TECHETHOS

FUTURE ○ TECHNOLOGY ○ ETHICS

Ethical and social impacts-driven horizon scanning of new and emerging technologies

Reflections and proposals on models and practices

Deliverable 1.3

Draft version submitted to the European Commission for review

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The TechEthos Project

Short project summary

TechEthos is an EU-funded project that deals with the ethics of the new and emerging technologies anticipated to have a high socio-economic impact. The project involves ten scientific partners and six science engagement organisations and runs from January 2021 to the end of 2023.

TechEthos aims to facilitate “ethics by design”, namely, to bring ethical and societal values into the design and development of new and emerging technologies from the very beginning of the process. Technologies covered are “climate engineering”, “digital extended reality” and “neuro-technologies”. The project will produce operational ethics guidelines for three to four technologies for users such as researchers, research ethics committees, and policy makers. To reconcile the needs of research and innovation and the concerns of society, the project will explore the awareness, acceptance, and aspirations of academia, industry, and the general public alike and reflect them in the guidelines.

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Definitions and abbreviations

Table 1: List of Definitions

Term	Explanation
New and emerging technologies	Any type of technology that performs a new function or improves some function significantly better than other commonly used technology, which is expected to be developed and deployed in the next 5 to 10 years[1]
Technology family	Set of technologies that are characterized by one or more of the following aspects: aim to perform similar functions; address similar goals/concerns/trends; are based on similar (scientific) working principles.

Table 2: List of Abbreviations

Term	Explanation
DoA	**Description of Action**
PC	Project Coordinator
WP	Work Package

[1] Definition adapted for TechEthos from OECD (2017) and EC (2018). See for details TechEthos D1.1

Executive Summary

This report provides a critical review of horizon scan studies on future technological developments performed by research institutions, businesses, and policy organisations at transnational (EU) and international levels. This served different purposes:

1) Find common practices and learn from the pros and the cons that horizon scanning can bring
2) Develop a model to carry out a horizon scan informed by potential social and ethical impacts (the TechEthos approach)
3) Distil a reasoned list of high socio-economic impact technology families, ordering and clustering hundreds of future technologies spotted by these studies.

TechEthos started its horizon scanning exercise considering that several authoritative and high-quality pieces of work had already been carried out on this topic in recent years. TechEthos took advantage of this situation and performed an in-depth investigation of the results and methodologies adopted by these resources. This analysis on already-published reports gave to the project with useful insights on past and ongoing experiences. We then developed a TechEthos specific "ethical and social-driven horizon scan" approach.

The first part of the report deals with the **review of practices and results of horizon scan initiatives** and the respective learnings for the TechEthos project. A comparison of these exercises is performed, looking for common elements and trends. From this, five significant analytical areas are identified: target audience, goals, tools and methods, technology focus (time horizon, granularity, taxonomy), and boundary conditions (impacts, trends, uncertainties). The analysis shows the variety of approaches used and results achieved by horizon scan exercises dealing with new and emerging technologies at an International, European, and National level.

The second part outlines the **TechEthos specific multidimensional approach, combining horizon scan methodology and impact analysis** to take industrial and economic, ethical, public, policy, and legal implications of technology development into account. It describes the key elements and choices of the TechEthos approach, and analyse the assumptions, constraints, and challenges faced in the analysis, based on the five analytical areas identified in the first part. Templates and guidance on how to apply this approach are provided.

- The **definition of criteria for impact assessment** is one of the novel aspects of this study. This has been inspired by the trends emerging from the analysis of resources (e.g., for public impacts, reference was made to sustainable development goals and the 20 principles of the European Pillar of Social Rights). The criteria are broad, qualitative, simple, and non-technical, to be assessed based on limited information and by experts from different disciplines (ensuring a certain degree of reliability). They are wide-ranging in terms of ethics, legal, and public principles and values covered, to adapt to the different possible impacts across sectors and areas of society of the identified technologies.

- We also developed a **novel method for the qualitative and multi-dimensional assessment of socio-economic impacts**. Our approach was inspired by Multi-Criteria Decision Analysis to create an impact assessment matrix to support decisions on the final choices of technologies with experts. This tool can be easily adapted and used for future studies.

The third part provides a **synthesis of socially and ethically disruptive future technologies**. We filtered and classified the hundreds of technologies emerging from the analysed reports, reducing overlap, and finding common ways of describing them. We also analysed the areas of application, the trends, and mega-trends identified by these reports. We made a qualitative assessment of socio-economic impacts on a selection of these technologies, against a set of specific criteria, following the TechEthos approach.

- Results have been summarised in a set of 35 technology families with a significant socio-economic impact, and later narrowed down further to a series of **16 families that have a high socio-economic impact with ethical relevance**.

- For each of these 16 families, **a factsheet is provided** including examples of specific technologies within the family, key industrial sectors of application, and an indication of potential ethics and socio-economic impacts. This provides a synthetic and easily accessible summary of several of the most relevant "future technologies" identified by the wide set of resources scanned for the analysis.

- A **taxonomy to classify and describe new and emerging technologies** is proposed, in terms of fields of application, disciplines, and indicates the different levels of granularity to use in the description.

- We further re-organised and merged some of the 16 families, to lead to a set of three that have been included in the **TechEthos technology portfolio: Climate Engineering, Extended Digital Reality, and Neuro-technologies.**

TechEthos will work on these three technology families to explore the interaction of technologies with the planet, the digital world, and the human body to develop operative ethics-by-design guidelines for researchers and innovators.

Eventually, we believe that this extensive, and documented TechEthos approach of combining horizon scan methodology and impact analysis provides a model for dealing with multi-dimensional challenges of new and emerging technologies.

1. Introduction

The goal of the TechEthos horizon scan was to identify a set of emerging technologies or technology families with a high socio-economic impact and significant ethics dimensions. This deliverable describes the assumptions and choices and reflects on the pros and cons, and the learnings of horizon scan activities, providing examples of models and practices for ethical and social-driven horizon scan. The process was performed through a critical review of the literature resources used in the TechEthos analysis, in terms of goals and methodologies, the type of technologies, application areas, trends, and socio-economic impacts. These are then compared with the overall TechEthos horizon scan approach and outcomes.

The TechEthos horizon scan led to the selection of three technology families with a high socio-economic impact and ethics relevance that are expected to be developed and deployed in Europe and worldwide in the next five to ten years. The process of technology families' selections is displayed in Figure 2 **Error! Reference source not found.**. Such results fed into the next phases of the TechEthos project, aiming to develop ethics guidelines for new and emerging technologies.

Figure 1: Word cloud of terms collected from the secondary sources for the TechEthos Horizon Scanning.

2. Methodology

The TechEthos horizon scan followed a stepwise approach (see Figure 2):

1) Identify
    - Scan of resources and identification of impact assessment criteria
    - Review selected resources and refine impact assessment criteria
    - Select a short list of technologies
2) Assess
    - Apply impact assessment matrix on the shortlisted technologies, based on expert review
3) Validate
    - Select final TechEthos Technology portfolio, based on expert review
4) Reflect
    - Provide suggestions for ethics and social impact-driven horizon scan method (TechEthos approach)

Within each step, an iterative approach combining quantitative and qualitative analysis, expert consultation, and review, has been applied to cluster, assess, and filter the families of technologies. This included:

- A series of interviews (6) with external experts on technology assessment and socio-economic impact analysis
- A desk analysis of a wide range of literature resources (described in this report)
- Data analysis on specific technology families, including data on patents (epo patstat database) and eu framework research projects (ait eupro database)
- A series of workshops (3) with external technical and social experts
- An online survey, including 77 external technical and social experts from 21 countries
- Meetings within an internal working group of multi-disciplinary experts (over 15 meetings), and several bilateral communications

Overall, almost 100 external and internal experts participated in the analysis. In the iterative process, we started with several hundreds of technologies, based on the literature resources described in this report, selected a list of around 150, then clustered in a set of 35 technology families, then filtered into 16, and finally a final list of 3 technology families.

