European Innovation Council

EIC WORKING PAPER 1/2022

IDENTIFICATION OF EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS

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This paper was prepared by Maciej Lopatka (maciej.lopatka@ec.europa.eu), Alexandre Pólvora, Sivasegaram Manimaaran and Roumen Borissov at the EIC and SMEs Executive Agency of the European Commission under the supervision of Keith Sequeira. The content and descriptions of the thematic areas relies on a large part to inputs from EIC Programme Managers: Iordanis Arzimanoglou, Enrique Claverol-Tinture, Francesco Matteucci and Antonio Pantaleo. The paper benefited from various discussions within the European Innovation Council and involving many colleagues who helped develop the ideas, shared good practices and have provided valuable feedback throughout.

The authors would like to give their special thanks to the EIC Programme Committee Delegates, EIC pilot Advisory Board Members and the officials of the European Commission for bringing high-level expertise and relevant contributions and comments to improve the paper.

Manuscript completed in February 2022.

Luxembourg: Publications Office of the European Union, 2021

EN BOOK	ISBN 978-92-9469-122-4	Doi: 10.2826/702758	EA-05-22-034-EN-C
EN PDF	ISBN 978-92-9469-123-1	Doi: 10.2826/06288	EA-05-22-034-EN-N

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ABOUT THIS REPORT

The **European Innovation Council** (EIC) has been established to identify, develop and scale up emerging technologies and breakthrough innovations. This report presents **a number of emerging technologies and breakthrough innovations** that have been identified during a first identification process conducted in 2021 and assessed to be of high interest to the EIC given their potential for future technological, economic and social impacts. It relies on a range of inputs and the views and insights of **EIC Programme Managers**.

The identification exercise was the first to be conducted following the launch of the EIC in March 2021 and was used as an input and evidence base for the EIC Challenge areas included for funding support under the EIC Work Programme 2022.

In this and future years, this approach will be strengthened and updated for ever-evolving developments in the fields of technology and innovation. We will also continue to strengthen our methodological approach and range of data sets and analytical tools used. In this context we would welcome comments and inputs to continually improve our identification of areas, anticipate their potential, future-proof their relevance and reflect on their multiple value propositions.

THE EIC ROLE IN IDENTIFYING EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS

The European Commission launched the **European Innovation Council** (EIC) in March 2021 as a flagship initiative to identify, develop and scale up emerging technologies and breakthrough innovations. With over €10 billion of funding for years 2021-27, the EIC supports the most talented and visionary European researchers and entrepreneurs, along the path from ground-breaking ideas to success in EU and global markets. The EIC provides support through a primarily bottom-up model which allows the submission of breakthrough ideas from various science and technology fields that could impact a range of sectors and applications. This model is complemented by funding for **EIC Challenges** that target specific fields of emerging science and technology or breakthrough innovations of strategic interest to the EU.

In line with its mission, the EIC's focus is on emerging technologies and breakthrough innovations in any domain, which can be scaled up and create new and fast-growing global markets. These technologies may be at the very early stages of development, where the very first scientific ideas are being observed and tested, and new technological concepts being formulated, or in more mature domains where a novel technology has just been validated or demonstrated in a relevant environment but needs significant financing to overcome the remaining technology and market risks. What characterizes technologies of particular interest for the EIC is their ground-breaking nature, a strong scientific component and the potential for high societal and market impact that will in turn place the EU at the leading edge of the sectors and markets of the future.

The EIC's targeted funding is integrated within its three funding instruments, each corresponding to a different stage in the technology (e.g., technology readiness level, TRL) and innovation lifecycle:

EIC Pathfinder supports early-stage high-risk / high gain and interdisciplinary cutting-edge science that underpin technological breakthroughs; **EIC Transition** bridges the gap between the research phase and potential commercial applications; while **EIC Accelerator** supports start-ups and SMEs to scale-up and commercialise breakthrough technologies and innovations. In each case there are a range of opportunities and associated challenges that must be overcome, which in turn are factors to be considered in identifying areas for targeted EIC support as indicated in the table below.

EIC CHALLENGE [funding scheme]	EXAMPLES OF POTENTIAL OPPORTUNITIES	EXAMPLES OF CHALLENGES TO BE OVERCOME
PATHFINDER CHALLENGES [early-stage research on emerging technologies, TRL 1-4]	• Scientific breakthroughs creating new technology opportunities	• Properties and limits of technology not fully understood • Unexplored potential for multiple areas of application with major technology/ economic/ societal impact
TRANSITION CHALLENGES [maturing technologies and development of business plans for commercial application, TRL 4-6]	• Exploitation of innovations stemming from results obtained in EIC Pathfinder or European Research Council Proof-of-Concept (PoC) projects	• Identification of applications having major societal, environmental, well-being, or economic benefits • Robustness of new technology in real world environments, including societal aspects, not tested at relevant scale • Business model and route to market to be defined
ACCELERATOR CHALLENGES [innovation development and commercial scale up, technology readiness levels 5/6 – 9]	• Targeted support aligned to Challenges for SMEs including start-ups/spinouts from the EIC (Pathfinder, Transition)	• Lack of investment and support to commercialise and bring breakthrough innovations to market • Ensuring EU providers of strategic technologies • Incumbents blocking the development of breakthrough innovations

A FIRST SET OF EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS

The first iteration of the process carried out in 2021 (see methodology in Section 4) led to identification of a series of areas that have been grouped into three broad categories, corresponding to the main objectives of EU policy, namely 'Green Deal', 'Health' and 'Digital & Industry'. The areas identified were cross checked against other reports and methodologies, such as the report on "100 Radical Innovation Breakthroughs[1]") [1]. A number of these areas have also been included for targeted EIC Challenge funding in the EIC 2022 Work Programme.

