industry".

Photonics21 WG3 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 WG 5 is planned in the context of its focus on "multi-analyte pervasive AI-supported photonic bio-sensing".

## Proposed roadmap for 2021–2027

| | 2021/2022 | 2023/2024 |
|---|---|---|
| **Overview**<br><br>**Technology Challenges** | Mobile Biosensors | Photonic diagnostics and intervention |
| **Critical milestones to move from Science to Market** | Biocompatible materials need to be found/investigated.<br>Further convergence and integration of photonics, electronics and microfluidics:<br>• The miniaturisation of optical components to enable smaller on-chip solutions (in-body devices with volume < $1cm^3$)<br>• Low cost miniaturised broadband sources and detectors<br>• Demonstration of higher efficiency concerning the state of the art, reliability and specificity in in-vivo conditions | Miniaturisation and integration of optical components to build a<br>• 3D label-free histopathology and treatment modality<br>• Imaging platform to measure cell/ brain oxygenation mountable on a cart<br>• Integration of optical, electronic and microfluidic components for POC systems for advanced analysis of body liquids to fit in a shoebox |
| **Photonics**<br><br>**Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges** | Improve optical contact for on-body/in-body biosensors (stable, reproducible and continuous) (R)<br><br>Biomarkers research (R)<br><br>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:<br>• Photonic components (R)<br>• System (I)<br><br>Advanced POC Device for fast analysis of body liquids (I)<br>Imaging platform to measure cell/ brain oxygenation (10x more precise than current gold standard) (R) |
| **Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)** | ETP: EuMaT for biocompatible materials<br><br>ETP 4 HPC for the development of data handling and evaluation<br><br>ETP Nanomedicine (biomarkers) | ETP Nanomedicine (biomarkers); European Technology Platform on Smart Systems Integration<br><br>EPoSS, ETP 4 HPC for the development of data handling and evaluation |

| 2025/2026 | 2025/2026 | 2027 |
|---|---|---|
| Understanding diseases and prevention | Photonic screening and guiding | Photonic screening and guiding |
| Further development of photonic components:[46]<br>• Broadband pulsed laser sources UV-Vis-MIR<br>• More sensitive detectors for all spectral ranges and components, broadband detectors spanning UV-Vis-MIR<br>• Development of corresponding, novel 'green' or low-cost optical components (e.g. freeform) and system integration<br>• Phantom development and standardisation (imaging applications) | | |
| 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)<br><br>Monitoring of tissue growth for organ replacement/Bioreactors, (R) Photonic tools for researching disease development/early disease detection and diagnosis (R) |
| ETP 4 HPC for the development of data handling and evaluation<br><br>ETP Nanomedicine (biomarkers) | | |

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

# 3.4 Emerging Lighting, Electronics & Displays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The use of LIFI could have a positive impact on the lighting industry business landscape.

## Main socio-economic challenges addressed

“Emerging Lighting, Electronic and Displays” has changed its character significantly during the past decade due to the increased maturity of the relevant technologies and the new opportunities related to both the Internet of Things (IoT) and Artificial Intelligence (AI). New technologies in Lighting, Electronic and Displays will play a crucial role in five major areas.

### 1. Intelligent Backbone for indoor/outdoor communication

The global smart home market is estimated[47] to grow from $24.1 billion in 2016 to $53.4 billion by 2022. Acting as the ‘intelligent backbone’, lighting is in an excellent 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.

### 2. Better quality of life

We live in an ageing society which poses unique 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 structuring to older people. A personalised and easy-to-use interface to the lighting control system will be critical to their success.

### 3. Healthy food in urban areas

In a population with rapidly increasing urbanisation, ‘vertical farming’ will become increasingly important[48], and perhaps even mandatory to


**Photonics technologies contribute to healthy food in urban areas.**

[47] 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
[48] http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-5069445.pdf

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 reduces 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.

**4. Ubiquitous Information**
Information becomes personal and universal – always and everywhere. This holds in all spheres of everyone's life, in private as well as in business environments.

Micro-Displays in glasses and even contact lenses will offer personalised information via augmented reality to make complex work more accessible 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.

**5. Energy Saving**
Lighting accounts for 12.4% of the overall use of electricity by the 28 Member States and corresponds to 132 million tonnes of $CO_2$ equivalent greenhouse gas emission[49]. Saving energy 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.

## Major photonics research & innovation challenges

Given today's global economy and the development of the relationship between regional economies and ecosystems, it is considered a key success factor that Europe's photonic industry maintains and strengthens critical parts of the value chains – from raw material, hardware, software, energy consumption to production – and its domestic market access.

A new focus should be put on services (from light-as-a-service to light-based data business) owing to the importance of being close to customers and being able to speak their languages.

Competitors from the Far East will find it hard to be successful. Further integration of photonic components and devices into objects or structures (for example the displays in windscreens) offers the opportunity to the European industry for the novel, value-added products.

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[49] Commission Regulation (EU) laying down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament and the Council and repealing Comission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012, p.3, paragraph (8).

The corresponding research and innovation challenges are ordered along three primary missions:

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

**1. Increase productivity 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 all kind of structures that surround us. This presents new research challenges: 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 the component development.

Besides this technical aspect of productivity, the impact of light on our species influences the productivity of each 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.

**2. Truly Circular Economy**
The field of Urban Farming is gaining momentum globally. Different aspects provide its driving force. While in Europe's cities, some of its appeal is 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 entirely different: agricultural business in the mega cities is a necessity.

Light, with all its features like intensity, light colour, control mechanisms, is one of the main ingredients to species-specific plant recipes. Today, we are only beginning to formulate the expertise and knowledge of the mechanisms of plant growth and the means to influence it. 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 shortage, successful research for optimised plant watering by proper lighting will help millions of people to enhance their quality of life.

Another aspect of the 'circular' economy is the saving of resources: in particular, energy in production facilities. Here, 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 waste reduction, thus implicitly enhancing the efficiency of resource input in production.

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

Further research challenges concerning how to reduce the need for water in plant growth by proper lighting and how to reuse photonics components to improve the eco-balance will need to be examined.

**3. Photonics as a flagship science for innovation.**
An emerging opportunity for Europe where automotive, transportation and aerospace industries are strong is structure-integrated photonics, combining traditional microelectronics, flexible, printed & hybrid electronics and mechanical structures together.

This process enables photonics functionalities integration (displays or lighting, large area sensors, user interfaces), inside traditional structures like cars, aeroplanes, trains, trams, elevators, escalators, providing displays inside 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, strong integration of electronics and mechanics, lean assembly and novel, innovative solutions and services.

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

To keep these markets in Europe and support them, not only are evolutionary steps necessary, but revolutionary steps will be essential. One example of the next-generation demands are on material and device development for Near InfraRed (NIR) to Mid InfraRed (MIR) emitters: broadband and narrow wavelength emitter and detection systems for example, for the frequency band from 1µm to 12µm, that are compatible to existing semiconductor and optoelectronic technology, will gain importance. They can be used as sensors for a medical, environmental and transportation system, but also in the context of Human Centric Lighting (HCL).

There are other important missions that drive research and innovation challenges for emerging lighting technologies which have been addressed in detail in two other photonics roadmaps: the ones for communication and automotive and transport. They were not duplicated here but are worth highlighting nonetheless. Those are "zero downtime in a terabit economy", with the emergence of LIFI that is expected to be incorporated into lighting and could have an impact on the lighting industry business landscape and "accident and congestion-free road transport" with the development of smart and glare free headlights, which improve road safety and could also be used for communication between vehicles.

## Cooperation needs with other disciplines or fields

As long as lighting, displays and electronics/OPV become more and more connected, the collaboration with the other Photonics21 workgroups will become more and more necessary. Lighting Machine Learning (ML) and Artificial Intelligence (AI), for example, will play a crucial role to learn user preferences and behaviour. These learned behaviours will improve the performance of the systems by interpreting the sensor data more accurately and allow for 'noisier' data.

Concerning displays, close collaboration with the entertainment industry (regarding potential applications), with medical research (to study the impact of light sources near the retina) and material research will be needed.