The activities related to steps 1 to 3, leading to the final TechEthos technology Portfolio, were performed in about 10 months (January 2021- October 2021). Three reports have been produced, including this one that completes the task (step 4). Deliverables 1.1 and 1.2 describe in detail the impact assessment criteria, the assessment process, and the technologies identified.

This study focuses on a detailed analysis of resources used in step 1, then is compared with the overall TechEthos approach (step 1 to 3), to provide reflections on a revised methodology for ethical and social impacts-driven horizon scan (step 4).

This report starts from the comprehensive literature analysis used in the initial phases of the TechEthos horizon scan (deliverable 1.1.), including updated, and authoritative horizon scan exercises (e.g., technology assessment, foresight, and socio-economic analysis) from international organisations, think tanks, industry, governments, and other key research, technology and business actors at international, EU and national level. The focus has been on reports published in the last two years.

A set of 32 studies, the most relevant one used to compile the original list of technologies identified in D1.1, have been analysed for this report, in terms of their goals and methodologies, the type of technologies and application areas, the trends and factors, and impacts identified.

They are briefly analysed in section 3 of this report, following these categories:

1. European initiatives and projects
2. International and national public institutions
3. Consulting companies
4. Digital platforms

In section 4 a comparison of these initiatives is provided, to identify the most relevant aspects that influenced the TechEthos analysis. Section 5 resumes the outcomes of the TechEthos horizon scan, to explain the choices made in the analysis and reflect on its pros and cons allowing recommendations for ethical and social impacts-driven horizon scanning to be drawn.

A data set of hundreds of technologies emerged from these reports. Figure 1 shows a word cloud of terms obtained from these secondary sources consulted in TechEthos. A selection of these technologies has been clustered by TechEthos in a set of 16 technology families, as reported in section 5 (and described in detail in deliverable D1.1).

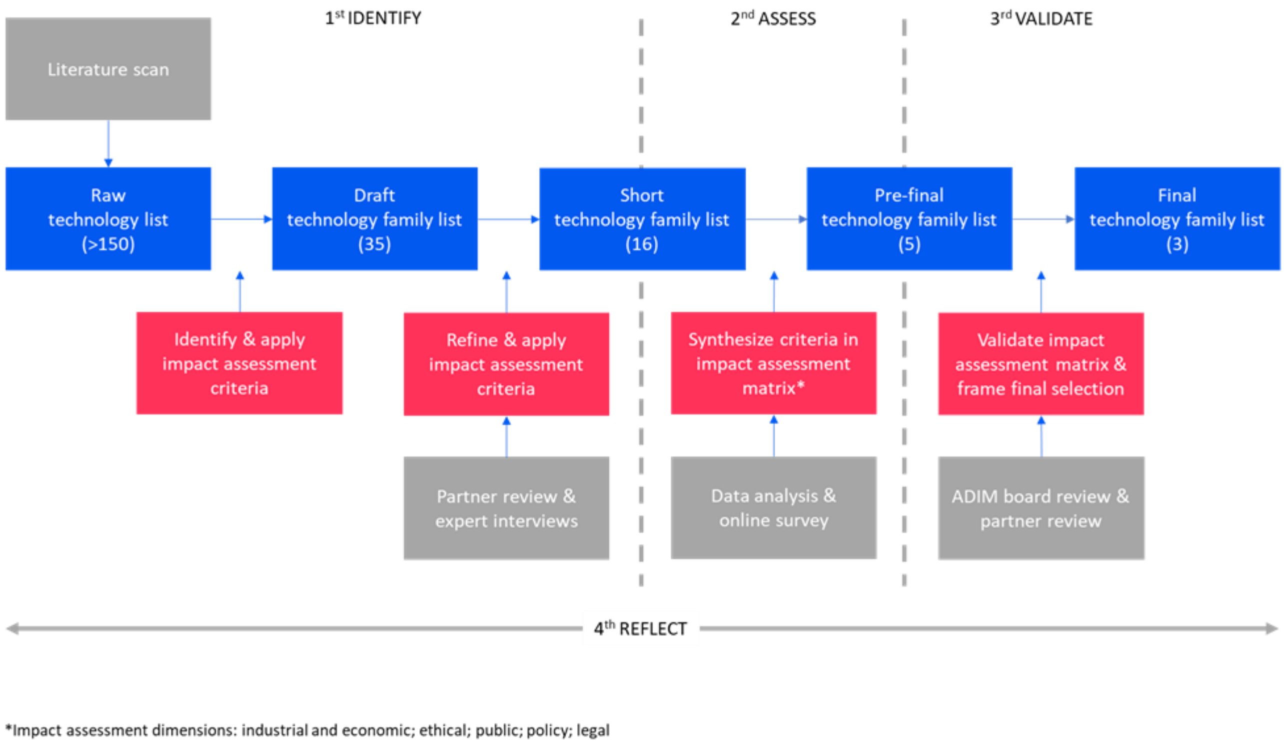

Figure 2: TechEthos horizon scan methodology for the technology family identification and selection: identify (Deliverable 1.1), assess and validate (deliverable D1.2), reflect (this report, deliverable 1.3)

3. Review of practices and results of horizon scan studies

The following sections (3.1 to 3.5) provide a summary of the main approaches and outcomes of a set of horizon scan exercises in terms of their goals and key outcomes (technologies and trends). As information publicly available on the methods & tools used by these different sources are quite limited, these have been summarized in a final section (3.6).

3.1 European initiatives and projects

When the TechEthos project started at the beginning of 2021, the task of performing a horizon scan of emerging technologies was far from being anything new in the EU research arena.

Already in 2008, the SESTI (*Scanning for emerging science and technology issues*) project (SESTI, 2011) was funded, and "*The overall goal of the project is to contribute to the development of an effective system for the early identification of weak signals of emerging issues". The project started knowing the fact that "Several countries, such as Finland, United Kingdom and the Netherlands, have initiated horizon scanning projects to identify disruptive events that are not on the RADAR of policy yet.*"

In 2009, the 3 years project EFP (*European foresight platform - supporting forward-looking decision making*) (EFP, 2012) was funded and resolved itself in a flavour of different activities like *"…providing and updating a knowledge-sharing platform for practitioners and newcomers; profiling of foresight and related activities and experts; a discussion forum for new activities, approaches, methods, and outcomes; providing support to policy makers, foresight practitioners and a wider audience interested in foresight and forward-looking studies; raising awareness of foresight and other FLAs (Forward-Looking Activities) as strategic policy instruments…*" Based on those types of experiences, in 2013, the policy brief (Cuhls K., 2015) "*Bringing Foresight to decision-making" by the RISE (Research, Innovation, and Science Policy Experts) envisaged "...the need for standards of quality and of good-practice for strategic intelligence and sense-making activities that the EC may wish to undertake…".* Soon after, in 2015, the report (Cuhls, K. et al., 2015), *Models of Horizon Scanning, How to integrate Horizon Scanning into European Research and Innovation Policies* was submitted to the European Commission by the Fraunhofer Institute and VTT Technical Research Centre of Finland, and the definition of Horizon Scanning was given to provide a reference guide for future EU Forward-Looking Activities (FLAs): *Horizon Scanning is the systematic outlook to detect early signs of potentially important developments. These can be weak (or early) signals, trends, wild cards or other developments, persistent problems, risks and threats, including matters at the margins of current thinking that challenge past assumptions. Horizon Scanning can be completely explorative and open or be a limited search for information in a specific field based on the objectives of the respective projects or tasks. It seeks to determine what is constant, what may change, and what is constantly changing in the time horizon under analysis. A set of criteria is used in the searching and/ or filtering process. The time horizon can be short-, medium- or long-term.*

This definition was adopted with one recommendation for the European Commission, "*There is not the one-fits-all possibilities Horizon Scanning model for the European Commission. The 'optimal' choice of a model depends a lot on the objectives and what the 'customers' in the European institutions really need".*

In the 2019 paper by Cuhls (Cuhls, 2019), *Horizon Scanning in Foresight – Why Horizon Scanning is only a part of the game,* the following narrative is adopted "*A broad range of experiences was represented in the cases: from completely automated Horizon Scanning processes to open searches via scouts (people), from national large-scale foresight processes to small, company-specific and target-oriented searches.*

There were resource-intensive processes as well as very small-scale and resource-saving approaches. Some examples intentionally pursued participation and stakeholder involvement, while others focused on expert participation, on single, detailed issues or automatically generated reports (dossiers). The Horizon Scanning results of the specified cases were communicated in reports, dossiers, newsletters (regular or irregular), internet platforms, in peer dialogues, or a combination of different channels".