1 https://ribri.isi-project.eu/index.html

AREAS OF EMERGING TECHNOLOGY/ INNOVATION IDENTIFIED

EIC CHALLENGES TO BE SUPPORTED IN 2022

GREEN DEAL

Areas of emerging technology/ innovation identified:

- Energy harvesting, conversion, and storage
- Cooling and cryogenics
- Industry and agriculture decarbonisation and pollution abatement
- Environmental intelligence and monitoring systems
- Water-energy nexus
- Sustainable, safe and regenerative buildings

EIC challenges to be supported in 2022:

- 'Mid-long term, systems-integrated energy storage' [Pathfinder Challenge]
- 'Process and system integration of clean energy technologies' [Transition Challenge]
- 'Carbon dioxide & Nitrogen management and valorisation' [Pathfinder Challenge]
- 'Fit for 55': higher clean energy conversion and use; decarbonisation of hard-to-abate industries; energy efficiency and safety in the built environment; zero emission mobility solutions; climate neutrality in the land use; water, gas and indoor air management/monitoring systems [Accelerator Challenge]
- 'Open Strategic Autonomy': sustainable and innovative approaches, including circular approaches to critical raw materials [Accelerator Challenge]

HEALTH

Areas of emerging technology/ innovation identified:

- Space-based regenerative medicine and tissue engineering
- Cardiogenomics
- AI-enabled drug discovery
- Companion diagnostics in cancer
- Optimisation of the healthcare continuum
- From single biomarkers to multi-marker big data maps
- High-tech mental health practitioner
- RNA-based therapies for cancer, complex, and rare genetic diseases
- Synthetic biology for industrial biotech
- Cell and gene therapies

EIC challenges to be supported in 2022:

- 'Cardiogenomics' [Pathfinder Challenge]
- 'Healthcare Continuum technologies' [Pathfinder Challenge]
- 'RNA-based therapies and diagnostics for complex or rare genetic diseases' [Transition Challenge]
- 'Open Strategic Autonomy': components, technologies and systems for the pharmaceutical industry; strategic healthcare technologies [Accelerator Challenge]

DIGITAL & INDUSTRY

Areas of emerging technology/ innovation identified:

- Next generation computing devices and architectures
- Chip-scale frequency combs
- Photon, phonon, electron triangle
- DNA-based digital data storage
- Alternative approaches to quantum computation
- AI-based local digital twins
- New uses of space
- 2D materials for low-power electronics
- Sustainable electronics [also GREEN DEAL]

EIC challenges to be supported in 2022:

- 'DNA-based digital data storage' [Pathfinder Challenge]
- 'Alternative Quantum Information Processing, Communication, and Sensing' [Pathfinder Challenge]
- Green digital devices for the future' [Transition Challenge]
- 'Fit for 55': green digital technologies [Accelerator Challenge]
- 'Open Strategic Autonomy': quantum technologies; edge computing applications; use of EU space infrastructures; space technologies, critical security technologies [Accelerator Challenge]

A FIRST SET OF EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS RELEVANT TO THE GREEN DEAL

In an era of very tense discussions on climate change, global warming, air, water and soil pollution the EU stands firmly as a front-runner and targets the very ambitious goal of (Europe) becoming a climate-neutral continent by 2050. This target seems very challenging when looking at where we stand today and the pace at which expected changes across different sectors are taking place. To limit global warming well below 2 degrees Celsius (compared to pre-industrial levels), reduce pollution and its negative impact on biodiversity and human health, there is a need for unprecedented joint efforts to be effectively leveraged by the development of breakthrough technologies and integrated solutions to disrupt current industrial and agricultural practices, and to propose new circular and sustainable consumption habits. A first set of areas of technology and innovation identified that offer breakthrough potential for the green transition are as follows.

Energy harvesting, conversion, and storage

Energy recovery, storage and conversion enable increased flexibility of energy systems, ensure more sustainable industrial processes, cross sector coupling and consequently contribute to the ecologic transition. The development of low cost, high round-trip efficiency, system-integrated and reliable solutions for mid- and long-term energy storage, based on life cycle and circular thinking approaches and without Critical Raw Materials, are important elements for efficient and sustainable future energy systems. In this area technologies such as metal-air batteries, power to heat, reactive metals energy storage, chemical looping, molecular storage, bio-inspired and engineered living technologies are of particular interest. In the field of heating/cooling storage or buildings/greenhouses integrated solutions, the development of innovative materials or innovative storage solutions, such as molecular based long-term storage, appear particularly promising.

This area draws on emerging technology trends such as: aluminium based energy, molten salt reactors, 2D materials, metamaterials, self-healing materials, hydrogels, hydrogen fuel, carbon nanotubes, optoelectronics, nanowires, airborne wind turbine, bioelectronics, graphene transistors, marine and tidal power technologies, smart windows, thermoelectric paint, wastewater nutrient recovery, artificial photosynthesis, flexible electronics and water splitting.

Cooling and cryogenics

Cooling, refrigeration, and cryogenics represent highly multidisciplinary sectors which are crucial in several value chains spanning from medical applications, data centres, agri-food, chemical and metallurgical industries. The demand for cooling is likely to overtake the demand for heating over the coming years and the whole cold supply chain requires added resilience and adequate technology advancement. Current systems and technologies for cooling and refrigeration are well established, but over recent years have not seen/provoked any breakthrough innovations. Smart interoperable solutions for electricity, heating and cooling network integration are also required, including for instance reversible heating and cooling infrastructures for buildings or districts, or cold-to-power solutions with waste heat, and cold energy streams recovery from industrial processes and/or air conditioning of buildings. There are several areas of research where breakthrough innovations are required, such as the use of artificial intelligence to increase energy efficiency, the development of advanced sustainable materials, innovative thermo-mechanical storage solutions, carbon-neutral cooling technologies for industrial and building applications, unconventional net-zero solid-state refrigeration principles, innovative concepts for CCUS leveraging on cryogenic and cold energy.

This area draws on emerging technology trends such as: nanowires, optoelectronics, flexible electronics, hydrogels and metamaterials.