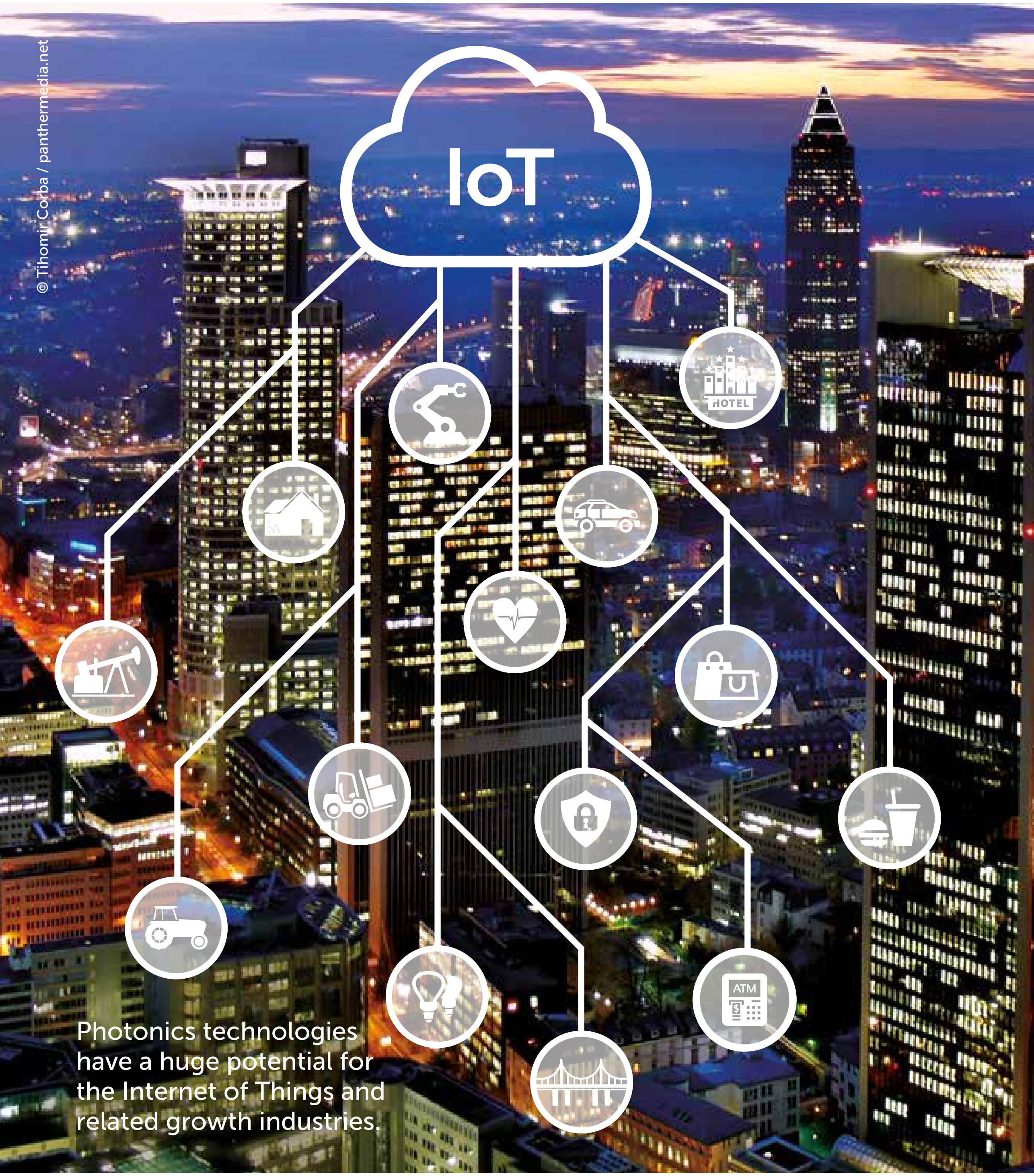
In the field of OPV, the major collaborations will be with the material research regarding new materials with better efficiency and long-term stability.

## Proposed roadmap for 2021–027

| | 2021 | 2022/2023 |
|---|---|---|
| **Overview**<br>**Technology Challenges** | • Cost-effective VHF and embedding<br>• High-efficiency luminaires and light sources<br>• Semiconductor-integration and System in a Package<br>• Sensing and energy harvesting/ wireless power<br>• Deep UV-LEDs<br>• IR based sensors<br>• Thin film technologies<br>• OPV efficiency + stability increase<br>• Next generation freeform optics<br>• LED in X (in cars, textiles,…) | • Multicolour high pixel density dice<br>• New materials (for light emitters, detectors, OPV,…)<br>• Transparent displays, OPV, luminaires<br>• Visible wavelength VCSEL + optics<br>• System in Package for higher power<br>• 3D printed optics<br>• Horticultural lighting<br>• Validation and verification of HCL |
| **Critical milestones to move from Science to Market** | • Complex ecosystem<br>• Proof of manufacturability<br>• Proof of business case<br>- Cost for manufacturing low enough<br>- Consumer persuaded of new concept<br>- Understand real demand of consumer (as part of HCL)<br>- Seamless product integration | • Scientific and business community able to judge the market/technology<br>• Open source vs alternative implementations decided<br>• Standardisation |
| **Photonics**<br>**Research (R) & Innovation (I) Challenges** | • Extension of VHF to SELV, higher power, wide output-range<br>• Cost-effective supply for IoT-devices, most probably also based on VHF<br>• Closed loop solutions for colour-temperature<br>• Sensor fusion<br>• Process improvements<br>• Realistic lifetime models | • Sensorics/camera with hyper-spectrum analysis (IR, UV) => cheap system-approach<br>• Wireless power (electromagnetic-resonance and radio) for sensors and small luminaires |
| **Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)** | • Industry 4.0<br>• IoT<br>• Artificial Intelligence<br>• Big Data<br>• Photonics21 WGs<br>• Photonics to enable AR/VR<br>• Energy monitoring systems<br>• Photonics in 5G<br>• Energy Efficient Building<br>• Medical | • Industry 4.0<br>• IoT<br>• Artificial Intelligence<br>• Big Data<br>• Photonics21 WGs<br>• Photonics to enable AR/VR<br>• Energy monitoring systems<br>• Photonics in 5G<br>• Energy Efficient Building<br>• Medical |

| 2024/2025 | 2026/2027 |
|---|---|
| • Extended 2D materials + integration in optoelectronic devices<br>• Integration of OPV<br>• Automotive lighting (LED, OLED, laser,…)<br>• LiFi, e.g. in transportation<br>• Enhanced lifetime OPV<br>• Photonic computer simulation models (aligned with experiment)<br>• Lighting for IoT<br>• Horticultural lighting | • New materials (for light emitters and detectors, OPV,…)<br>• Smart GaN for HF/VHF<br>• In-vivo sensors coupled with AI<br>• Subwavelength light guidance |
| • Cost-effective integration of passives with usable performance<br>• Single-chip-solution/topology for Lifi receivers<br>• Fast phosphors for LiFi | • High-speed detectors<br>• Low voltage photonic detectors<br>• Long lifetime |
| • Single-chip-solution/topology for light-source: GaN transistor on LED<br>• Phosphor with high time-constant and high efficacy for low light-ripple | • Energy-Harvesting concepts based on light (IR, visible-light), temperature and radio |
| • Industry 4.0<br>• IoT<br>• Artificial Intelligence<br>• Big Data<br>• Photonics21 WGs<br>• Photonics to enable AR/VR<br>• Energy monitoring systems<br>• Photonics in 5G<br>• Energy Efficient Building<br>• Medical | • Industry 4.0<br>• IoT<br>• Artificial Intelligence<br>• Big Data<br>• Photonics21 WGs<br>• Photonics to enable AR/VR<br>• Energy monitoring systems<br>• Photonics in 5G<br>• Energy Efficient Building<br>• Medical |

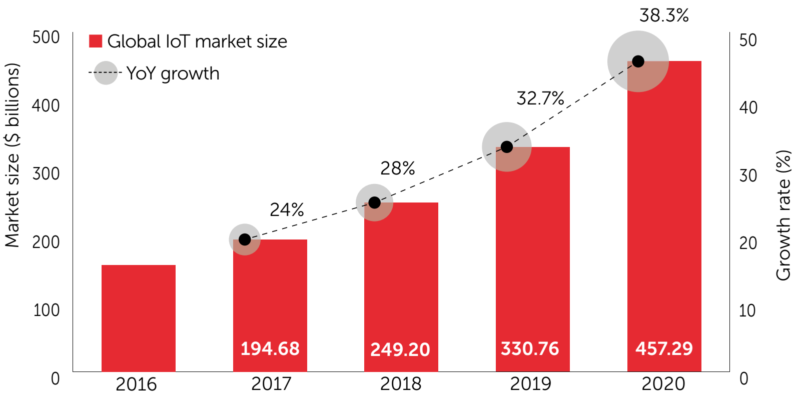
# 3.5 Security, Metrology & Sensors



## Main socio-economic challenges addressed

Our society has embarked on an unprecedented path: the 'Fourth Industrial Revolution', epitomised by the Internet of Things (IoT) transformation. Our machines will sense, operate, decide and communicate without our intervention, becoming truly autonomous. Huge economic potential is seen in the IoT revolution with the number of installed IoT devices forecast to grow to more than 75 billion by 2025[50]. As expected the worldwide IoT market will be substantial, however, there are some discrepancies in estimates[51]. 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[52].

**Figure n°6:** Market size and growth rate of the global IoT market for the period 2016–2020[52].




Source: Growth Enabler IoT Report, April 2017.

The dominant four IoT market segments will be Smart Cities (26%), Industrial IoT (24%), Connected Health (20%) and Smart Homes (14%), accounting together for 84% of the total IoT market, as illustrated in figure 7[52]. Primarily, every economic and societal area will be affected. As summarised and quantified in figure 9, all application areas of Photonic21 will be heavily influenced by the IoT revolution. We will see effects in Healthcare, Agriculture and Food, Transportation and Infrastructure, Circular Economy through Smart Cities and Utility Transformation, Manufacturing and Industry 4.0, Urban Life in SmartHomes/Connected Buildings and Hospitality, as well as the Digital Society through IT Defence /Logistics/Retail etc[52].

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[50] Statista, "Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025", Nov 2016.
[51] L. Columbus, "2017 Roundup of Internet of Things Forecast", Forbes Media, Dec 2017.
[52] GrowthEnabler, "Market Pulse Report, Internet of Things (IoT)", April 2017.