The EU is committed to having research and innovation programmes aiming to strengthen science, technology, and innovation, fostering European industrial competitiveness, and helping to achieve the Sustainable Development Goals. In this perspective, several EU projects, reports, policy briefs, studies have been conducted to map the state of the art of the European technological landscape and to spot possible gaps with other countries. This distributed effort has produced different approaches with a variety of points of view and categorizations, as is shown by the few examples included in this section. A benchmark has been the definition in 2009, and a major update in 2015, of Key Enabling Technologies (KETs), i.e., those families of technologies of systemic relevance which provide the basis for innovation in a wide range of products and processes across all industrial sectors (emerging and traditional). In the most recent years, contributions came from several projects.

3.1.1 BOHEMIA - Transitions on the Horizon: Perspectives for the European Union's Future Research and Innovation Policies

The Bohemia project (BOHEMIA, 2018) aimed to support ongoing debates about European R&I policy by providing a view of needs and opportunities for R&I in Europe from the perspective of a time horizon to 2035-2040, and the result was a list of 19 target scenarios reported below (see Annex, Table 11 for more details). The approach provided an interesting insight into possible future R&I directions, trends and application areas,while giving only limited information on (future) specific technology developments. This is mainly due to the focus of the project on the type of applications and uses of technologies, the granularity of the scenarios, and the limits connected to long-term foresight exercises. The 19 target scenarios are:

- Assisted Living
- The Bio-economy
- Cheap Renewable Energy
- Continuous Cyberwar
- Defeating Communicable Diseases
- Emotional Intelligence Online
- Human Organ Replacement
- ICT-Based Security and Defence
- Low Carbon Economy
- Material Resource Efficiency
- Nano-to-Macro Integral Manufacturing
- Nature Valued
- Precision Medicine
- Reframing Work
- Smart Sustainable Mobility
- The Electro-sphere of Sensors
- Towards a More Diverse Food Supply System
- Towards a New Knowledge System
- Ubiquitous Expert Systems

3.1.2 Future technology for prosperity: horizon scanning by Europe's technology leaders

Future technology for prosperity report (Müller J., Potters L., 2019) is the result of a horizon scanning exercise orientated towards 'prosperity.' Europe's technology leaders, namely Directors of research and technology organisations and funding bodies from 18 European countries, convened in a workshop in Oslo in July 2019 and the final report recognize that "*there is no single answer to the question of what 'the next game-changer technology' will be. A variety and broad range of technologies were presented. However, common factors were the convergence of technologies and interdisciplinary cooperation as a breakthrough factor… instead of 'applications' we identified 'purpose' as the driver of creative and market relevant new solutions to sustainability challenges. We distinguished between 'needs' and 'demand' and discussed the task of policy makers to lay down the right framework conditions for successful business which itself respects inclusiveness and acts within environmental (planetary) boundaries"*. All this resulted in a list of 13 technologies distributed (see Annex section, Table 14 for more details) in 5 technological frameworks (outside ICT):

- Biological transformation
- Low energy data transmission
- Marine technologies
- Power to x
- Smart Materials

3.1.3 PREFET - Windows to the future around Top trends in Emerging Technologies. Roadmapping exercise

The PREFET project (PREFET, 2020) focused on detecting early-stage technology trends with relevant effects from 2020 to 2025 and beyond. These trends were considered in terms of strength as drivers for the creation of new science-based technological horizons, and the potential to impact the future of humanity and all other life on Earth. The project claimed the adoption of the most advanced data mining AI engines with human intelligence, the perception of citizens, and opinions from experts in the fields. The outcome was a list of 20 areas of major trends, along with three broad technology areas (see Table 19 in Annex):

- ICT for an interconnected society
- Biotechnology & Health Sciences
- Environment, Energy & Climate change

The topics related to *quantum Computing and autonomous systems* are in common with other research while the focus on *Arctic climate change* and *High-temperature superconductivity* could reflect individual sensibility inside the scientific board of the project.

3.1.4 SIENNA

The SIENNA project was designed to make an ethical analysis of human enhancement, human genomics, and AI and robotics. The project centred its research assuming a landscape of 50 emerging **Socially Disruptive Technologies** (SDTs) grouped in 4 domains, as detailed in Table 22 in the Annex section (NWO, 2021):

- Bio-Technologies
- Digital Technologies
- Energy & Environment
- and New Materials.

This is an interesting outcome, as these broad technology areas have been identified also by most of the other scan work analysed. Granularity in aggregating technologies remains large, for example for *Space vehicles* and *Energy Storage* but the list is rather complete in mapping the domain.

3.1.5 RIBRI - 100 Radical Innovation Breakthroughs for the future

The Radical Innovation Breakthrough Inquirer was an identification model at the heart of the RIBRI project and identified a set of **100 Radical Innovation Breakthroughs** (RIBs) organized under 8 thematic areas (see Table 21 in Annex for more details):

- Artificial Intelligence and Robots
- Biohybrids
- Breaking Resource Boundaries
- Electronics & Computing
- Energy, Society
- Printing and Materials
- Human-Machine Interaction & Biomimetics

The report has got a particular eye on those technologies expected to be game-changers in the coming future (RIBRI,2019). The list includes technical developments such as biodegradable sensors and 4D printing, as well as societal concepts such as basic income or car-free cities. A semi-automated process was used to identify and analyse the RIBs. A learning language-analysis algorithm analysed the contents of around 500.000 news items on scientific and technical platforms. Topics were filtered out that appeared for the first time during the period of investigation. These topics and any related patents and publications were evaluated by scientists from the respective field. The evaluation was carried out concerning the degree of maturity, the probability of widespread use in 20 years, and Europe's position.

The RIBRI project appears as one of the most complete sources of information identified. The list of 100 emerging technologies is presented with an attractive user interface in the project website and each topic has its score in terms of 7 parameters: Current Maturity, European Position, Significance by 2038, Patent EU, Country Leading in Patents, Publications EU, Country Leading in Publications. The RIBRI experience could be a basis for further improvement in the harmonization of the EU research activities about Horizon Scanning of technology developments.

3.1.6 EU takeaways

The full set of projects and reports in the EU area provides a tremendous amount of data and insights but, at the same time, the variety of representations (very detailed in RIBRI, organized under 4 themes in SIENNA, 13 technologies vs 5 frameworks in Technologies for Prosperity, looking at major trends in PREFET or scenarios in BOHEMIA) witnesses the **difficulty in providing a clear picture, based on a shared reference frame**. This gap leaves the door open to overlap and duplication of efforts and makes it hard to compare and aggregate the different results.

3.2 Public institutions and research organizations

In 1995, amid broader efforts to reduce the size of government, the US Congress eliminated funding for the Office of Technology Assessment (OTA). The agency, created in 1972 "*to provide Congress with early indications of the probable beneficial and adverse impacts of technology applications*" came under criticisms under different forms and in particular"…*the time it took for OTA to define a report, collect information, gather expert opinions, analyse the topic, and issue a report was not consistent with the fast* *pace of legislative decision making...and that the agency was inconsistent in its identification of ethical and social implications of developments in science and technology..."* (CRS,2020).

This story shows that Forward-Looking Activities or FLAs have started more than 50 years ago along with many controversies, in particular on the added value of this kind of research. Nevertheless, several national and international institutions routinely make their own horizon scanning exercises. We present here a short selection from the vast panorama of experiences.

3.2.1 Airi – Italian Association for the Industrial Research

Since 1995, Airi - Italian Association for Industrial Research (one of the authors of this report), publishes every three years a technology assessment and foresight analysis on the most relevant short to medium-term priorities for industrial research at the national level (1–3-year time frame). The study is based on the consultation of over 200 R&D Managers for private and public research.