Decarbonisation and pollution abatement in industry and agriculture

Global warming and water/air/soil pollution are unprecedented challenges for our planet. Key approaches to face climate mitigation challenges are based on more sustainable agricultural practices (nitrogen, methane emissions abatement, bio-fertilizers, biochar, carbon stocks), which may include the increase of photosynthetic efficiency and increased resilience of crops, and decarbonisation of hard-to-abate industries (decarbonisation of steel industries using electric furnaces, green hydrogen, reuse of industrial CO2 streams, near zero ammonia production and cross sectors coupling approaches). Breakthrough integrated solutions to disrupt the current agricultural and industrial processes, change human resource consumption habits and reduce pressure on natural resources are needed to guarantee the future of the planet. Managing and valorising CO2 and nitrogen (N) is a key-enabler to reduce greenhouse gases and nitrogen losses. The concept is twofold and in particular addresses: (i) a carbon-neutral cycle involving conversion of CO2 from various sources into high energy density fuels, energy carriers or other carbon neutral materials for industrial or agricultural applications. Such a management cycle involves CO2 capture (e.g., directly from air, through photosynthetic or biological processes), sequestration (e.g., through biophysical process), storage (e.g., through biogenic processes or in geological reservoirs), and further valorisation in added value products; and (ii) a N circular economy or N integrated management avoiding or minimizing its release (e.g., from industrial processes, manure and wastewater) while recovering (e.g., using physical or biological systems) and recycling (e.g., into agriculture or as ammonia fuel), reusing it as feedstock for added-value products or for biological fixation into renewable fuels.

This area draws on emerging technology trends such as: artificial photosynthesis, carbon nanotubes, bioplastic, plastic-eating bugs, wastewater nutrient recovery, microbial fuel cells, precision farming, bioelectronics, carbon capture and sequestration, splitting carbon dioxide, automated indoor farming, flexible electronics, metamaterials, plant communication, soft robot.

Environmental intelligence and monitoring systems

Intelligent systems based on AI methods are able to collect data on the environment, monitor natural resources as well as the climate and measure the human impact on the environment. They are fundamental tools to help us develop tailor-made strategies to mitigate or reverse the effects of climate change. Highly novel ideas bridging cutting-edge digital with green technologies into integrated intelligence systems for environmental applications can accelerate the green transition. Key areas for urgent innovations lie within early warning tools and low cost, interconnected, bio-inspired technologies for air, soil and water quality diagnostics, global warming measurements, early warning tools, leakage monitoring and pollution abatement systems.

This area draws on emerging technology trends such as: artificial intelligence, bioluminescence, underwater living, geoengineering: changing landscapes, precision farming, technologies for disaster preparedness, molecular recognition, artificial photosynthesis, flexible electronics, metamaterials, plant communication, soft robot and water splitting.

Water-energy nexus

Water resources have become globally more scarce, variable and uncertain while energy demand is increasing due to an expanding global population, economic growth and rapid urbanisation. Consequently, a more integrated approach to address challenges and opportunities of the water-energy nexus are needed. Water and energy are interdependent, as water is a key asset for energy systems, while energy is essential to extract, convey and deliver water for human use and for the treatment of wastewaters. The main areas of innovation in the water-energy nexus focus on water-efficient energy production (both electrical and thermal), coupled water and energy efficiency in buildings, combined energy and fresh water from solar energy and desalination, energy storage with water, wastewater treatment plant circularity, energy recovery from salinity gradients and heat.

This area draws on emerging technology trends such as: energy harvesting, water splitting, desalination, local food circle, precision farming, technologies for disaster preparedness, bioelectronics, marine and tidal power technologies, wastewater nutrient recovery

Sustainable, safe, and regenerative buildings

Considering the high-energy consumption of the construction sector, new multidisciplinary approaches for sustainable buildings offer a very high potential to accelerate the green transition. Bottom-up technological, social and policy innovation for adaptive integrated sustainable renovation solutions have already demonstrated decarbonisation pathways for the built-environment, both for urban and rural areas. Yet, there are still many outstanding challenges in the sector such as better integrating the energy generation, storage and end-use technologies in buildings and increasing energy efficiency – particularly for heating and cooling. Life cycle thinking and approaches need to be tailored to the particularities of the buildings/ construction sector. Living architecture concepts that enable buildings to adapt to their surrounding and adopt engineered living approaches provide further possibilities for regenerative transition, climate adaptation and improved management and use of resources in buildings (including energy, water, wastes, food).

This area draws on emerging technology trends such as: energy harvesting, smart windows, thermoelectric paint, hydrogen fuel, nanoleds, self-healing materials, underwater living, local food circle, technologies for disaster preparedness, 3D printing of glass, wastewater nutrient recovery, 3D printing of large objects, artificial photosynthesis, automated indoor farming, flexible electronics, metamaterials, soft robot, water splitting.

A FIRST SET OF EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS RELEVANT TO **HEALTH**

The last two years have demonstrated to an even greater extent, the importance of investment in, and adequate resources for health-related priorities, systems and emerging technologies. The coronavirus pandemic created unprecedented pressures on many national healthcare systems and underlined the need to improve our ability to prepare for such emergencies and establish clear priorities for health-related challenges including on the levels of investments and in establishing key partnerships. On the other hand, the coordinated effort from leaders and a mostly unprecedented level of global R&I partnership, building on the commitment of the scientific, medical, and pharmaceutical communities ensured the express development and manufacture of Covid-19 vaccines. The coronavirus is only one example of a global unmet medical need, but there are many others such as cancer, cardiovascular diseases, rare and genetic diseases, neurodegenerative disorders, diabetes etc. Other urgent requirements include access to adequate health infrastructures, new methods, processes and materials for pharmaceuticals or to enable the wider deployment of remote care and telemedicine. Many of today's challenges require pan-European and international collaboration involving health and other closely related sectors. In such a complex health and care setting, the EIC has identified a range of emerging technologies and breakthrough innovations.