## 3.5 Security, Metrology & Sensors

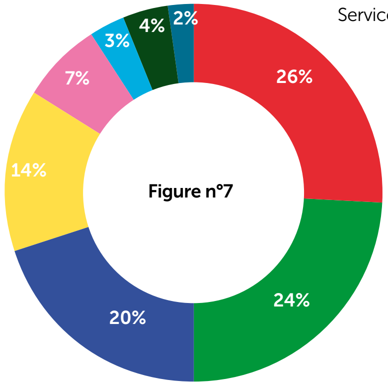


**Figure n°7:** Global IOT market share by segments in 2020[52].

- Smart cities
- Industrial IoT
- Connected health
- Smart homes
- Connected cars
- Wearables
- Smart utilities
- Others

Source: Growth Enabler IoT Report, April 2017.

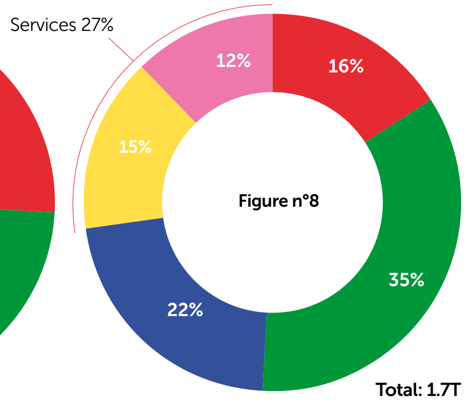


**Figure n°8:** Investment types in IOT solutions by 2020[56].

- Software ($261 billion)
- Hardware ($585 billion)
- Connectivity ($362 billion)
- IT and installation services ($252 billion)
- XaaS ($217 billion)

Source: PWC, Leveraging Upcoming Disruptions from AI and IoT, February 2017.

At present, the most rapid growth of IoT nodes has been observed in manufacturing: from 2016 to 2017, the number of IoT connections in manufacturing grew by 84% (compared with 11% in healthcare/pharma)[53]. Since Europe is the world's largest manufacturer of machine tools and the industry's leader in technology[54], we have a unique opportunity to leverage the IoT revolution in a market where Europe is dominant. However, many more economic opportunities to exploit IoT do exist.

At present, there are more than 4,600 IoT globally active start-ups, sporting an average valuation of $4.9 million[55]. A cumulative total of $6 trillion will be spent on IoT solutions between 2015 and 2020, with the most significant portion to be spent on hardware, accounting for 35% of the IoT investments in 2020[56], as illustrated in figure 8. Since the main components of an IoT device are sensors, actuators (in the simplest case LED indicator lights), a signal processor, wireless communication infrastructure and a battery, a significant part of an IoT device's cost goes into sensor subsystems.

Hence, an enormous opportunity is currently arising to bring more and extremely valuable photonic sensing capabilities into future IoT devices: The electromagnetic spectrum offers unique advantages in terms of selectivity (offering a large range of spectroscopic sensing techniques), measurement speed (light propagates at about 300,000 km per second through air), sensitivity (single-photon image sensors operating at room temperature are becoming available), power-efficiency (for one Euro, more than 1025 photons can be generated), sensing depth (up to many kilometers), miniaturization potential (a single photosensor pixel can be smaller than 1x1 square micron) and cost-effectiveness (a complete, auto-focus cell-phone camera costs less than 5 Euros today).

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[53] Verizon, "State of the Market: Internet of Things 2017. Making way for the enterprise", 2017.
[54] CCECIMO, "Study on the Competitiveness of the European Machine Tool Industry", Dec 2011.
[55] Web resource: Global IoT startups and investments: https://angel.co/internet-of-things
[56] PWC, "Leveraging the Upcoming Disruptions from AI and IoT", Feb 2017.

## The Top IoT Growth Industries

**Figure n°9:** Top IoT growth industries with key market figures[3], 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.

## Major photonic research and innovation challenges

It is expected that by 2022, pressure sensors, temperature sensors and photodetectors will account for almost 80% of all globally enabled IoT sensors. Surprisingly, photodetectors are predicted to contribute only 17.3%[57], as illustrated in figure 10. This is related to the fact that although the IoT market will doubtlessly dominate the sensing field, there are also other markets whose 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 $24.8 billion by 2023, growing at a CAGR of 9.75% between 2017 and 2023[58]. These numbers also show the differences that arise when markets are analysed in terms of pieces sold or concerning turnover: The high-volume applications will not necessarily generate the highest revenues.

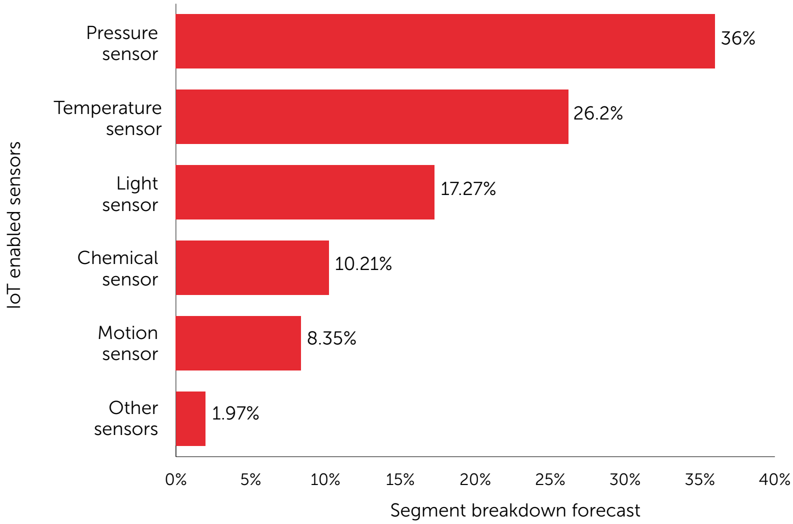


**Figure n°10:** Global IoT enabled sensors market in 2022 by segment[57].

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

Compared to temperature and pressure sensors, the integration of image sensors into IoT systems faces two problems: first, the complexity (and therefore the price) of temperature and pressure sensors are much lower than those within photosensors, which often require additional passive components such as lenses, filters, mirrors, gratings, optomechanical parts or even micro-electromechanical systems (MOEMS). Second, the data rate of an image sensor is usually significantly higher than that of a 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 data rate of 1 billion data points per second.

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[57] Statista, “Projected global Internet of Things enabled sensors market in 2022, by segment”, 2017.
[58] Research And Markets, “Image Sensor Market by Technology... Global Forecast to 2023”, Jan 2018.


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

This is part of a huge problem the IoT revolution has to cope with: during the past decade, twice as much data was being produced compared to the expansion of bandwidth; 90% of the data created over the last ten years were never processed or analysed. Today the collective computing and storage capacity of smartphones surpasses all worldwide servers[59]. By necessity, a new IT paradigm is therefore emerging: "Data at the edge", requiring the huge amount of data acquired by IoT devices, smartphones, and tablets, for example, must be pre-processed and analysed in the device itself. A case in point is the speech recognition offered by Amazon's Alexa, Apple's Siri, Google's Assistant or Samsung's Bixby: they still require real-time data transmission and cloud computing to work[60]. This is not sustainable – the IoT devices, our smartphones and tablets, the autonomous cars and our smart homes must become "intelligent". They will have to be capable of analysing and "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[61]. Our IoT devices and photonic sub-systems must follow suit to become AI-empowered, as well.

*"Today the collective computing and storage capacity of smartphones surpasses all worldwide servers."*

[59] H.A. Peter and D. Krick, "Data at the Edge – Watson Down to Earth. IBM Global Technology Outlook", CIO Club of Excellence, IBM 2015.

[60] J. Hindi, "Google Assistant vs Siri vs Bixby vs Amazon Alexa vs Cortana – Best virtual assistant showdown!", Android Authority, Aug 2017.

[61] F. Agomuoh, "AI-powered smartphones and the features that will make you want to buy them", Business Insider UK, Jan 2018.

In conclusion, the future of "embedded photonics" in IoT, smartphone, tablet, white goods and other industrial products must meet the following requirements:

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).

2. **Miniaturisation:** the form factor of any sensor sub-system is of utmost importance for its integration into the cramped space of an IoT or smartphone product. Consequentially, photonic measurement methods must be selected allowing ultimate miniaturisation and 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 cost fabrication of the photonic sub-systems, the maximum use of manufacturing techniques related to semiconductor production should be made. Since photonic solutions usually require highly complex MOEMS fabrication technologies (Micro-Opto-Mechanical-Systems, possibly including thermo-electric components), specialised PIC fabs (Photonic Integrated Circuits) will be necessary and should be encouraged.

4. **Platforms, not individual solutions:** for utmost cost-efficiency, minimum NRE (non-recurring engineering) costs are mandatory. This can be achieved by developing widely-usable photonic platforms that can be configured by firmware adaptations, or they can be customised by simple wafer-scale post-processing steps (i.e. application-specific coating, physico-chemical 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:** interpretation of the acquired data must occur within the photonic sub-system, to reduce the bandwidth requirement maximally. Only insights should be communicated and not raw data. The goal is to leverage Photonics with the forthcoming IoT and AI disruptions[56].

6. **Multi-analytes:** today's IoT sensors are typically restricted to single-channel detectors with limited bandwidth (e.g. pressure, temperature,

[56] PWC, "Leveraging the Upcoming Disruptions from AI and IoT", Feb 2017.


light intensity, acceleration, colour, chemical parameters[57]). The future will lie in the simultaneous acquisition of data, in the form of massively parallel multi-parameter/multi-analyte sensor systems, capable of acquiring, processing and interpreting vast amounts of data simultaneously, while communicating only the essential "insights" to the outside world.