The latest report was released at the end of 2020 and highlights the relationship between technology development, industrial competitiveness and investment, sustainability goals, and global challenges. (Airi, 2020). The report provides an overview of the Italian innovation ecosystems, and led to the identification of over 100 key technologies grouped into 9 relevant industrial scenarios:

1. Advanced Manufacturing
2. Chemistry
3. Digital Technologies
4. Energy
5. Environment
6. Health and Biotech
7. Microelectronics and semiconductors
8. Space
9. Transportation

The 100 technologies were selected based on criteria such as medium-long term competitiveness impact, time to reach the market, evaluation of the investment required, socioeconomic and environmental impacts, and alignment with EU R&D priorities, among others. The list of the selected technologies is reported in Table 10 in the Annex section.

The study is presented here, as it provided the authors of this report background knowledge and information to search and perform the analysis presented in this section. Data provided have as well contributed to the overall collection of future technologies used by TechEthos, similarly to all the other literature resources described.

3.2.2 Joint Research Centre (JRC)

In the EU JRC report, Strategic Foresight Report – The EU's capacity and freedom to act, is presented "*a forward-looking and multi-disciplinary perspective on the EU's capacity and freedom to act in the coming decades. Based on an expert-led, cross-sectoral foresight process, it presents global trends, uncertainties and choices that will shape Europe's future*" (JRC, 2021). The report provides the context for possible policy responses, and it is built on the 2020 Strategic Foresight Report, which introduces resilience as a new compass for EU policymaking through policy-driven foresight and horizon scanning exercises.

This report first identifies important structural global trends towards 2050 that will affect the "EU's capacity and freedom to act":

1. Climate change and other environmental challenges

2. Digital hyperconnectivity and technological transformations
3. Pressure on democracy and values
4. Shifts in the global order and demography

The report stresses the importance for Europe to make ambitious choices today, guided by its values and interests, across the identified policy areas. Therefore, the JRC study sets out the following ten priority areas to strengthen the open strategic autonomy and global leadership of the EU:

1. Sustainable and resilient health and food systems
2. Decarbonised and affordable energy
3. Capacity in data management
4. Artificial intelligence and cutting-edge technologies
5. Securing and diversifying the supply of critical raw materials
6. Ensuring first-mover global position in standard-setting
7. Building resilient and future-proof economic and financial systems
8. Developing and retaining skills and talents matching EU ambitions
9. Strengthening security and defence capacities and access to space
10. Working with global partners to promote peace, security, and prosperity for all and strengthening the resilience of institutions.

3.2.3 Massachusetts Institute of Technology - MIT

The 2020 Breakthrough Technologies list marks 20 years since MIT began compiling an annual selection of the year's 10 most important technologies, a list that they call a "*glimpse" into our collective future*. The selection of the items is not the outcome of internal research activities or a group of experts but rather an editorial choice (private communication) based on the flow of information managed all year by the *MIT Technology Review* editorial board. The 2021 choices included (see Table 17 in the annex for more details:

- Artificial Intelligence, multi-skilled
- Data trust
- Digital contact tracing
- Gpt-3
- Green hydrogen
- Lithium-metal batteries
- Messenger RNA vaccines
- Remote everything
- Tiktok recommendation algorithms

Looking at the data of all the 20 years in (Table 17 in the Annex section) it is interesting to note which technologies eventually became game-changers like Wireless Sensor Networks (2003), Grid Computing (2003), synthetic biology (2004), with others disappearing and others still on the table today, like Brain-Machine Interface (2001), and Natural Language Processing (2001).

3.2.4 Minister of Defence of United Kingdon (UK MoD)

The UK MoD report: Global Strategic Trends – The Future Starts Today (MoD, 2021), set out a future strategic context for the UK, first edition of GST was published in 2003. The 2021 edition stresses that: "We are at an inflection point. Many future trends are familiar; environmental stress and changing demography, accelerating technological change, the increasing importance of information, greater human empowerment, and national and international transitions in both economic, political, and military power. Much less familiar is the unprecedented acceleration in the speed of change, driving ever more complex interactions between these trends. The cumulative effect represents a strategic challenge that requires a strategic response." The DoD report concentrates its attention on specific scenarios of different geographic areas: Central Asia, Southwest Asia, South Asia, East Asia, Southeast Asia, Russia North America, Latin America and the Caribbean, The Antarctic, and the Arctic. The trends that require action according to the MoD report are:

- Increasing environmental stress
- Increasing human empowerment
- Power transition and diffusion
- Accelerating technological advancement
- Centrality of information
- Changing populations and evolving habitats

3.2.5 National Intelligence Council of United State (US NIC) Companies

The 2021 US NIC report: Global Trends 2040, a more contested world, is published every four years since 1997 to assess the key trends and uncertainties for the coming two decades (NIC, 2021). The report is designed to provide an analytic framework for policymakers, and the goal is not to offer a specific prediction of the world in 2040 but to help policymakers and citizens see what may lie beyond the horizon and prepare for an array of possible futures. The NIC works report the following four structural forces:

- Environment
- Technology
- Demographic & human development
- Economic trends

The NIC report describes the wide-broaden process of examining and evaluating previous editions of Global Trends for lessons learned, widespread consultations, data collection, and commissioned research synthesizing, outlining, drafting, and soliciting internal and external feedback to revise and sharpen the analysis. Furthermore, it focuses part of the work on conversations with esteemed academics and researchers across a range of disciplines and citizens to identify and understand biases and blind spots.

3.2.6 National Security Council – NSC (US White House)

The NSC (National Security Council) list was released in October 2020 under the Trump presidency and presented with a "market-oriented approach" rather than "state-directed models," which the administration claims, "produce waste and disincentivize innovation" and was based on a strategy that enabled the government to "protect themselves from unfair competition," citing China and Russia, specifically. The NSC listed 19 emerging technologies:

1. Aero-engine technologies
2. Agricultural technologies
3. Artificial intelligence
4. Autonomous systems
5. Biotechnologies
6. Chemical, biological, radiological, and nuclear (CBRN) mitigation
7. Communication and networking technologies
8. Advanced computing
9. Advanced conventional weapons technologies
10. Data science and storage
11. Distributed ledger technologies
12. Energy technologies
13. Advanced engineering materials
14. Human-machine interfaces
15. Advanced manufacturing

16. Medical and public health technologies
17. Quantum information science
18. Semiconductors and microelectronics
19. The Advanced sensing

This is more a list of broad families of technologies covering all disciplines, with no specific priority based on future impact. The official document with the list is no longer available and information on the 2020 NSC list can be found only indirectly on news digital platforms (Nextgov, 2020).

3.2.7 The North Atlantic Treaty Organization - NATO

The NATO **Science & Technology Trends: 2020-2040** report (NATO,2021) has a particular point of view as it provides an assessment of emerging or disruptive technologies for their potential impact on NATO military operations, defence capabilities, and political decisions. Nevertheless, many of the technologies cited in the report have dual-use and then can significantly impact well beyond the military applications. "*This assessment draws upon the collective insights of the NATO Science & Technology Organization (STO), its collaborative network of over 6000 active scientists, analysts, researchers, engineers, and associated research facilities. These insights have been combined with an extensive review of existing open-source S&T futures literature and selected national research programs*". (NATO,2021).

The resulting list distinguishes between Disruptive and Emerging Technologies (see Table 18 in Annex) according to the following definitions presented in this NATO report: "*For purposes of this report, we narrowly define technologies as:*

- ***Emerging****: Those technologies or scientific discoveries that are expected to reach maturity in the period 2020-2040; and are not widely in use currently or whose effects on Alliance defence, security, and enterprise functions are not entirely clear.*
- ***Disruptive****: Those technologies or scientific discoveries that are expected to have a major, or perhaps revolutionary, effect on NATO defence, security or enterprise functions in the period 2020-2040."*

The NATO report was first published in March 2020. The short list of Science and Technology (S&T) trends includes:

Emerging:

- Quantum (Technologies) (QT)
- Bio-(& Human Enhancement) Technologies (BHET)
- Novel Materials and Manufacturing (NMM)

Disruptive:

- Data: Big Data and Advanced Analytics (BDAA)
- Artificial Intelligence (AI)
- Space Technologies (ST)
- Autonomy

Among the Disruptive Technologies is Hypersonic (Weapon Systems) (HWS). In August 2021, China tests new space capability with a hypersonic missile (FT,2021).