Space-based regenerative medicine and tissue engineering

Regenerative Medicine (RM) is a rapidly growing area that aims to model human physiology and pathophysiology (Disease Modelling) by creating 3D bio-printed organs and tissues and using Organ-on-a-Chip (OoC), 3D cell culture organoids and other systems. OoC is increasingly regarded as a potential game-changing technology in RM/DM born from the convergence of tissue engineering and microfluidic culture technology. Despite that, the sector has not yet incorporated OoCs into routine diagnostic nor therapeutic processes because of a series of challenges and barriers requiring technological breakthroughs. In space, several profound changes take place in cells, including changes in cell signalling, cell aggregation or in the physics of fluid movement due to microgravity. A key focus could be on space-located experimental models for studying diseases affecting the heart, immune system, bones and muscles and include stem-cell based investigations, bio-printed tissues and gene expression. Experimentation outside earth conditions provides opportunities for discoveries that cannot be made on earth that might be fundamental in better studying key genetic and biological phenomena such as cell signalling and aggregation, the physics of fluid movement due to microgravity and gene expression. In the long run, stem cell-based and non-regenerative medicine including tissue engineering, which is the successful replacement of diseased organs or organ parts by in-vitro produced surrogates with potential for full integration into the patient's body, will impact the treatment of a wide range of conditions. Multiple reprogramming factors are known which can induce tissue de-differentiation and subsequent recapitulation of developmental stages, resulting in cell cultures anatomically and physiologically similar to the target organ. With a combined space regenerative medicine with tissue engineering approach, we have the potential to gain key insights into major biological functions related to areas of unmet medical need.

This area draws on emerging technology trends such as: bionics (medicine), Lab-on-a-chip, molecular recognition, bio-printed human parts, control of gene expression, epigenetic change technologies, microbiome, regenerative medicine, reprogrammed human cells, artificial photosynthesis, self-healing materials.

Cardiogenomics

Cardiogenomics holds the potential to address existing gaps in the diagnosis and treatment of cardiovascular (CVS) diseases, which would enable better patient outcomes. Combining genetic testing with the clinical phenotype can improve clinical management of CVS diseases and identify those likely to be at risk. Many gene variants associated with CVS diseases are of unknown significance and thus of limited clinical utility. Identifying potential pathogenicity, is a key challenge. Identifying potentially pathogenic mutations that have actionable effects will have a substantive impact on the practice of cardiology. The genetic basis of, not just classic inherited cardiovascular conditions, but major common diseases such as heart attacks and atrial fibrillation is yet to be uncovered. Deciphering the molecular pathogenesis underlying the pathology of a disease is key for personalized care. Our ability to sub-classify diseases according to their underlying molecular mechanisms, has been enhanced by technological approaches such as, spatial and single cell transcriptomics, and others.

This area draws on emerging technology trends such as: bioinformatics, gene editing, control of gene expression, epigenetic change technologies, reprogrammed human cells.

AI-enabled drug discovery

A recent surge of interest in the use of AI tools to target drug research, discovery and development is no surprise considering its wide deployment across many different sectors. The use of AI to efficiently analyse a vast amount of data and identify relevant patterns, not easily detected by humans could help design small molecules with desirable properties, and thereby help overcome the main bottleneck for advancing new medicines to the clinic. The technology has the potential to make the drug discovery process faster saving years of research, be more potent and cost-effective, better targeted and more specific, taking drug computational screening to next level. AI gives the hope of bringing new drugs, possibly personalised, much quicker to the market and potentially at more affordable prices. The Covid-19 pandemic has provided a tangible proof of the real potential and benefits brought to the sector through the application of AI technology.

This area draws on emerging technology trends such as: artificial Intelligence, artificial synapse/brain, Lab-on-a-chip, bioinformatics, gene editing, control of gene expression, drug delivery, epigenetic change technologies, microbiome, targeting cell death pathways.

Companion diagnostics in cancer

Cancer is a generic term describing a group of diseases affecting almost every organ/tissue of the human body provoked by the transformation of normal cells into tumour cells in a multi-stage process with potential to invade or spread to other parts of the body. Genetic factors and external agents such as physical (e.g., ionizing radiation), chemical (e.g., tobacco, asbestos) and biological (e.g., infections from viruses, bacteria) are key factors for cancer incidence, growing dramatically with age. Companion diagnostics is a key factor to achieve more effective and less costly cancer treatment in a personalized and precise manner for monitoring the progress of the disease. By identifying those who are more likely to see recurrence after treatment or develop side effects while also informing the right dosage to be administered, it provides a unique prognostic profile for every patient and ensures more efficient and effective treatment.

This area draws on emerging technology trends such as: control of gene expression, epigenetic change technologies, targeting cell death pathways.

Optimisation of the healthcare continuum

Today, public healthcare systems are based on an episodic i.e., symptom-triggered approach. To a large extent, individuals are entrusted with the responsibility to self-monitor themselves and trigger requests to the health system upon identification of relevant symptoms. While the episodic (reactive) model could be perceived as economically advantageous, drawing on healthcare resources only intermittently (when required by the individuals), it is not optimal when looking at the end result. In fact, in self-assessing their health status independently, individuals very often miss early signs of disease, sometimes with devastating results for themselves, but also for the healthcare system and associated treatment costs. The latest advancements in technology can support much needed progress towards continuous healthcare very efficiently, in which individuals are accompanied continuously and unobtrusively by health monitoring technologies and practitioners, proactively offering diagnosis, treatment or follow up at an optimal pace and with the optimal protocol as dictated by clinical evidence. Under this model, human beings will rely on technology seamlessly integrated into their lives and become recipients of proactive healthcare with minimal disruption and cognitive load. The burden of early disease spotting is shifted to unobtrusive technology. Successful examples of such technologies already exist e.g., continuous glucose monitoring (CGMs) devices in skin-patch formats, wearable ECG monitors, fall detectors, respiration monitors and SpO2 sensors, cell phone-enabled behavioural analysis and fitness devices. The full potential of the continuous healthcare model has not yet been fully embraced and some important challenges still lie ahead such as full-unobtrusiveness (environment-embedded, body-embedded, object-embedded, home-integrated, etc.), clinical grade reliability, and affordability. The hope is that future healthcare systems will be improving quality of live, life expectancy and save lives through technology-enabled optimisation of the healthcare continuum, from prevention through life-style changes by wearable technologies and home-based screening to hospital workflow optimisation and post-treatment remote follow-up software.

This area draws on emerging technology trends such as: artificial intelligence, bioinformatics.