**Above:** Photonics technologies empower smart glasses and augmented reality.

7. **Maintenance-free:** for a hassle-free user experience, two properties of a sensor sub-system are imperative:
   (1) No maintenance is necessary both during long periods, and, if possible, during the full lifetime of the system. This implies that no initial calibration is required during setup of the system, and – if necessary – the sensor can carry out self-calibration without user intervention, for example, from printers or scanners.
   (2) The integrity and accuracy of the provided data must be assured, for example through regular self-analysis of the sensor system. The delivery of inaccurate data, or interpretations of data, cannot be tolerated.

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

*"In a nutshell, for the 2021–2027 Roadmap, these key requirements imply that Europe should focus on multi-analyte pervasive AI-supported photonic bio-sensing (MAPAIPBS) to improve the quality of life for all EU citizens."*

8. **Robustness:** the sensor sub-system must be fault-tolerant and show "graceful degradation". This implies for example that suitable interpolation mechanisms are included (for example to fill in failing pixels), and the sub-system must communicate its impending degradation and lifetime.
9. **Low Power:** Photonic measurement methods and components must be selected making maximum use of the information in each photon. As a consequence, no photon should be wasted, by employing high-efficiency light sources (LEDs, lasers), low-noise/high-QE photo-detectors, and by avoiding the use of absorptive components such as optical absorption filters.
10. **Eco-Friendliness:** complementing Europe's successful and responsible RoHS regulation (Restriction of Hazardous Substances), it is desirable that the photonic sub-systems of the future exhibit pronounced longevity (longer than the duration of the containing product), that they have the potential to be re-used, and that recycling of its components and materials is facilitated.
11. **Focus on high-growth/high-value markets:** it is estimated that in 2018, more than 23 billion connected IoT devices with their embedded sensors have been installed[50]. It is concluded that the future lies not in the "simple" sensor sub-system already available today[8]. Rather, Europe should concentrate on becoming the leader in advanced, high-performance, AI-empowered photonic sub-systems of tomorrow. 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 numbers in figure 6 are very clear[52]: these markets are related to healthcare ("4P Medicine"), environmental sensing (smart homes/cities, mining, "green" utilities, transportation), manufacturing (Industry 4.0), and agriculture and food ("Precision Agriculture", "safe and healthy food with reduced waste").

These requirements are translated into the following key target figures (**R&I challenges**) to be achieved by 2028 for resounding market success:

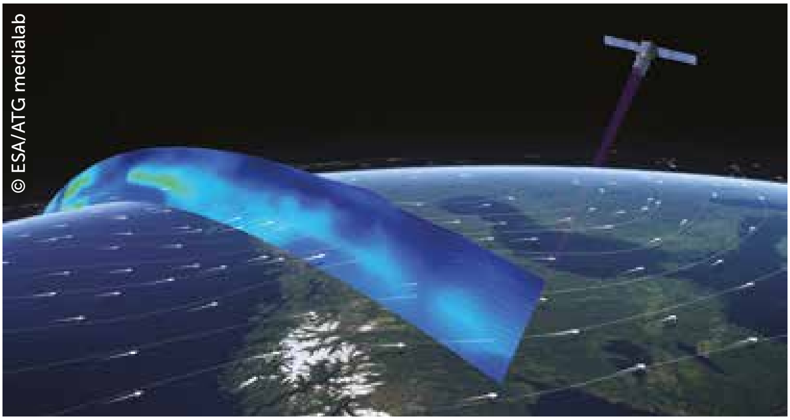
- Photonic sub-systems with the highest integration level (including standard digital interfaces and maximum ease of system integration): on-package solutions;
- Platform solutions with high-volume production: > 1 Million pieces per year;
- High-revenue products: > €10 million annual turnover;

[50] Statista, "Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025", Nov 2016.
[52] GrowthEnabler, "Market Pulse Report, Internet of Things (IoT)", April 2017.

- Sub-systems with wide application: > 100 business opportunities/ design-ins per year;
- Stabilized, narrow-line light sources for the 3-12 µm spectral range: < €10 per piece in volume;
- Stabilized, broad-band VISNIR light sources for 0.3-2 µm: <€2 in volume;
- Uncooled point and line photodetectors for 0.3-12 µm: <€10 in volume;
- Image sensors with >100×100 pixels for the 0.3-2 µm spectral range: <€10 in volume;
- Low-cost, high-reliability and calibration-free physico-chemical, wafer-scale surface functionalization;
- Micro-spectroscopy subsystems for gaseous and liquids samples: suitable form factor for integration into IoT/smartphone/tablet products.

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

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




## Cooperation needs with other disciplines or fields

Since it is evident that photonic sensors need to become "smart" through AI-empowerment, it is apparent that close and strong 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")[7].

However, 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). For this purpose, data 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"[56].

As a consequence, the convergence that will transform our business world is not restricted to IoT, and AI – deep cooperation and partial convergence with the respective fields of application 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 (see also figure 7), in particular, Smart Homes, Smart Cities, Connected Buildings, Green Utilities, Transportation, Healthcare, Agriculture and Food, as well as Manufacturing.

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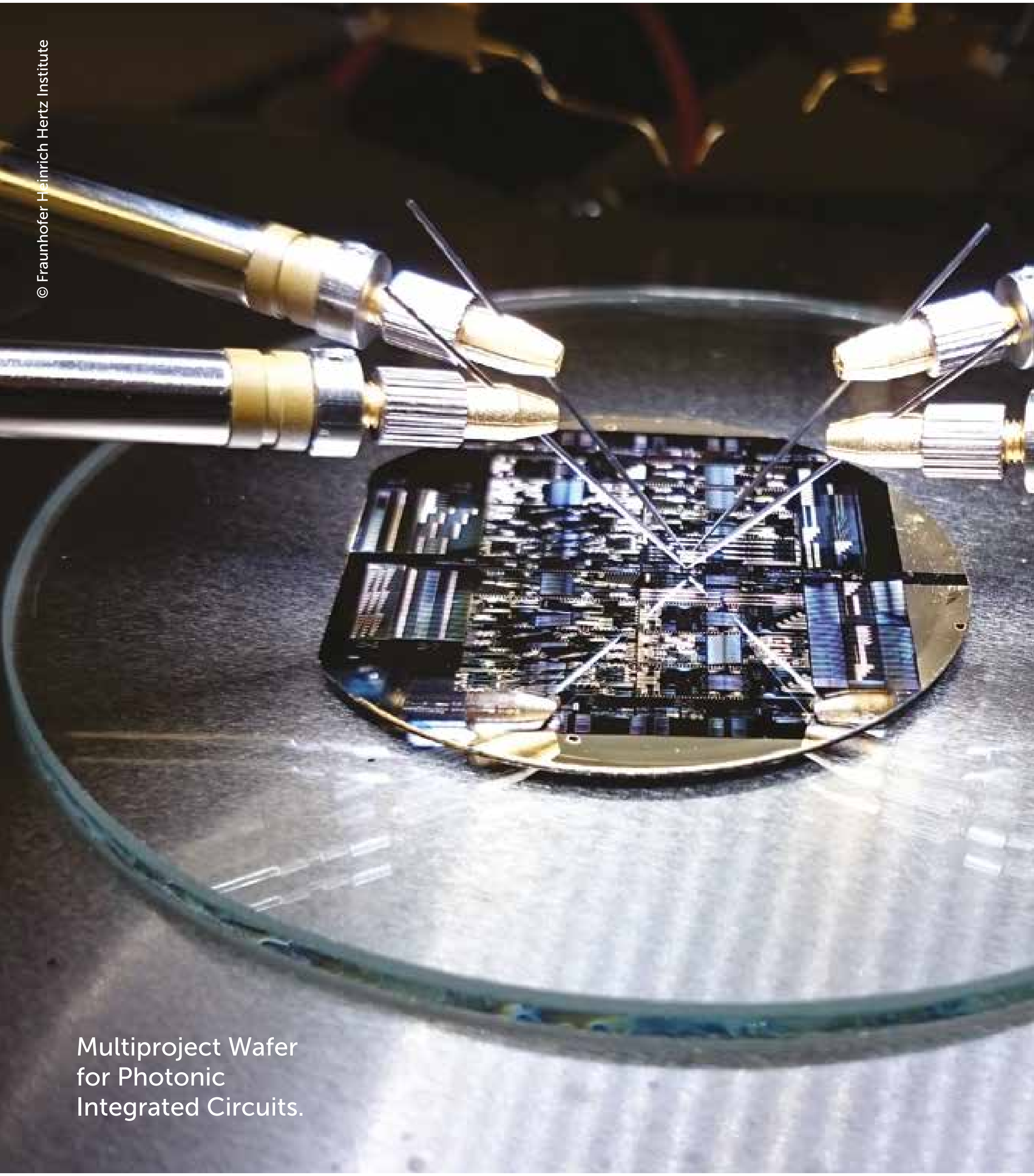
[56] PWC, "Leveraging the Upcoming Disruptions from AI and IoT", Feb 2017.