3.2.8 The Organisation for Economic Co-operation and Development - OECD

The OECD gives high relevance to horizon scanning and, in its 2021 meeting "*Recommendation of the Council for agile regulatory governance to harness innovation*" (OECD,2021), the Council recommended the OECD member states to develop and adopt:

"... "1. governance frameworks and regulatory approaches so that they are forward-looking by developing institutional capacity and assigning clear mandates, accordingly, conducting systematic and co-ordinated horizon scanning and scenario analysis, anticipating and monitoring the regulatory implications of high-impact innovations, and fostering continuous learning and adaptation."

OECD is always committed in providing guidelines in the broader field of Technology Governance "*Technology governance can be defined as the process of exercising political, economic and administrative authority in the development, diffusion and operation of technology in societies. It can consist of norms (e.g., regulations, standards and customs), but can also be operationalised through physical and virtual architectures that manage risks and benefits. Technology governance pertains to formal government activities, but also to the activities of firms, civil society organisations and communities of practice. In its broadest sense, it represents the sum of the many ways in which individuals and organisations shape technology and how, conversely, technology shapes social order*." (OECD, 2020)

The OECD website contains many sections dealing with the governance of technologies, first in the health area, but it does not have its own list of emerging technologies. It does however produce many country reports. Among its publications, the most popular, and long-awaited each year, is the annual *Science, Technology and Innovation Outlook*. (OECD,2021) This is the publication where OECD elaborates recommendations to the policy makers. In the 2021 report "*remind that policy needs to be able to guide innovation efforts to where they are most needed*", "*underscores the need for transdisciplinary research … to address complex challenges*", "*link support for emerging technologies, such as engineering biology and robotics, to broader missions like health resilience*", demands to "*reform Ph.D. and post-doctoral training to support a diversity of career paths is essential for improving the ability of societies to react to crises*", "*global challenges require global solutions that draw on international STI co-operation" and put "policy emphasis on building resilience*".

3.2.9 World Economic Forum - WEF

The World Economic Forum (WEF) makes its annual horizon scanning exercise (WEF, 2021) convening, in coordination with Scientific American, an international steering group of experts to select a "Top 10 Emerging Technologies" likely to have a major impact within 5 years. The list of technologies for the year of 2021 includes (see Table 23 in the annex for more details):

- Ammonia goes green
- Biomarker devices go wireless
- Crops that make their own fertilizer
- Decarbonization Rises
- Diagnosing diseases with a puff of breath
- Energy from wireless signals
- Engineering a longer "healthspan"
- Houses printed with local materials
- Making pharmaceuticals on demand
- Space connects the globe

It's worth noting that items change completely from one year to the next and broad trends like "Decarbonization Rises" are there side by side with more specific ones like "Ammonia goes green". Overall, it seems that from circumstantiated technologies like "Microneedles for Painless Injections and Tests "in 2020, WEF changed its approach in 2021 towards general technological trends like "Making pharmaceuticals on-demand" and "Space connects the globe".

3.3 Business and Consulting Companies

"To discuss the future of emerging technologies for your enterprise, contact us". This is the typical statement that accompanies the description of research efforts carried out by private companies offering consulting services in horizon scanning and foresight activities. Consulting companies are most interested in technology trends that are critical to business: "*CEOs know they must accelerate the adoption of digital business and are seeking more direct digital routes to connect with their customers*," says David Groombridge, VP Analyst, Gartner (Groombridge D, 2021). Digitalisation is overwhelmingly the main driver of innovation and for many companies keeping the pace of digital transition is a matter of survival. This explains why most of the horizon exercises from consulting companies are in the field of digital technologies.

3.3.1 Consultants to Governments and Industries - CGI

CGI is among the largest **IT and business consulting services firms** in the world. They offer customized services for insights-driven and outcome-based to help accelerate returns on IT and business investments. the provide a map (Emerging Technologies Future Scan) with a future scan of maturing, scaling and emerging technologies contributing to driving innovation and change, including an elaborated classification into broad and specific technologies. They distinguish the two main categories of methodologies and technologies, a set of sub-categories and technologies:

Methodologies include

- *Creative*: innovation management, design, experience, agile
- *Technical: developments, cloud-native*

Technologies include

- *Channels: mobile solutions, augmented reality*
- *Data-Driven: advanced analytics, video analytics, artificial intelligence, digital twins*
- *Sensors and Automation: IoT, Intelligent automation*
- *Computing and Infrastructure: High-Performance Computing*
- *Security: cybersecurity, blockchain*

Then, there is a further splitting into peculiar items which are eventually accommodated into three levels of development: Emerging, Scaling and Maturing. The approach is peculiar to CGI, as none of the other organizations used it.

3.3.2 Deloitte

Building on more than 175 years of service, the network of member firms spans more than 150 countries and territories for a total of more than 330,000 people worldwide. Deloitte focuses on technology able to augment human decision-making, rethink the workplace and bolster equity initiatives (Deloitte, 2021). Deloitte is elaborating on trends of technology under 6 baskets: Business of Technology, Cyber & Trust, Core Modernization, Digital Experience & Digital Reality, Data and Analytics &Artificial Intelligence, Cloud & Distributed Platforms. Figure 6 gives a pictorial view of the baskets and the time series of technology trends since 2010. While Table 12 lists the detailed trends in the last 3 years. Both categories and subcategories which aggregate technologies appear as broad application areas whose definition is hard to compare year by year and different from a similar analysis of other consulting companies. For example, *Ethical technology & trust or Digital or Blockchain: Ready for business* are items in common with similar research but *the tech stack goes physical* or *Field notes from the future* are very peculiar to the Deloitte approach. The technology trends for 2022 are:

- Blockchain: Ready for business
- Cloud goes vertical
- Cyber AI: Real defense
- Data-sharing made easy
- Field notes from the future
- IT, disrupt thyself: Automating at scale
- The tech stack goes physical

3.3.3 Future Today Institute

The 2021 Tech Trends Report is designed "*to confront deep uncertainty, adapt and thrive. The magnitude of new signals required us to create 12 separate volumes, and each report focuses on a cluster of related trends. In total, nearly 500 technology and science trends have been analyzed across multiple industry sectors. Disruptive forces, opportunities and strategies are analyzed to drive organizations soon".* (FTI, 2021). The resulting list (see Table 15) is much on the same track as the Frost & Sullivan style but the grouping follows a different approach classifying the technologies by 7 clusters:

- Artificial intelligence
- Consumer
- Creative
- Enterprise
- Health
- Medicine and Science
- Research
- Talent.

3.3.4 Frost & Sullivan

For more than a decade, Frost & Sullivan's Emerging Technology experts provide the Top 50 Emerging Technologies Platform poised to effect change over the next 4 years. The 2021 Top 50 technologies program started with the team evaluating more than 3,000 technologies that are at a Technology Readiness Level (TRL) between 3 to 9 across corporate, government, academic, and research organizations worldwide (Frost&Sullivan, 2021). The result is shown in Figure 7 in Annex and gives a very informative picture. The technologies span 9 areas:

- Advanced manufacturing and automation
- Chemicals and advanced materials
- Energy and utilities
- Environment and sustainability
- Health and wellness
- Information and communication technologies
- Medical devices and imaging
- Sensors and instrumentation
- Microelectronics.

Using proprietary Frost & Sullivan methodology, each technology is evaluated considering market potential, IP activity, funding, Mega-Trend impact, regional adoption, sectors of economic impact, and disruptiveness to arrive at the Top 50 emerging technologies.