From single biomarkers to multi-marker big data maps

In the last few decades biomarkers, cellular and molecular imaging, have been increasingly gaining interest within scientific and bio-medical fields. As measurable indicators of biological state or physiological condition they have been measuring and evaluating body fluids and soft tissues in order to determine the likely pharmacologic response to treatments and assess biological or pathogenic processes. Important advancements in digital technologies and miniaturisation have pushed progress towards smart digital biomarkers which have been emerging during last decade, mostly as biosensors and have been monitoring vital body parameters. The use of artificial intelligence for analysis of data collected by digital biosensors opened new opportunities for diagnostics in a clinical setting. A multi-parametric massively parallel multi-marker approach could move this quickly developing area to the next level. Integration of mass spectroscopy, capillary electrophoresis, use of array olfactory sensors (inspired by volatile compound diagnostics), disposal of full maps of protein content and application of AI tools into small-sized desktop units suitable for building large proteomic maps for diagnosis could also enable (with higher sensitivity), quicker and more specifically diagnostics for key diseases e.g., cancer, Alzheimer.

This area draws on emerging technology trends such as: artificial intelligence, bioinformatics.

High-tech mental health practitioner

Mental health disorders, conditioned by our lifestyles, more complex realities and genetic disposition, continue to grow worldwide with significant impacts on health, society and the economy. Their treatment may raise important ethical concerns touching on human rights. Mental illness may manifest through abnormal thoughts and emotions, anomalous behaviour and relations with others. Anxiety, depression, ADHD, bipolar disorders, psychoses, dementia, autism and other developmental disorders are the most common. Many different strategies for preventing mental disorders and sophisticated treatments to cure or mitigate their consequences exist and are widely operated. An extreme suffering from mental disease could provoke an extreme/ unwanted reaction like self-harm and impact those around the individual. The statistics show that more accurate early diagnosis is needed to reduce the risk of self-harm and alleviate related mental suffering. The increasing number of individuals affected by mental disorders requires novel approaches involving precise medicine (quantitative) non-invasive technologies for psychiatric diagnosis of mental condition and personalized treatments which can be used in universal settings, suitable for private psychiatric practices as well as hospitals. This may also involve more complementary approaches including for instance novel EEG headsets suitable for rapid placement and data acquisition, gut microbiome analysis and therapy, application of compact PET, fMRI, MEG, optoacoustic imaging and advanced techniques for behavioural analysis.

This area draws on emerging technology trends such as: brain functional mapping, brain machine interface, emotion recognition.

RNA-based therapies for cancer, complex, and rare genetic diseases

In the last decade, the advances in biological drugs development process have been constantly widening the spectrum of therapeutics for human diseases. Most of the technical challenges relating to the inherent instability of RNA, its potentially immunogenic nature or its delivery to targeted cells seem to have been overcome with the messenger RNA (mRNA)-based platforms. mRNA-based therapeutics are in the process of becoming an important new element for a wide range of diseases in the coming years. The COVID mRNA vaccines have expanded the already significant interest in RNA related research and taken mRNA manufacturing to a new level. The wide diversity of mRNA-based therapeutic applications including infectious diseases, genetic disorders, cancer, or HIV infection, has led to increased interest in using synthetic mRNA. For transfer RNA (tRNA) based therapies for rare and severe genetic disease, the aim is to create a portfolio of new tRNA-based therapeutic programs for patients with rare and severe genetic disease and advance these preclinical programs into the clinic. For small interfering RNA (siRNA) based therapies for complex diseases with high unmet medical need, the aim is to create a portfolio of new siRNA-based therapeutic programs in areas where no siRNA-based medicines currently exist.

This area draws on emerging technology trends such as: genomic vaccines, gene editing, gene therapy, reprogrammed human cells.

Synthetic biology for industrial biotech

Industrial biotechnology covers a wide range of application areas from health (enzymes, biopharmaceuticals, vitamins...) to food (food ingredients) to environment (pollution prevention, resource conservation) and others. Indeed, 60% of the physical inputs to the global economy could, in principle, be produced biologically. About one third of these inputs are biological materials (wood or animals bred for food) and the remaining two thirds are non-biological (plastics or fuels) but could potentially be produced or substituted using biology. New synthetic biology-based applications related to cancer, gut microbiology and environmental surveillance can be scaled up to provide (Europe with – do we want to say this, as the text until now has been factual and not EU/ Europe specific?) critical know-how and the capabilities to manufacture critical synthetic biology-based products and tackle key health, climate, and environment related challenges.

This area draws on emerging technology trends such as: bioinformatics, hydrogels.

Cell and gene therapies

Cell and gene therapies have the potential for a transformative effect in stopping or slowing down the effects of diseases by targeting them at the genetic level. When the genetic driver for a disease is known, patients can be molecularly matched to therapies. However, gene therapy clinical trials need to tackle two major current hurdles, in vivo efficacy and safety. Three decades of research in cell and gene therapy (CGT) have brought the field to a mature level creating reasonable hope that the new CGT therapeutic strategies and solutions will be more successful in the clinic to the benefit of our society However, new strategies are needed to mitigate the technological and supply chain risks, and complexity and specialized requirement when bringing CGT through clinical trials. Firstly, gene therapy SMEs are dependent on GMP-graded Contract Development Manufacturing Organizations. GMP-manufacturing is a critical bottleneck in the development of AAV vector-based therapies. Secondly, there is currently a capacity shortage of gene therapy doses, as multiple companies are performing more clinical trials leading to an unprecedented global increase in demand from local administration to systemic delivery. In addition, patient populations are also getting larger as gene therapy applications are no longer only targeting rare diseases. Thirdly, supply chain logistics in AAV vector-based gene therapies in the post-pandemic era are very complex and require strategies to navigate this period of change.

This area draws on emerging technology trends such as: gene therapy, gene editing, genomic vaccines, reprogrammed human cells.

A FIRST SET OF EMERGING TECHNOLOGIES AND BREAKTHROUGH INNOVATIONS RELEVANT TO **DIGITAL**

Nowadays digital technologies are omnipresent, facilitate almost every aspect of our lives, and influence the way we live and work. They have a profound impact on our economy, make it more productive and sustainable, but also foster progress in other areas such as scientific research and breakthrough technology development which are key drivers of sustainable growth and post-pandemic recovery. The most advanced industry sectors are driven by digital technologies which also facilitate the faster design and deployment of innovative solutions. Digital technologies could thus underpin future growth in Europe, foster an open and democratic society, enable a vibrant and sustainable economy, and contribute significantly to the fight against climate change. They are key enablers for achieving the green transition and public health system transformation. A first set of emerging areas likely to deliver a material impact to the digital transition and foster breakthrough developments are as follows.