## Proposed roadmap for 2021–027

| | 2021 | 2022/2023 | 2024/2025 | 2026/2027 |
|---|---|---|---|---|
| **Overview**<br>**Technology Challenges** | • AI/ML empowerment of photonic solutions<br>• New materials/ fabrication processes for NIR/MIR components and sub-systems | Integration of cost-effective, low-power, miniaturised multi-analyte sensing system platforms Demonstration with cloud-based AI/ML engines | Novel concepts for "smart" multi-analyte photonic systems with built-in AI/ML data interpretation ("data at the edge": cloud-free autonomous systems) | Novel concepts for maintenance-free, self-calibrating, fault-tolerant, self-diagnosing "smart" multi-analyte photonic sensor (IoT) systems |
| **Critical milestones to move from Science to Market** | Alliances created between partners in Photonics, AI/ML and applications | PoC studies and demonstrations in selected high-potential applications and markets | Field tests in selected high-potential applications and markets | International market penetration with first MAPAIPBS products/ services |
| **Photonics**<br>**Research (R) & Innovation (I) Challenges** | • Lower costs of NIR/MIR components and sub-systems<br>• Create value through AI/ML empowerment of photonics solutions | • Miniaturise multi-analyte PIC-based photonic sensing platforms<br>• Select most promising applications for cloud-based proof-of-concept demonstrations | • Make sensor systems "smart" by embedding AI/ML engines<br>• Fabricate/ demonstrate cost-effective, autonomous high-value systems without cloud-computing | • Optimise user value through robust, self-calibrating "smart" products<br>• Focus on "green" products, including recyclable or biodegradable consumables |
| **Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)** | AI/ML and big-data analytics: Create tools and solution platforms for "smart" photonic sensor sub-systems | Identify high-impact applications in relevant markets: Health, Food/ Agriculture, Smart Cities, Transport, Industry 4.0, Secure Society | Joint spec creation, demonstrations and insight generation in relevant markets and applications | • Joint field tests and insight generation<br>• Mutual investigation of regulatory aspects and novel industry standards |

# 3.6 Design & Manufacturing of Components & Systems




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 report, 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 WG6 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, micro-electro-mechanical systems (MEMS), micro-electronics 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 priorities noted by WG5, Sensors and Internet of Things, 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 organizational 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, personalized 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.); Research & Innovation Action (RIA), Innovation Action (IA);
- Compact non-imaging monitor and sensor systems (Point of Care (POC) diagnostics, environmental scanners, etc.); RIA, IA;
- Photonics for augmented reality (not only for displays); RIA.

## 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, but it also has to be transferred. Today, a significant bottleneck for all big-, secure-data applications/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.

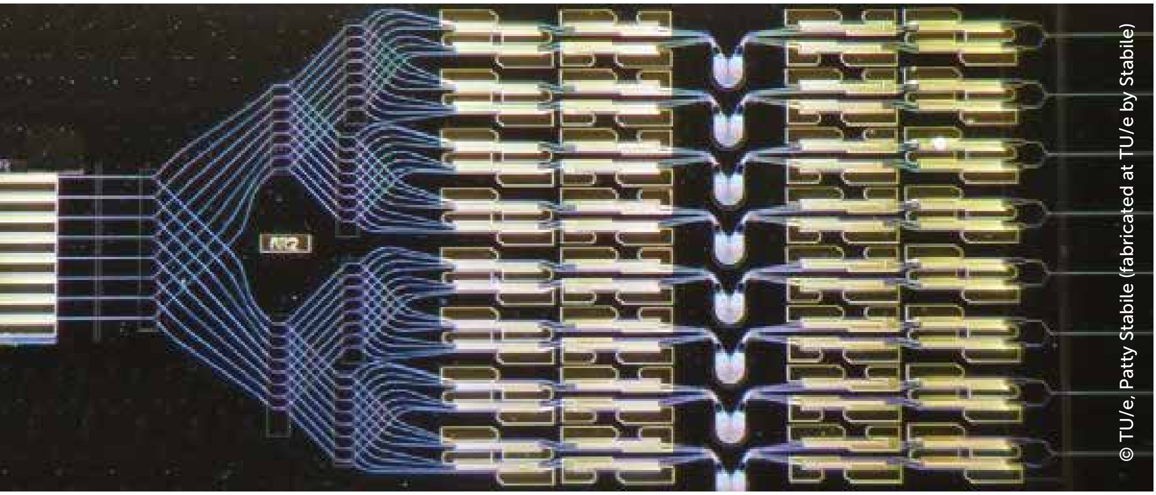
### Research and Innovation challenges

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

**Below:** Photonics systems lay the foundation for future innovation.



electronics and optics on a single die or on a single multi-chip module 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; RIA & IA.

– 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 ystems. We note that there will be a critical need for standardisation of all interfaces in such an initiative; RIA & IA.

• 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:

a) Increasing performance at acceptable costs for High-Performance Computing (HPC) and low power and ultra-low power computing,

b) Making computing systems more integrated into the real world,

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


c) Making "intelligent" machines, and

d) 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). RIA
- **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. RIA

### 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;
- Technology for free space optical communication, supplementing conventional RF wireless techniques for office, industrial and outdoor (e.g. automotive) applications;
- 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

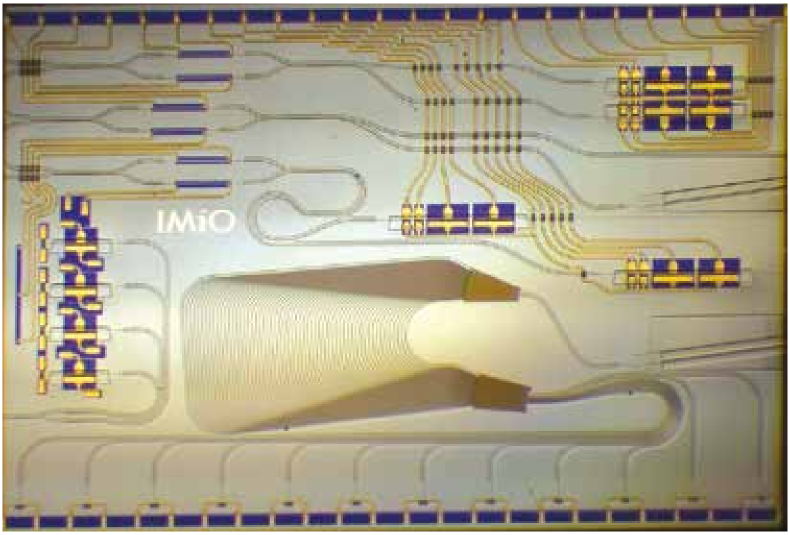
To serve all of our chosen application areas, our integration platforms need to be augmented with new functions and performance enhancements, requiring in many cases the development of new semiconductor materials and innovative device structures. We also emphasise the need for developments in the fabrication 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;

**Right:** Fiber sensor interrogator (Design: Warsaw University of Technology; Fabrication:Fraunhofer Heinrich Hertz Institute).






- High-efficiency semiconductor lasers operating at high temperatures (>85°C) across all wavelength bands;
- Incorporation of new building blocks such as magneto-optic elements for non-reciprocal functionality (e.g. optical isolation).

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. This objective should be addressed partly by RIA activities, along with specific innovation actions (IA) in which new equipment and processes could 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, in particular, 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.

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 users industry's competitiveness internationally. It may also constitute an evolution path for pilot lines and Horizon 2020 projects.

**Research and Innovation challenges**

The Innovation Factory Photonics should be implemented in a single IA, complemented by 1 to 3 RIAs:

- **Setting up a virtual Innovation Factory Photonics.** 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; RIA;
  - 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; IA.

**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 Road Map should be implemented in a Coordination and Support Action (CSA), covering both 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

As the mission of WG6 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 across the 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.

## Proposed roadmap for 2021–2027

| | 2021 | 2022/2023 | 2024/2025 | 2026/2027 |
|---|---|---|---|---|
| **Overview**<br><br>**(Technology) Challenges** | Photonic Components and Systems<br>Enhanced functionality, spectral coverage, performance to enable new applications<br>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**<br><br>**Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges** | Photonic Systems Integration →<br>PICS for sensing; PICS for communications →<br>Pervasive Photonics in Next-Generation Electronic Systems →<br>Enabling component technologies → | | | |
| **Joint actions required with other disciplines (e.g. Artificial Intelligence) or fields (e.g. robotics)** | Microelectronics, microfluidics, imaging sensors, MEMS →<br>Production equipment, techniques, materials →<br>Roadmapping, international liaison → | | | |

# 3.7 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 significant 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, economic growth and 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, economic growth and citizens' well-being, there is plenty of work still to be done.

Attracting the next generation to Science, Technology, Engineering and Maths (STEM) disciplines and science and engineering in 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 and industrial competitiveness.

Photonics education and exploitation should not be confined to the area of science and technology. The potential of light and light-based technologies offer incredible opportunities in social sciences, art and humanities, with a significant impact on everyday life.
The need to approach different and unexplored areas of applications requires, on the 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 the 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.

Active 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 significant role in supporting long term innovation. Topics that have seen significant 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 (2D-materials, nonlinear materials, Micro- and Nano-engineered materials, freeform optics, adaptive optics, laser-based advanced manufacturing and material processing, etc.);
- 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 primary challenge is to translate the new knowledge coming from fundamental research into real innovation potential, thereby making it disruptive. This requires a two-fold approach. On one side it requires a change of mindset: fundamental research should no longer be considered as a standalone priority, it should instead 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 can make the change, thus initiating and establishing the value chain.