3.3.5 Gartner

The company's products and services include research, executive programs, consulting, and conferences. Gartner's clients include large corporations, government agencies, technology companies, and the investment community. In 2018, the company reported that its client base consisted of over 12,000 organizations in over 100 countries. Founded in 1979, Gartner has over 15,000 employees located in 100+ offices worldwide. Gartner releases every year a list of top strategic technology trends. Table 16 (in annex section) shows both 2021 and 2022 selections and 4 over 9 technologies survived the update. The naming of technologies varies from specific technology like *Generative AI* to broad methodologies like *Data Fabric* which "*provides flexible, resilient integration of data sources across platforms and business users, making data available everywhere it's needed regardless where the data lives*". (Gartner,2021). The list of top emerging technologies in 2022:

- Artificial intelligence engineering
- Autonomic Systems
- Cloud-Native Platforms
- Composable Applications
- Cybersecurity mesh
- Data Fabric
- Decision Intelligence
- Distributed Enterprises
- Generative AI
- Hyperautomation
- Privacy-Enhancing Computation
- Total-experience (TX)

It's worth noting that Gartner does not start from scratch every year, but some technologies keep being listed in multiple years. Besides the list, Gartner adopts a meaningful insight, the hype cycle (see Figure 3), which is a graphical presentation on how technologies go through five phases of maturity, adoption, and social application. The hype cycle provides a view of how a technology or application will evolve over time, providing a guide on how to manage its deployment within the context of specific business goals.

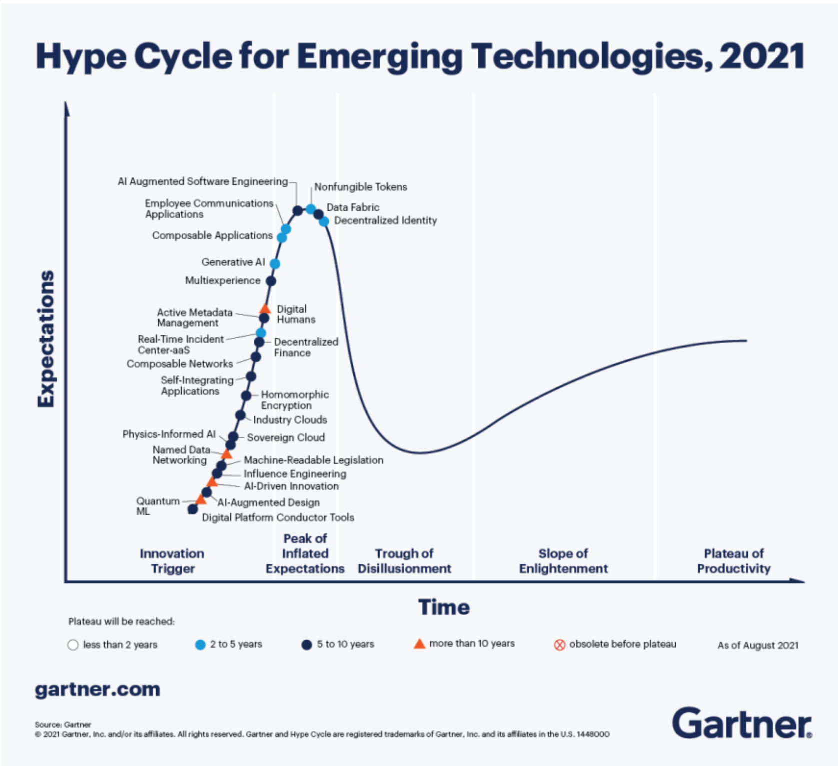

Figure 3: Example of Gartner Hype Cycle for emerging technologies.

3.3.6 Lux Research

Technologies are ranked based on proprietary data but also at the rate of improvement, innovation history, and other factors. Rankings are not only a function of the innovation data but also the insight of domain experts on Lux's analyst team. For example, flag technologies with high innovation scores may still face market roadblocks that make them dubious bets, or technologies that have less impressive scores but fit a key unmet market need, will enable them to make a major impact.

1. 3D printing
2. Alternative proteins
3. Artificial intelligence-enabled sensors
4. Autonomous vehicles
5. Bioinformatics
6. Green hydrogen
7. Materials informatics
8. Natural language processing
9. Plastic recycling
10. Precision agriculture
11. Shared mobility
12. Synthetic biology

The final choices presented in the above list are thought "to represent a breadth of innovation across energy, materials, health but digital innovations would dominate the list due to the world's intense recent focus on digital transformation". (Lux Research, 2021)

3.3.7 McKinsey

As described in the latest McKinsey report, "*In the next decade, we'll experience more progress than in the past 100 years combined*, *as technology reshapes health and materials sciences, energy, transportation, and a wide range of other industries and domains. The implications for corporations are broad. New convergences between technologies, startling breakthroughs in health and materials sciences, astonishing new product and service functionalities, and an irresistible foundation for the reinvention of companies, markets, industries, and sectors."* (McKinsey,2021).

The McKinsey graph (see Figure 4) is much more than just a list of topics and tries to figure out the time scale of the expected industrial impact of the different technologies. It shows that *Applied AI* is a cross-cutting technology with *High Industry applicability* but at the Market-entry stage in terms of *technical maturity*. Beyond the digital world, McKinsey points out how the *Bio revolution* is little above Nanomaterials, both on their way to enhance from the Niche/Fundamental Research status.

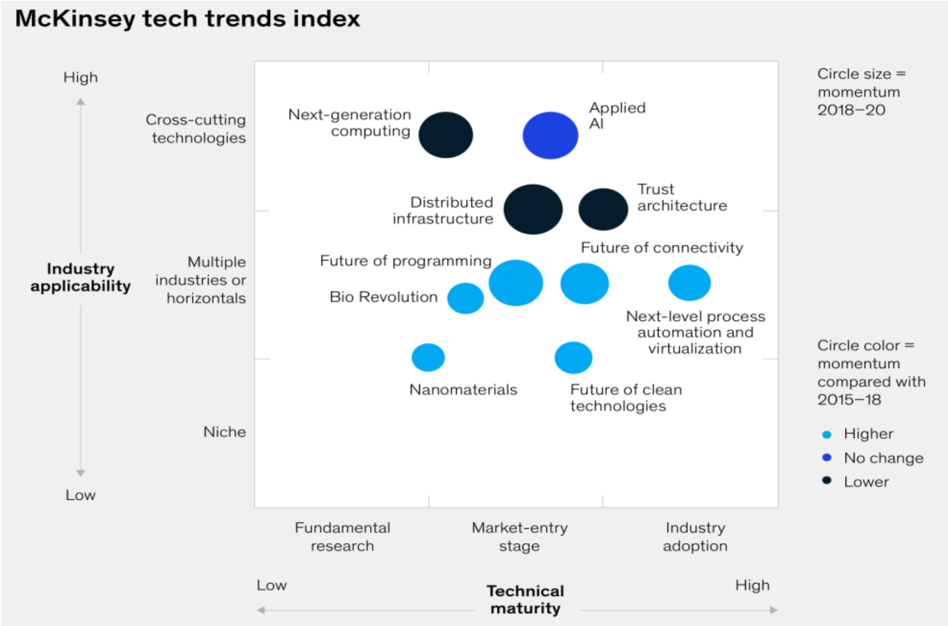

Figure 4: McKinsey tech trends index in a graph "industry applicability vs Technical maturity".

3.3.8 Pitchbook

PitchBook is a financial data and software company which through its Institutional Research Group published in 2021 Emerging Technology Research reports to help customers better segment and size markets, understand company and investor landscapes, evaluate opportunities, and develop conviction around the growth trajectories of emerging industries. (Pitchbook,2021). The Pitchbook list of 2021 Emerging Technologies are:

1. Agtech
2. Artificial intelligence and machine learning
3. Cloudtech and DevOps
4. Enterprise health and wellness tech
5. Fintech
6. Foodtech
7. Information security
8. Insurtech
9. Internet of things
10. Mobility tech
11. Retail health and wellness tech
12. Supply chain tech
13. Adaptive assurance of autonomous systems

The above Pitchbook list shows interest beyond the digital area and in fact in their view "emerging technologies represent growing areas of technological innovation that attract capital for their disruptive, thematic or secular growth potential". Then it makes sense to look at areas like Foodtech or Mobility tech where "industry verticals", defined as a group of companies that focus on a shared niche or specialized market spanning multiple industries, can explore their potential.