Next generation computing devices and architectures

In the last half-century, computers have been shaping and redefining many different areas of our personal lives, our work, fostering our ability and capacity to understand ourselves and the world around us. Computing is an essential component in an increasing range of disciplines, from new materials through biology to drug discovery, but are also a core part of all digital devices. Since the beginning, computers have been driven by the same classical computing paradigm envisaged by A. Turing and J. von Neumann. In a digital age of exponential increases in computing demand, modern computers based on silicon and conventional architecture come to their limits defined by the laws of physics, but also face issues related to economics and reliability. The current computing performance, especially in certain kinds of problem domains such as weather forecasting, bioinformatics, robotics, and autonomous systems, is bound by the conventional computing paradigm. Revolutionary rethinking, harnessing physical, chemical, or biological process not previously explored as the basis for computing or operating existing devices in novel modes or regimes could potentially lead to radically new forms of computing with a clear and quantifiable advantage to address critical problems or applications. The main opportunities surround novel information processing devices and/or architectures based on unconventional computing paradigms (for example, but not limited to, chaotic, entropic, optical, bacterial or chemical computing), availability of a range of new computational approaches that will enable new solutions, including new forms of non-conventional knowledge automation beyond current AI trends, identifying and quantifying the limits of the current computing paradigms and associated input/output and interface aspects.

This area draws on emerging technology trends such as: computing memory, quantum computers, graphene transistors, neuromorphic chip, spintronics.

Chip scale frequency combs

Photonic integrated frequency combs (micro-combs) are a novel class of on chip frequency combs, generated by nonlinear parametric gain. In contrast to laser frequency combs, they are compact, offer large mode spacing that matches the telecommunication grid, can be integrated with other functionality, and most importantly are compatible with semiconducting volume fabrication. Over the past decade such micro-combs have made remarkable advances: they can now be operated battery powered and integrated with III-V gain media. They have been shown in numerous novel system level applications, ranging from terabit per second coherent communication, parallel LIDAR, to neuromorphic computing, to microwave generation or astro-physical spectrometer calibration. Frequency combs at micro-scale may soon leave the metrology lab and enter the mainstream, but before it happens some important challenges need to be addressed e.g., development of novel nonlinear platforms (GaP, Lithium Niobate), more efficient conversion efficiencies, extensions to new wavelength ranges, enabling new on-chip functionalities. By bringing the precision of optical frequency combs together with integrated photonics, it may become possible to firmly establish and deploy frequency combs widely, across all spectral regions with integrated photonic technologies. This will make them common in virtually all applications which requires multiple frequencies of coherent laser light. Priority areas include nonlinear photonics and microcomb generation in integrated devices which have clear potential of leading to unforeseen discoveries, as nonlinear interaction in complex systems may lead to emergent phenomena.

This area draws on emerging technology trends such as: high-precision clock, optoelectronics, quantum computers, quantum cryptography.

Photon, phonon, electron triangle

In recent years, interactions between photons (particles carrying light), phonons (quasi-particles carrying energy and momentum through lattice vibrations) and electrons (particles carrying charge) have attracted a lot of research attention because of their primary roles in condensed matter physics. Lattice vibrations on electronic states cause scattering, whereby electrons change their states by emitting or absorbing phonons. The interaction of electrons with an electromagnetic field will be represented as scattering processes in which electrons emit or absorb photons. In 2021, for one of the first times, a successful experiment demonstrated interaction between light and phonons to manipulate in a robust and controllable way, the propagation of lattice vibrations. In nano-electronic devices, interconnects i.e., the connections between various elements of the circuits use more energy than microprocessors. Charge-based (electron) and light-based (photon) approaches are well established for integrated on-chip information processing. Phonons less so, though they can be used to transmit information using small amounts of energy. This requires us to easily switch between (or combine) photon, phonons, and electrons as carrier of the same information (multi-state variables). The incorporation of the phonon in the list is crucial, as this is the showstopper in many upscaling or temperature operations above helium temperatures (and cryo-electronics not being an obvious route to take). The main challenges remain, like footprint, losses, frequency range (still too low) and their integration potential in order to exploit the potential of photon, phonon and electron triangle – multi-state variables in integrated devices.

This area draws on emerging technology trends such as: 2D materials, metamaterials, optoelectronics, spintronics, quantum computers, computing memory.

DNA-based digital data storage

In the digital era that sees the exponential growth of numerical content, the current approach and technology for big data storage and archiving will not be sustainable beyond 2040, mainly due to limitations related to energy consumption, the need for rare and toxic materials, and issues linked to data integrity over time. There is an urgent need to propose radically novel approaches to satisfy extremely fast increases of data storage requirements, none of which are currently sufficiently mature for deployment. Molecular carriers of information, such as DNA (used as a chemical rather than a biological agent) or certain non-DNA sequence-controlled polymers, are very good alternatives considering clear advantages such as information densities ten million times higher than those of currently used traditional memories, and stability at ordinary temperature for several millennia without energy consumption. Furthermore, data can be easily manipulated, multiplied, or destroyed at will. Some calculations can be physically implemented with DNA fragments. Moreover, DNA-based data storage can naturally benefit from the rapidly growing range of DNA research, newly developed breakthrough tools and techniques from the life sciences, while also contributing reciprocally to it (e.g., for in-vivo data collection). Proof of concept for DNA-based data archiving in vitro is now well established. Several studies have shown that such archiving can support selective and scalable access to data, as well as error-free storage and retrieval of information. However, technical challenges remain to make this process economically viable for a broad spectrum of data types. These relate to improving the cost, speed, and efficiency of technologies for reading, and especially writing and editing the medium, DNA or other polymers. Large corporates and governments are starting to show an interest and smaller companies offer solutions for certain archiving applications.