On the other side, 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. This closes the values 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 essential 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 enormous 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;


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

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


- the mobility of students and a workforce have to be stimulated, since the required skill set is often highly specialised, with educational and industrial needs not often aligned geographically;
- lifelong learning programs should be set-up by academia 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 devoted explicitly 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.

## 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, nanotechnology, biotechnology, and advanced manufacturing.

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 adequately addressed. Cross-discipline work programs and actions should be foreseen to foster transversal knowledge creation and effective cooperation. Strengthening links with excellent science 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 a 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 significant 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 and high-quality urban life. Such a broad approach will help to direct technology developments and maximise their overall impact, thus fostering optimal exploitation of a cross-KET approach.

*"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."*


**Left:** Photonics experiments with the lego laser demonstrate the fascination for light among students.

## Proposed roadmap for 2021–2027

| | 2021 | 2022/2023 |
|---|---|---|
| **Overview**<br><br>**(Technology) Challenges** | Define skills for the future workforce and create the future photonics workforce<br><br>Outreach towards young minds and students, photonics and non-photonics professionals and the general public | Develop new approaches to Education & Training<br><br>Take up disruptive research in the Photonics Innovation Hubs and across the value chain; Support the creation of Photonics innovation hubs |
| **Critical milestones to move from Science to Market** | Create alliances with excellent science programs (ERC, MSCA, FET-Flagship) on one side and with programs focusing on applications and societal challenges<br><br>Identify favourable and unfavourable conditions regarding 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<br><br>Connect isolated Regions to Photonics hotspots<br><br>Expand the role of Photonics in STEM and social sciences/ humanities education and training programs |
| **Photonics**<br><br>**Research (R) & Innovation (I) Challenges, Education (E) & Training (T) Challenges** | R&I: Develop new knowledge through active cooperation between academia and industry at lower TRLs<br><br>E&T: team-up with industry for better tailored E&T programs, including life-long learning<br><br>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<br><br>E&T: Train researchers towards an entrepreneurial mindset;<br><br>Develop innovative platforms and tools for teaching and training<br><br>Continue to strengthen the presence of Photonics technologies in the FabLabs |
| **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;<br><br>Set-up interdisciplinary E&T programs including Photonics as a flagship science for digital innovation;<br><br>Team-up with experts in education and communication to include new instruments and approaches in Photonics E&T programs (e.g. gamification) | 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 |

| 2024/2025 | 2026/2027 |
|---|---|
| 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 |
| Bring Photonics technologies as key enablers in non-photonics Innovation Hubs | Expand the presence and position of Photonics in all products and technologies for the digital society |
| R&I: Increase the number of flexible facilities for closing the gap between new knowledge creation and industrial research<br>Increase the number of pilot lines<br>E&T: expand the use of photonics instruments and platforms in non-photonics E&T programs<br>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<br>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 |
| 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 connecting different enabling technologies for a more efficient approach to the development of innovative products and systems for new markets and new societal needs |

# 3.8 Agriculture & Food


Photonics technologies and the Internet of Things concept benefit smart agriculture

## 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 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 real-world needs of agro-food industries. Considering these visions, we ask: 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.

## Socio-Economic Challenges

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.

By utilising more precise connected sensors with the IoT, artificial intelligence and affordable, portable measuring devices, farmers, food processors and the public will be able to monitor and certify the safety, quality, content and origin of food – anytime and anywhere.

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[62], 24% of greenhouse gas emissions[63] 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. A growing concern is expressed about food waste: 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.

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

*"Food processing is becoming safer, more efficient and less wasteful thanks to photonics technologies such as optical sensors, imaging and labelling."*

- Photonics technologies contribute to a powerful toolbox for solving these challenges: 'agri-photonics' is already established as a fast-growing discipline in precision farming and environmental management.
- 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.
- Food processing is becoming safer, more efficient and less wasteful thanks to photonics technologies such as optical sensors, imaging and labelling. 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%[64].

**Pioneering solution: safe and transparent food production**
In a future of efficient high-tech 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 'no-gaps' 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.

- On the farm, sensitive imaging can detect the earliest onset of fungus, mildew, pests and disease, vastly reducing the need for agricultural chemicals. Spectrometry and laser scanning can detect produce ripeness and determine the perfect 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.
- Fluorescence spectroscopy can monitor amino acids, vitamins, allergens and other components in foods.
- At the retailer and consumer level, spectrometers connected via smartphones have already appeared on the market but are still limited

[64] 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.

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. A significant leap forward in protecting the European Union's 'Guarantee of Origin' system against cheap substitutes and counterfeit products will be made by photonics[65].

- Food and farming, including hydroponics and aquaculture, are a vast and complex area where photonics technology has already seen widespread deployment at many links in 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 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 the taste of produce. Research into specialised LEDs and lighting algorithms will optimise growth and yield in greenhouse and indoor

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

environments. 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 photonic sensors 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**
The agriculture and food sectors have unique characteristics that 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 help farmers understand and access new technology, 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 very careful to find the right balance.
- **Support technology uptake by smaller farms.** Unlike other agricultural superpowers such as the United States, Canada and


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

Brazil, 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 specialty 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

#### Introduction

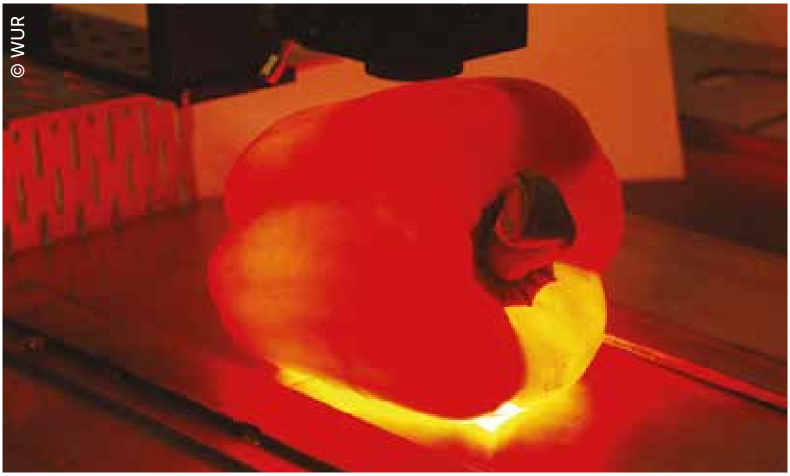
- **Short-term.** The meeting on September 24th 2018 confirmed the perception that the farming and food processing sectors are slow to adapt to new technologies. Low margins and fluctuating food prices limit farmers' willingness and ability to invest in new technology. Many players along the entire food value chain tend to rely on traditional know-how 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. Clients are therefore focused on discrete components rather than solutions on a chip.
- **Longer-term (2021 onwards).** The longer 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.

a) 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 were 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 putting 1500 sensors into one fibre and developed an 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. Use is made 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 being of interest 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




**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 based on the spectra are developed. Prototype developed at Wageningen University & Research.

mature. Scaling up sub-assembly, series production and operational functions of these products will, therefore, be imperative.

b) 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 have been agreed. Photonic sensors aboard aircraft, satellites and automated drones do much more than watching 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 just over 200 photonics companies in Finland, generating annual revenue of around €1 billion and employment for over 4000 highly-skilled professionals. About 50% of the companies are focused on serving the domestic forestry industry, and the other half is exporting its technology. The Finnish photonics sector is currently experiencing annual growth of 15 to 20 per cent.

c) 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-

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

narrow line width, as well as broadband tuning and is all packed into a small size. 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.

d) 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 other wavelengths than 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.

## Cooperation needs with other disciplines or fields

*Work Group 5 (IoT) describes the cooperation needed for Agro-Food with other disciplines.*

Photonic sensors need to become "smart" through AI-empowerment, and a 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**<br>**Technology Challenges** | Mapping and gapping:<br>• AI & photonic solutions<br>• Identify powerful applications | Mapping & gapping:<br>• Continuous alignment of crossover research agendas<br>• 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 novel products/ services |
| **Photonics**<br>**Research (R) & Innovation (I) Challenges** | • Precision agriculture and novel sensors<br>• Vertical Farms & autonomous systems through AI/ML empowerment of photonics solutions | • Miniaturisation/ featherweight sensor developments<br>• Select most promising applications for cloud-based proof-of-concept demonstrations | • Make sensor systems "smart" by embedding AI/ML engines<br>• Fabricate/ demonstrate cost-effective sensors aimed for a large number of sales (> 1000) | • Optimise user value through robust, self-calibrating "smart" products<br>• 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 on: AI & Photonics Sensors for field Robotics for autonomous navigation<br>• Exploit crossover calls | • Workshops on: Identify high-impact applications in relevant markets: Health, Food/ Agriculture, Transport, Industry 4.0<br>• Exploit crossover calls | • Workshops on: Joint spec creation, demonstrations and insight generation in relevant markets and applications<br>• Exploit crossover calls | • Joint field tests and insight generation<br>• Mutual investigation of regulatory aspects and novel industry standards |

# 3.9 Automotive & Transport




Self-driving cars rely on photonics technologies which provide essential components, systems and production tools for all aspects of connected mobility.