3.3.9 PwC

About five years ago, PwC analysed more than 250 emerging technologies to pinpoint those - the Essential Eight - that would have the greatest business impact across industries: artificial intelligence

(AI), augmented reality (AR), blockchain, drones, Internet of Things (IoT), robotics, 3D printing and virtual reality (VR). Today, the Essential Eight continue to evolve and make their mark. Some, like AI, are becoming integral to every type of company. Others, such as 3D printing, have been more concentrated in certain areas like manufacturing. While there are other promising technologies like quantum computing and nanotechnology, the most practical and profound impact in the next five years will continue to come from whether they will work together. This convergence reconfigures the eight essential technologies into six power combinations: automating trust, immersive interfaces, extended reality, working autonomy, digital reflection, and hyperconnected networks.

The PwC list of emerging technologies is shown in Table 20 in the annex section. It shows a focus on digital technologies but not because the PwC report underestimates other emerging technologies but "while there are other promising technologies like quantum computing and nanotechnology, the most practical and profound impact in the next five years will continue to come from the Essential Eight..." and "...how they will work together to deliver this impact..." (PwC,2021)

3.4 Digital platforms

"In January, we wrote about the Top 10 Technologies of The Next Decade. In as much as these technologies are still relevant today (July), a lot has changed since then" (Techstartups, 2020). The statement above seems, at a glance, counter-intuitive. Authors of a list of technologies expected to be the game changers for the coming decade, feel the need to update deeply ("a lot has changed") the same list in a matter of 4 months. The way they admit the need for the update appears naïve and alarming at the same time. The question raises: why one should care of a list, supposed to be a guide for a decade if you know it could be denial in a matter of months? This type of concern is particularly true in the case of digital platforms whose information could reflect the mood of the web more than result from research activities. Below are presented some of the most influential digital platforms dealing with emerging technologies.

3.4.1 Analytics Insight

The Analytics Insight platform, based in India, uses extensive market research, historical data, and algorithms to pinpoint emerging trends and future growth opportunities (Analytics Insight, 2020). The 2020 list is shown in Table 13 the annex section.

3.4.2 The Computing Technology Industry Association - CompTIA

The CompTIA is the voice of the world's information technology industry. Its members are the companies at the forefront of innovation and professionals responsible for maximizing benefits in technology 's investments. CompTIA offers educational programs, market research, networking events, professional certifications, and public policy advocacy. In addition, it elaborates its annual list of emerging technologies mainly in the demands of a technology-enabled consumer base. The top 15 emerging technologies that, in its view, businesses need to keep an eye on in 2020 and 2021 (CompTIA, 2021) is shown in Table 13 the annex section. It's easy to recognize that the items listed are not that different from other sources with a broader focus revealing that digital is at the very heart of the coming changes.

3.4.3 Forbes

Twelve tech industry leaders from Forbes Technology Council share their predictions on the technologies that will be game-changers in the months and years ahead. The 2020 Forbes list is shown in Table 13 the annex section (Forbes,2020)

3.4.4 The Economist

The list comes from the article appeared in the What next? section of the print edition of The World Ahead 2022 under the headline "What next?" (The Economist, 2021) and represent the picks from the Science and technology correspondents of The Economist. The list is shown in Table 13 the annex section.

3.4.5 Techstartups

Based in the Washington D.C. Metropolitan area, TechStartups.com is a digital platform dedicated to covering technology startups. It's an independent media publication not funded by corporate backers with a primary mission to help technology startups from around the world. They elaborate list of emerging technology, and the 2020 version (Techstartups,2020) takes into consideration current events around the world, the use of emerging technologies in tackling the ongoing coronavirus pandemic, impact in the post-coronavirus world, input from 800 experts and executives surveyed by the World Economic Forum (WEF), and findings from the Emerging Technology Community of CompTIA, the non-profit association for the global technology industry. The outcomes can be seen in Table 13 the annex section.

3.5 Overview of tools and methods

As reported in previous sections, different and varied types of reports and resources were consulted for the TechEthos horizon scanning exercise, observing a variety of methodologies to perform their analysis. Table 3 provides an overview of the different methodologies (when available) followed in the consulted documents.

Table 3: Methodology adopted by the different sources in making the list of emerging technologies (alphabetical order)

Source	Methodology	Time horizon	Countr y
Airi	The foresight analysis "Innovation of the Near Future: Key technologies for the industry" is based on the consultation of a panel of over 200 R&D managers in Italy, through interviews and working groups.	1-3 years	Italy
Analytics Insight	The Analytics Insight platform uses extensive market research, historical data, and algorithms to pinpoint emerging trends and future growth opportunities	Immediate tomorrow	India
Bohemia	Data from a Delphi survey investigating future trends in science, technology, the economy, society, and research and innovation systems	Up to 2035-2040	EU
CompTIA	No details available	Short-medium term years	US
Deloitte	…For enterprise technology, we spotlight the importance of aligning corporate and technology strategy; we revisit the critical core and how digital non-natives are using cloud, low-code, and platform-first strategies to juice legacy assets; and we take a deep dive into supply chain transformation. For data, we investigate how leading organizations are industrializing their AI initiatives with "MLOps" and, consequently, developing new approaches to managing data for the machine, rather than human, consumption. We also discuss emerging trends in cybersecurity. For human and machine interaction, we look at emerging trends in the future of the workplace, digital experiences, and technology that supports diversity, equity, and inclusion…	Next 18 to 24 months	US/UK

Forbes technology council	12 tech industry leaders from Forbes Technology Council share their predictions on the technologies that will be game-changers in the months and years ahead	In the months and years ahead	US
Frost & Sullivan	The Top 50 technologies program started with the team evaluating more than 3,000 technologies that are at a Technology Readiness Level (TRL) between 3 to 9 across corporate, government, academic, and research organizations worldwide...Using proprietary Frost & Sullivan methodology, each technology is evaluated considering market potential, IP activity, funding, Mega Trend impact, regional adoption, sectors of economic impact, and disruptiveness.	Coming 4 years	US
FTI (Future of Today Institute)	...nearly 500 technology and science trends have been analyzed across multiple industry sectors. Disruptive forces, opportunities and strategies are analyzed to drive organizaations in the near future…	From 2 to 10+	US
Gartner	Gartner analysts select the top technology trends on the basis of CEOs' priorities for their organizations and the resulting technology demands that flow down to CIOs and IT leaders.	Short-term and strategic business objectives	US
Joint Research Centre (RC)	The report is based on an expert-led, cross-sectoral foresight process. It presents global trends, uncertainties and choices that will shape Europe's future. The report provides the context for possible policy responses, and it is built on the 2020 Strategic Foresight Report, which introduces resilience as a new compass for EU policymaking through policy-driven foresight and horizon scanning exercises.	Towards 2050	EU
Lux research	... analysts combine their insights with innovation data such as patents, papers, and investments...Technologies are ranked based on proprietary data but also at the rate of improvement, the innovation history, and other factors. Rankings are not only a function of the innovation data but also of the insight of domain experts on Lux's analyst team. For example, flag technologies with high innovation scores, may still face market roadblocks that make them dubious bets or technologies that have less impressive scores but fit a key unmet market need, will enable them to make a major impact.	10 years	US
McKinsey	For every technology trend, a momentum score is calculated on the growth rate of the technologies derived from an indepth analysis of six proxy metrics: patent filings, publications, news mentions, online search trends, private-investment amount, and the number of companies making investments. In addition, search trends and news coverage. Finally, the analytical results are reviewed with external experts on McKinsey's Technology Council.	Next few decades	US
MIT	Editorial choice of MIT Technology Review	Short-medium term years	US
MoD	Each topic was researched by a member of the Development, Concepts and Doctrine Centre's (DCDC's) Futures Team. A literature review was the starting point, followed by workshops, interviews and, in most cases, the commissioning of at least one research paper. In total, over 70 pieces of academic research were commissioned from 42 different institutions. A key output of the research was identifying the trends, and the projection of those trends' forwards. Data has been used to generate projections, where appropriate, whilst recognising the limitations of this technique (the future rarely follows the smooth projections of statistical models). These projections do, however, give a direction, and often a sense of the speed of	30 years	UK