This area draws on emerging technology trends such as bioelectronics.

Alternative approaches to quantum computation

Quantum computation holds the promise of immense computing power beyond the capabilities of any classical computer. It has the potential to revolutionize many areas of science, technology, as well as our daily life. This new computational paradigm builds on the physical laws of quantum mechanics and exploits fundamentally new modes of computation. Since the first basic quantum circuit built in 1995, considerable effort has been made to understand and develop quantum-computing technologies. However, the field is still considered to be in its infancy. Novel approaches to encode, manipulate, and store information in quantum objects are needed to accelerate the development and the deployment of breakthrough innovations across many sectors, and enable new players to offer unique solutions for the architecture and critical building blocks of new quantum computing systems. Such innovations may then lead to applications in chemistry, material science, and logistics, among others. To ensure faster exploitation and take up of practical solutions in the realm of quantum computation, advancements in scalability and fault-tolerance in alternative yet promising approaches should be explored. Measurement-based computation using entangled states of light is such an approach that promises universality, scalability, and fault-tolerance. Key developments in state generation, encoding, system control, fabrication, software stack, and applications are needed to go beyond the conceptual stage and bring forward the full promises of the approach.

This area draws on emerging technology trends such as: flexible electronics, computing memory, quantum computers, optoelectronics, spintronics.

AI-based local digital twins

City planners, urban architects and policy makers require simulation models to understand, predict, design and manage future forms of cities to make them more sustainable, equitable and efficient. Local Digital Twins (LDTs) are digital replicas of cities that involve not only the physical aspects, but also the people and the influence of their decisions and behaviours. Cities are complex systems. To unleash the full potential of LDTs, a complexity science-based approach needs to be designed around different perspectives on cities, their structures and problems. Complex dynamical systems are self-organizing with various emergent patterns typically robust to reasonable disruptions. They are adaptive, and self-organization happens spontaneously in an efficient way. To reach expected outcomes, one needs to focus on interactions rather than on system components, and thus prepare designs and interventions consistent with self-organization and emergence. We need to observe and track the emergence of collective behaviour. If the system (city) does not change very quickly, we may be able to learn using optimization algorithms (top-down) or build hybrid, top-down/self-organized systems.

This area draws on emerging technology trends such as artificial intelligence.

New uses of space

Space technologies are widely used to explore space, understand the earth better as part of the universe, its climate, but also to get a different perspective on the human body and health. Space technologies deliver many everyday services such as telecommunications, navigation, security, weather forecast, remote sensing etc. Advances in these technologies ensure new opportunities and approaches to solve emerging societal challenges including climate change, violent weather events, or serious human diseases. Novel breakthrough concepts and approaches for access to space, its surveillance, more inclusive space transportation solutions, new applications of quantum technologies for space use, in-orbit testing/validation of new space-based services for a wide range of sectors (e.g. telecom, security, satellite navigation and tracking), earth observation or innovative use of signals and data collected by space infrastructure for new functionalities are clearly seen as enablers for breakthrough innovations across multiple downstream sectors.

This area draws on emerging technology trends such as asteroid mining.

2D materials for low-power electronics

ICT systems are the fastest growing consumer of electricity worldwide, with >15% of the total carbon footprint caused by computer data centres (expected to double by 2050). Power consumption in CMOS technology can only be reduced by reducing the on/off voltage in the transistor operation: for example, dropping the operational voltage by 70% would reduce the power consumption by 90%. The challenge is to use 2DM to create new materials for low-power semiconductor electronics, by optimising their characteristics through band gap engineering, enabling wafer scale growth of such materials, achieving room-temperature ferromagnetic semiconductors and their integration in components for scalable manufacturing.

This area draws on emerging technology trends such as: 2D materials, carbon nanotubes, graphene transistors.

Sustainable electronics

Electronics is one of the main underpinning industries supporting society today. The fast-growing ICT sector has significant carbon footprint, which is expected to double by 2050. Outstanding challenges in the development and production of ICT are, among others, the reduction of power consumption and the dependency on noble metals and critical raw materials. Sustainable electronics represent not only a need, but also a unique challenging opportunity for a decarbonized and digital society. Different solutions are under development to address these challenges, including: (i)use of sustainable materials such as bio-based materials as flexible substrate and non-conductive components, conductive carbon materials, bio-based organic and inorganic semiconductors, use of highly abundant and recyclable non-noble metals and metal compounds; (ii) use of scalable manufacturing processes including wet water-based processing, printing and additive manufacturing techniques, dry low temperature processing, minimizing process waste, and using safer and low toxicity chemicals; and (iii) implementation of new hybrid systems and devices, as well as implementation of self-powered devices and development of bio-inspired and hybrid systems (e.g., bio-electronics and interfaces with microbes, plants functionalization) including eco-design and circular-by-design strategies, self-healing and self-repairing materials, predictive maintenance strategies.

This area draws on emerging technology trends such as: flexible electronics, biodegradable sensors, bioelectronics, bioluminescence, energy harvesting, smart windows, self-healing materials, plant communication, 2D materials, nanowires, optoelectronics, spintronics, splitting carbon dioxide, graphene transistors, artificial photosynthesis, metamaterials.

METHODOLOGY USED TO IDENTIFY THE AREAS

The identification of emerging technologies and breakthrough innovations at an early stage is a challenge in itself. Our approach on this occasion was largely anchored in secondary research aggregating internal and external data, drawing on inputs from a diverse range of actors and information sources with wider strategic considerations related to EU priorities and policies also factored in.