## Main socio-economic challenges addressed

The importance of the automotive industry for the EU's economy is crucial. 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 towers above the trade surplus of goods for EU-28, which was €22.9 billion in total in 2017, while the trade surplus for services was €133B in 2016[66].

Automobile taxation is a vital source of government revenue with €413 billion in fiscal income from motor vehicles in EU15 alone. Transport stands as one of the critical sectors of the EU economy: a total of 13.3 million jobs (6.1% of all EU jobs) represent this sector, with automotive manufacturing generating 2.5m jobs (8.3% of U employment in manufacturing) and another 0.9m 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 by far the world's largest investor in automotive R&D[67].

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 is €74.8 billion (nearly €80 billion in current prices), of which Smart, green and integrated transport receive 8.23% (€6.339 million)[68]. Therefore, EU-funded research represents less than 2% of the money spent on automotive innovation, yet the EU innovation funding is an essential factor to promote further innovation activity to ensure that the European automotive industry, and its suppliers, maintain and strengthen its position on the market.

It is promising that 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 higher value-added production in the future. 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.

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[66] 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 2018-10-16.

[67] Key Figures, ACEA, the European Automobile Manufacturers' Association www.acea.be/statistics/tag/category/key-figures. Retrieved 2018-10-16.

[68] Factsheet: Horizon 2020 budget, European Commission, Research and Innovation https://ec.europa.eu/research/horizon2020/pdf/press/fact_sheet_on_horizon2020_budget.pdf. Retrieved 2018-12-12.

## 3.9 Automotive & Transport

*"Sufficiently performing photonics sensors are one of the main roadblocks that prevent Europe from deploying fully automated and connected vehicles at scale."*

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[69].

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 to improve 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 roadmap shall be considered in this context.

**Right:** Photonics technologies enhance autonomous cars.

[69] 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 2018-11-26.

| EMPLOYMENT | | |
|---|---|---|
| Manufatcure of motor vehicles (EU28) | 2.5 million people = 8.3% of EU employment in manufatcuring | 2016 |
| Total (EU28m anufatcuring, services and const ruction) | 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 globlal motor vehicle production | 2017 |
| Passenger cars (world) | 80.2 million units | 2017 |
| Passenger cars (EU28) | 17.0 million units = 21% o f globlal passenger car produtcion | 2017 |
| **REGISTRATIONS** | | |
| Motor vehicles (world) | 97.9 million units | 2017 |
| Motor vehicles (EU27) | 17.5 million units = 18% of globlal motor vehicle registrations/sales | 2017 |
| Passenger cars (world) | 79.8m illion units | 2017 |
| Passenger cars (EU27) | 15.1 million units = 19% of globlal 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 $CO_2$k/m | 2017 |
| **INNOVATION** | | |
| Automoibles and parts sector | €53.8 billion | 2016 |
| **TAXATION** | | |
| Fiscal income from motor vehicles( EUl 5) | €413 billion | 2016/17 |

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

**Four main societal objectives driving the challenges**
There are four main societal objectives involving photonics technologies that are driving societal challenges:

1. **Autonomous vehicles and improved road safety** are important factors that can lead to the transformation of 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 automation levels 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 lost their life in 2017, and the Commission estimates that 135,000 people are seriously injured on Europe's roads every year[70]. Consolidated progress towards accident-free road transport has substantial societal benefits, concerning social and economic impact.

2. **Cleaner mobility** in every regard, such as electric vehicles or other forms of low emission vehicles, will be indispensable. Each generation has grown in mobility needs, requiring more cars per person, and with each person driving further distance. Although the trend provides strong benefits from a social point of view, it also brings complications regarding sustainability and greenhouse emissions. Both transport and the automotive sector, in general, need to reduce their environmental footprints, reducing $CO_2$ emissions in production and use[71].

3. **Reduced transport congestion (also concerning Urban Freight Transport – UFT)** that optimise the use of available road infrastructure is coinciding with a growing need for cleaner mobility and with it a critical improvement in the quality of life of all citizens and goods. Cities and urban areas are becoming more and more concentrated with enormous implications for the mobility of its citizens. The cost of road congestion in Europe is estimated to be over €110 billion a year, which is equivalent to 1% of its GDP[72].

4. **The digitisation of the automotive 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

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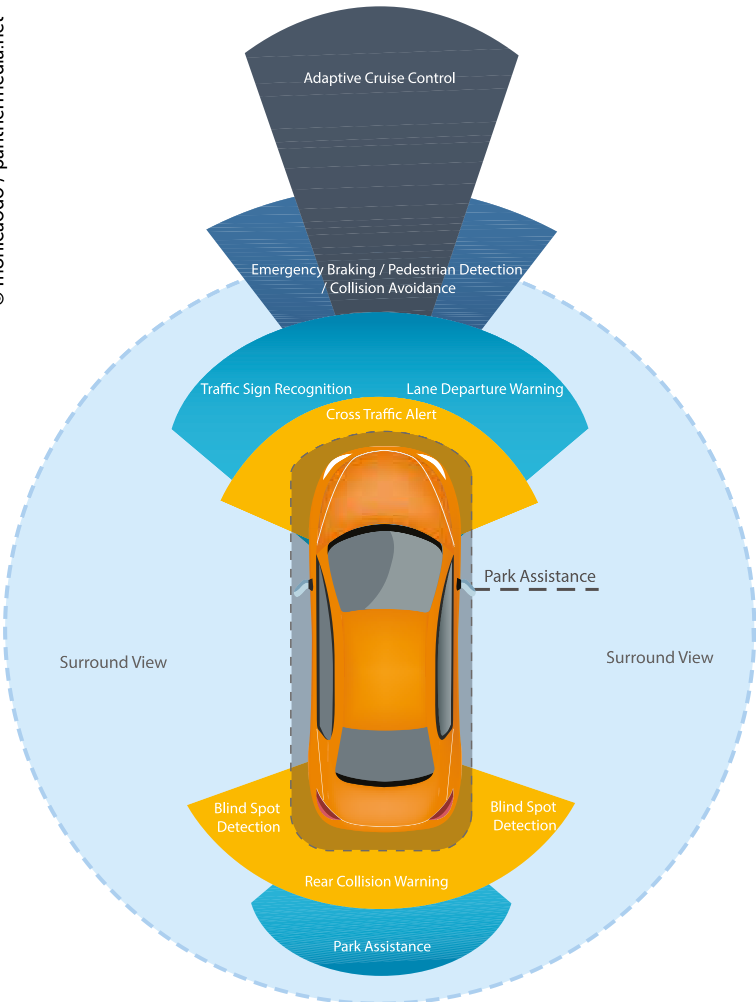
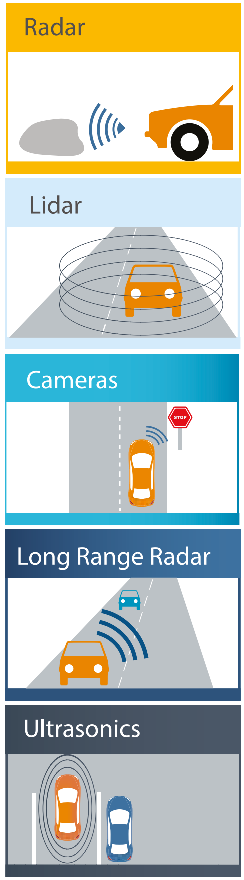
[70] 2017 road safety statistics: What is behind the figures?, European Commission – Fact Sheet. http://europa.eu/rapid/press-release_MEMO-18-2762_en.pdf. Retrieved 2018-10-16.
[71] Reducing $CO_2$ emissions from passenger cars, European Commission Climate Action. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en. Retrieved 2018-10-16.
[72] Measuring road congestion. European Commission, Joint Research Centre. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC69961/congestion%20report%20final.pdf. Retrieved 2018-10-16.

sector of transport. Novel connectivity will develop services and modes of transportation by using the communication from vehicles with other vehicles, with infrastructure, or with other road users (like pedestrians or cyclists). This connectivity paves the way to a plethora of new services for the driver and passengers which, in turn, create a wealth of jobs and economic opportunities. The development of mobility-based apps and novel functions to be added to a better-connected vehicle has enormous economic and societal implications and enable the more efficient use of the car of the future.






**Left:** Photonics components and systems used in an autonomous car.



These trends will need strong development efforts, where photonics technologies will play a key role in sensing or communication[73]. Addressing the four 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 players (e.g., Amazon, Apple, Google), which are developing autonomous technologies outside of Europe. It will, therefore, be essential to keep European competitiveness and leadership in the automotive industry to sustain jobs and economic progress.

**Significant photonic research and innovation challenges**

The trends presented may be achieved due to the convergence of a group of disruptive game changers which are appearing in the market. Such developments involve advances in the hardware, the software, and even the business models of the vehicles we knew in 2018. The disruptive technology changes will shape the transport 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 (e.g., 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 allowing eyes off the road[74] are ready for introduction, once the legal issues have been resolved. This trend is going to progress and consolidate as more and more pressure will be directed to development teams to advance the level of automated control of the vehicles further.

The level of complexity (and presumably costs) of the vehicle is expected to increase with rising levels of automation on roads. This is expected to introduce a revolution in our concept of mobility, and ownership of vehicles, which is generally referred to as Mobility as a Service (MaaS). In contrast with the current situation with mainly individual ownership

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[73] 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 2018-10-18.