Recognising that that it is not an exact science, a leading role was also played by the EIC Programme Managers. These experts are tasked with contributing expert technology and market knowledge to help identify and transform early technology visions into reality, advancing innovative projects and companies across the EIC pipeline from early-stage research to commercially successful innovations. The EIC Programme Managers thus played a key role in identifying the priorities outlined here based on the full range of inputs received. The steps taken can be broadly summarised as below:

THE METHODOLOGY INVOLVED THE FOLLOWING ACTIVITIES:

a. *Desk review of relevant literature such as third-party research, science and technology foresight and business reports, with particular attention paid to methodological and empirical differences [2][3][4][5][6];*

b. *Informal consultations across the European Commission services and with representatives of other EU funded bodies and initiatives (e.g., the European Institute of Innovation and Technology, EIT) to identify relevant policy priorities (e.g., Horizon Missions, EU industrial strategy, innovation drivers and barriers);*

c. *Multiple discussions and exchanges with researchers, entrepreneurs, and other key innovation stakeholders;*

d. *Thematic expert workshops in the areas of Digital, Green and Health organised by EIC Programme Managers and involving leading experts appointed by Member States;*

e. *Advice from members of the EIC pilot Advisory Board;*

f. *Portfolio analysis of proposals submitted and projects funded by previous EIC calls (including legacy programmes such as Future Emerging Technologies);*

g. *Content review of the projects funded under the EIC (including the legacy programmes) and ERC (European Research Council) PoC (Proof-of-Concept) instrument [7][8];*

h. *Consultation with Member States through the EIC and European Innovation Ecosystems configuration of the Horizon Europe Programme Committee.*

As part of the exercise, we also mapped the areas identified here against the list of Radical Innovation Breakthroughs composed of 100 emerging technology trends [1]. The goal was not to evaluate, or quality check the outcome of the identification process, but rather, to position these areas against these emerging trends. The areas identified in this first exercise cover more than one third of the emerging technology trends. It is also worth noting that some of the areas cover several trends, while others were linked to only one or two, and in some cases, none. This underlines the heterogeneous or novel nature of the areas identified, with some more traditional (mono-disciplinary), and others drawing together developments across different fields of science and technology thus representing new directions for breakthrough developments.

This first exercise was undertaken between April and September 2021. We are aware of potential shortcomings of our methodological approach and the limited extent of related activities. In keeping with the mission of the EIC, we have an ambition therefore to make the methodology more robust and improve the related process and activities with the aim of continuously improving the EIC's strategic intelligence and capabilities to detect potentially important emerging areas of technology and innovation, and to support them appropriately from an early stage.

OUTLOOK FOR THE FUTURE

At the **EIC**, we want to match the ambition of our most talented and visionary researchers and innovators and to work together towards a broader forward-looking capability in the coming years. We are aware that we can only do so if we are at the cutting edge of developments in science and technology, from early-stage ideas to market uptake across the world. We need to establish a continuous assessment process to monitor how the projects and sectors, supported by the EIC, are linked with, or compare to those across the globe and recognise weak and strong signals of breakthrough innovations in deep tech throughout the whole value-chain. We also need to observe and analyse the major trends and potential impacts at a scientific, technological, economic, environmental, social, ethical, legal, and policy levels as appropriate, to better assess their value proposition.

We are therefore already building on the first exercise and moving towards the co-creation of a broader and more structured permanent strategic intelligence framework, which will rely on three main intelligence types: Anticipatory, Collective, and Hybrid.

Anticipatory, as we will build up a short and medium-term future-oriented EIC toolbox for the detection and monitoring of innovation signals, trends, drivers, and more, via horizon scanning, and other foresight-based tools.

Collective, as we will ground the EIC on participatory models that can help us to mobilise a wider set of insights, from sense making to priority setting and decision-making, boosting stakeholder outreach and community building, and opening space for new partnerships.

Hybrid, as we will embrace a fusion of machine and human-driven multi-criteria analytics for EIC knowledge extraction and examination of past, present, and future-oriented data sets, from internal and external investment patterns to impacts on innovation ecosystems.

A first layer of this framework will allow us to develop and update the current overview of areas towards a multi-annual perspective that supports the work of EIC Programme Managers and other EIC activities. By way of example, this will see us improve our use of in-house data and combine it with third party data sets, alongside the development of advanced internal data analysis and visualisation tools, relying on novel resources and collaborations.

The role of EIC Programme Managers will also be reinforced, with up to six new EIC Programme Managers joining in 2022 to expand our expertise and coverage. A new collaboration between the EIC and the Competence Centre on Foresight of the European Commission's Joint Research Centre will also begin in 2022. This will comprise horizon scanning activities, data and text mining analytics and tools, and research on topics from new methods for signal and trend scouting to strategic visioning or immersive ways to experience potential futures. We will also look to further develop partnerships, such as with European Institute of Innovation and Technology (EIT) and European Research Council (ERC), including collaborations on data and strategic intelligence.

We understand that no future can be predicted even with the most accurate extrapolations of current data sets and the best expert insights. This is not the goal of the EIC strategic intelligence objectives. Rather, our intention is to use the best data, insights, and processes available to better guide decision making, avoiding oversimplification, and identifying high risk – high potential areas, sufficiently in advance to make an impact on their development and direction, from supporting early ideas, proofs of concept, or technology transfer, to the financing for scaling up high potential start-ups and SMEs.

We welcome comments, ideas, and new partnerships to increase, diversify and improve the EIC's capacity. If you wish to be part of the discussion, please contact the author including EIC Programme Managers on domain specific issues (their contact details can be found on the EIC website).

ANNEX 1:

LIST OF MAIN REFERENCE SOURCES USED AS INPUT FOR THE IDENTIFICATION PROCESS

- [1] 100 Radical Innovation Breakthroughs for the future, European Commission DG RTD (2019)
- [2] Science and technology trends 2020-2040, Exploring S&T Edge, NATO Science and Technology Organisation (2020)
- [3] Weak signals in Science and Technologies, European Commission DG JRC (2021)
- [4] An OECD horizon scan of megatrends and technology trends in the context of future research policy, OECD (2016)
- [5] Deep tech: the great wave of innovation, Hello Tomorrow (2021)
- [6] The top trends in Tech, McKinsey & Co. (2021)
- [7] Windows to the future around Top trends in Emerging Technologies. Roadmapping exercise, PREFET project (2020)
- [8] A glimpse on tomorrow's potential technological trends, technical report, Opscidia (2020)

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EN BOOK	ISBN 978-92-9469-122-4	Doi: 10.2826/702758	EA-05-22-034-EN-C
EN PDF	ISBN 978-92-9469-123-1	Doi: 10.2826/06288	EA-05-22-034-EN-N

Publications Office
of the European Union