[74] Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE SURFACE VEHICLE RECOMMENDED PRACTICE J3016, Jun 2018. www.sae.org/standards/content/j3016_201806/. Retrieved 2018-10-16.

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

*"The autonomous vehicle has the potential to bring a real social and economic revolution."*

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[75]. 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.

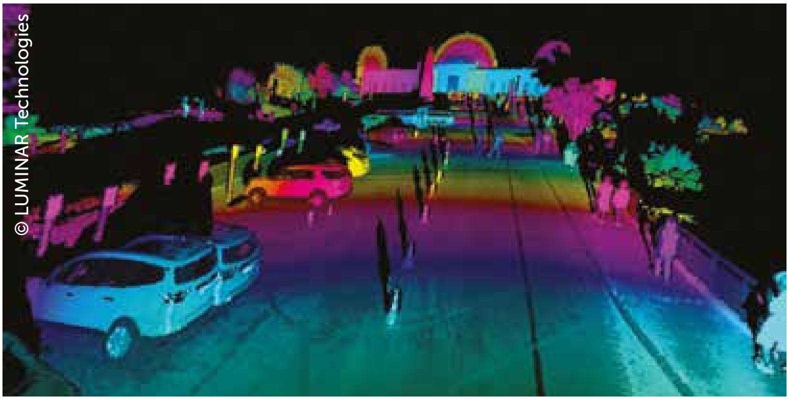
All of this will require novel concepts of vehicle capabilities in all transport modes related to connectivity. Such a change in paradigm requires the development and deployment of connected mobility systems which enable vehicle to vehicle (V2V) communication, vehicle to infrastructure (V2I) and the communication of the vehicle with other road users, especially with vulnerable road users such as pedestrians and cyclists (V2X – vehicle to everything).

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.

The identified technological needs involve the following key developments:

**Photonic sensing**

Improved and robust sensing capabilities at affordable costs are required (see the example point-cloud image as outlined in the photo by LUMINAR Technologies). In parallel to developments related to IoT




**Left:** Photonics technologies offer sensing capabilities.

[75] 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.

*"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."*

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

- 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 for the evaluation of its condition will be required. An entirely reliable evaluation of system state and performance, and the use of redundant systems to allow for fault-tolerant and resilient operation are needed for the sensor-set of the vehicle. Graceful degradation of sensor performance, when exposed to adverse weather conditions, is also essential.
- Key aspects to enable extensive industrialisation are the technologies' scalability, cost, packaging, and integration in future vehicles.
- 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. Does sensor fusion affect photonic sensor requirements?

**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 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 on page 137 in the photos provided by Daimler AG.

- Current ADB technologies that already have a high TRL will enable the development of cooperative lighting schemes, where optimal

**Traditional illumination**

**Glare-free illumination**

Example of glare free headlights. © Daimler AG

use of cameras, exterior illumination, headlamps, and infrastructure information has the potential to increase visibility in darkness or adverse weather conditions significantly;

- 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-efficient 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 achieve consumer benefits.

### 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 consist of different types, for example, warning symbols and driving path guidance. The photos by Daimler AG below illustrate some cases. Therefore, advanced lighting functionality will also be required in the most automated vehicles.

**Information projection**

Example of driver interface through projected symbols. © Daimler AG

- A high-resolution matrix-beam can project a large 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 ), together with the implementation of V2V and V2I communications will enable new capabilities of interaction between 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. This provides for integrating additional capabilities into the lighting systems. These novel designs should improve capacity, shape, and maintainability.

**Immersive Interaction**

Photonics technologies involvement in new tasks, such as in communication and entertainment of the passengers, is also 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 with the vehicle, both from the driver and passengers' point of view but also with other road users that in some way may interact with the vehicle.

Better, advanced HMIs are required to cope with the extended amount of information available through digitalisation, enabling safe vehicle control of the car. Successful implementation will require cooperation between the photonics industry and other areas such as human factors specialists.[76]

- The automated vehicle is expected to modify the patterns of vehicle use, enabling eyes off-the-road, from short-duration tasks such as email handling, web interaction, to longer duration tasks such as movies, reading, or gaming. The physiological effects of lighting under the new situation, which combine different levels of visual performance, together with aesthetics and comfort, will need a detailed analysis. Moreover, new strategies for monitoring the state of the occupants are required to sense their readiness to resume control of driving when called upon;

[76] 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 2018-11-15.

- A more immersive system interaction experience is expected to be the next trend in future vehicles. This involves various modalities, including novel displays which involve conformal, congruent, larger, frameless displays enabling multiple levels of three-dimensional engagement such as through holographic displays;
- 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 of relevant information in semiautonomous modes (SAE Level 2-3[74]). 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 (e.g., eye-tracking). The cockpit of the autonomous vehicle is still 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 and should be able to be utilised in an efficient way depending on the task at hand for the vehicle occupants in question. 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 use more and more enabling technologies based on photonics from consumer electronics, the costs should decrease, and the integration level should increase.

## Cooperation needs with other disciplines or fields

Automotive and transport industries are new end-users for photonics applications. It is evident that straightforward interaction with WG4 (Lighting) and WG5 (Sensors) is needed, and the whole Photonics21 partnership community has potential benefits from this interaction.

A human-centric design approach may be beneficial, where the changes introduced by the novel automotive 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.

Finally, high volume, cost-driven, established industries such as automotive and transport, require efficient integration of the components, systems, and platforms at large manufacturing scales. This implies strict quality assurance and cost control for successful introduction in the market at the pace required by the current technology change.

## Proposed roadmap for 2021–2027

| | 2021 | 2022/2023 | 2024/2025 | 2026/2027 | 2028 |
|---|---|---|---|---|---|
| **Overview**<br>**(Technology) Challenges** | Photonic sensing →<br>Affordable and efficient Adaptive Driving Beam →<br>Information projection →<br>Communication with Light (Lifi) →<br>Immersive Interaction with displays having new properties →<br>Compact optical systems for immersive Interaction → | | | | |
| **Critical milestones to move from Science to Market** | Sensing sufficient for automated highway driving<br>Highbeam always on, except where glare | Sensing and Adaptive Driving Beam adverse weather performance | Daylight versus night-time information projection requirements | LiFi range, bandwidth and immunity requirements | Distraction measures |
| **Photonics**<br>**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<br>Efficient light sources and optical systems with appropriate colour temperature and colour change abilities | | Wavelength selection<br>Communication protocols and interference handling | Virtual displays<br>Augmented reality<br>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 cognitive absorb information projection without causing a distraction | | V2X community | Human factors and ergonomics related to immersive interaction |

# 4. 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.

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:

- Information & Communication;
- Industrial Manufacturing & Quality;
- Life Sciences & Health;
- Emerging Lighting, Electronics & Displays;
- Security, Metrology, & Sensors;
- Design & Manufacturing of Components & Systems;
- Photonics Research, Education & Training.

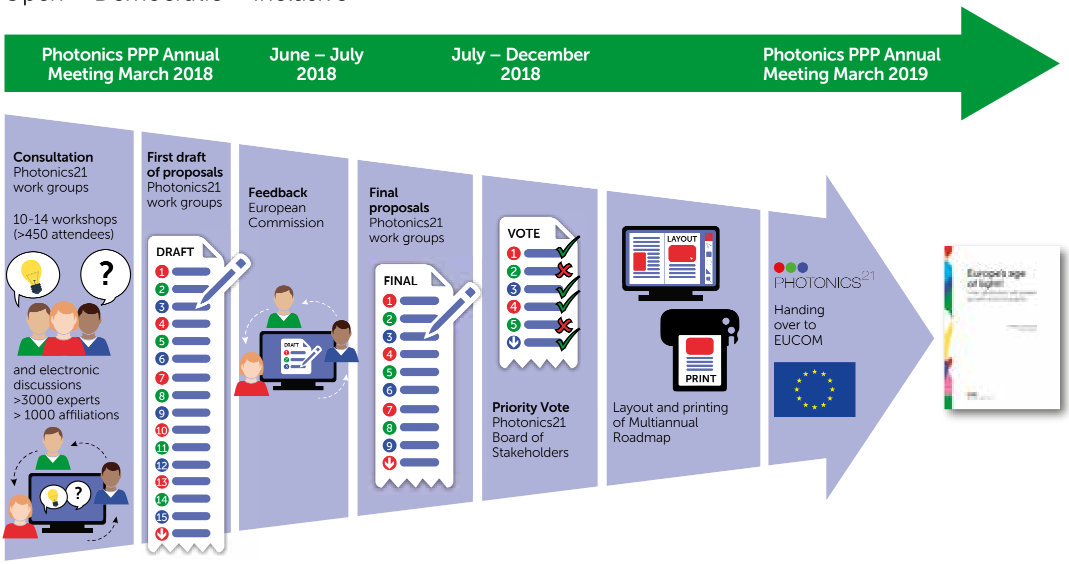
In addition to these two further work areas, which are also relevant to the European photonics community, focused on:

- Automotive & Transport;
- Agriculture & Food.

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.

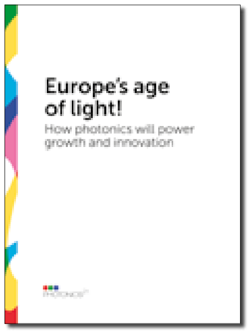
The collected workshop input was taken into consideration for the subsequent editing of the respective thematic chapters of the photonics roadmap.

**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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