	change. Finally, the findings from the various activities were brought together into a single paper for each topic.		
NATO	This assessment draws upon the collective insights of the NATO Science & Technology Organization (STO), its collaborative network of over 6000 active scientists, analysts, researchers, and engineers, and associated research facilities. These insights have been combined with an extensive review of the open-source S&T futures literature and selected national research programs.	Up to 2040	Int
NSC (US)	…as its authors on the National Intelligence Council develop a methodology and formulate the analysis. This process involved numerous steps: examining and evaluating previous editions of Global Trends for lessons learned; research and discovery involving widespread consultations, data collection, and commissioned research; synthesizing, outlining, and drafting; and soliciting internal and external feedback to revise and sharpen the analysis…	20 years	US
NWO Gravitation/ Sienna (unpublished)	early findings of an ongoing study about currently emerging Socially Disruptive Technologies (SDTs) (Research briefing written for the NWO Gravitation programme Ethics of Socially Disruptive Technologies in collaboration with the EU Horizon 2020 SIENNA project.)	Next 1–2 decades	EU
PitchBook	Pitchbook's Institutional Research Group—a provider of research services that brings insights, trends and forecasts to the private capital markets—selects emerging technologies based on several factors. The most important is the amount of venture capital being invested into a specific category or group of startups focused on a similar growth opportunity, current industry growth themes, opportunities and investor sentiment		US
PREFET	...from manually identified "trend seeds" to Intelligence-Augmented desktop research supported with text-mining, data-mining and machine-learning. "Weak signals" were detected, and trends were "informed" (insight generation), resulting in a list of "45 Pre-validated Trends". These trends were mapped to UN's Sustainable Development Goals to leverage responsible research and innovation (RRI). An on-line consultation is done with more than 2,000 international researchers and additional input was provided by interviews with artists, architects, and designers. A final workshop focused on the exploration and prioritisation of technology trends	Coming decades	EU
PwC	Work in this area started about five years ago, when PwC analyzed more than 250 emerging technologies to pinpoint those that would have the greatest business impact across industries. Those with the most potential are named the Essential Eight. They include: AI, AR, blockchain, drones, IoT, robotics, 3D printing and VR.	5 years	EU
RIBRI	An innovative, semi-automated process was used to identify and analyze the RIBs. A learning language-analysis algorithm (NLP Natural Language Processing) analyzed the contents of around 500 000 news items on scientific and technical platforms. Topics were filtered out that appeared for the first time during the period of investigation. These topics and any related patents and publications were evaluated by scientists from the respective field. The evaluation was carried out in relation to the degree of maturity, the probability of widespread use in 20-year time and Europe's position.	20 years	EU
Technology for prosperity	This report is a summary of the workshop in Oslo on 2-3 July 2019 that brought together Directors of research and technology organisations and funding bodies of 20 different organisations from EU countries.	Coming future	EU

Techstartups	the list takes into consideration current events around the world, the use of these emerging technologies in tackling the ongoing coronavirus pandemic, impact in the post-coronavirus world, input from 800 experts and executives surveyed by the World Economic Forum (WEF), and findings from the Emerging Technology Community of CompTIA, the nonprofit association for the global technology industry.	Next decade	US
The Economist	Editorial choice from the Science and technology correspondents of The Economist	Coming years	UK
WEF	Selected by a panel of scientists and experts selected in cooperation with Scientific American	3-5 years	Int

4. Learnings from horizon scan studies

"Don't think that there is any consistent understanding of what Horizon Scanning is about – there is a lack of a common understanding within the Horizon Scanning and Futures community and a common language. The various disciplines that have contributed to Horizon Scanning have resulted in a variety of views of what it is. Furthermore, the inconsistency of application means the term Horizon Scanning is widely used and, in many cases, misused. You should define your terms and meanings" - Carney, 2018

The analysis of the multiple resources provided in the previous sections, shows a variety of purposes, focuses and methods used in different horizon scanning exercises. This heterogeneity resulted in wide-ranging approaches to cluster, prioritise, select, and present the results.

By comparing these resources, a series of factors, constraints and choices influencing the way a horizon scan is performed, and the possible outcomes of the exercise, have been identified. These are relevant aspects to consider in performing a horizon scan exercise, which are clustered in this section in five areas (target audience, goals, tools & methods, focus, boundary conditions).

4.1 Target audience

The target audience is probably the most important aspect to define when developing a horizon scanning exercise. Our analysis shows this is much related to the type of organisation performing the study:

- For most European projects, public institutions and research organisations, the final audience is represented by **policy and decision-makers**. They have an interest in receiving advice and updates on developments on emerging technologies not to be overridden by innovation in the governance of social phenomena, and to gain strategic advice concerning other economies in the world.
- Business and consulting firms have as target **customers in specific market segments (companies, policy makers, investors and other organisations dealing with research and innovation)** who must see added value to their economic and market prospects in exchange for consulting fees. In this case, the proposal is therefore a service proposal. They might produce good Horizon Scanning works, but they serve to be accredited as innovation experts and are designed to be integrated and contextualised within the slice of the market in which the specific customer is interested. Often the focus is on digital or the digitization of the production process.
- Digital platforms market their views. Their target audiences are **digital users and potential clients (any type of stakeholder, including the public)** visiting their website. Their goal is to produce quality information that accredits them and increases the attractiveness of their sites whose value is quantitatively measured by accesses and citations. They are digital operators working with digital users, with a focus on the digital world. Many non-digital technological innovations might be out of the scope of their analysis. For horizon scanning, they are essential but do not cover the full spectrum.

4.2 Goals

Each foresight exercise is designed and developed for different purposes and target audiences, and this strongly influences several aspects, including the time horizon, the tools and methods used to retrieve information, the criteria adopted to organise the data and analyse and present the results. Broadly speaking, we identified two main purposes of horizon scan:

- **Technology evolution:** Identifying the feasible evolution pathways of a set of technologies. The main purpose is to inform strategic/governance decisions, such as guiding industrial/R&D strategies and informing regulatory developments.
- **Upcoming applications (scenarios & trends):** foreseeing actual and future applications scenarios of a single technology or a cluster of technologies. It might include identifying social trends, and societal challenges (e.g., by redefining the urban life, workplaces, mobility, health, or educational system), and showing how different technologies could contribute to them. The final goal could be different, such as: identifying new market opportunities; developing investment strategies; anticipating and preventing societal impacts of technologies; inform long-term policies (e.g., R&I policies).

Of course, there could be other purposes that can inspire foresight exercises, according to specific target audience needs.

4.3 Tools and methods

There is no single recipe to carry out a technological horizon scanning exercise, as is shown by the diversity of tools and methods summarised in section 3.5.

Given the often-limited information on the methodology used in the analysis and the diversity of approaches, it is difficult to make a systematic comparison. However, some common grounds can be identified:

- The **use of desk-based research** (looking at R&D indicators, market trends, research funding and other relevant signals)
- **Consultation of experts**, by interviews, surveys, and data-gathering workshops
- Few studies also used **automated search strategies**.

For example, PREFET employed AI-based desktop research along with text-mining, data-mining and machine-learning. The RIBRI project used an innovative, semi-automated process: a learning language-analysis algorithm (NLP - Natural Language Processing) that analysed the contents of around 500,000 news items on scientific and technical platforms. Outcomes were then analysed in-depth by experts in the field. These types of tools are often used in connection with the need to identify “weak signals” of change, in scientific, public, or policy debate.

Overall, emerging technologies grow at the intersection of heterogeneous technological areas and research fields, where a conceptual body of knowledge is still emerging too. Therefore, any analysis has limitations in terms of the reliability of results, regardless of the method used.

4.4 Technology focus

Different choices can be made to focus the research, interpretation and description of the technologies emerging from the horizon scan. We identified three main aspects:

- **Time Horizon:** it sets the horizon of the foresight exercise.

It depends on the chosen goals and target groups of the exercise and influences the selection of data, and the interpretation (and reliability) of the result.

The analysis of the different resources (resumed in section 3.5) highlights the variety of possible time horizons adopted. For example, Gartner’s work has a short time horizon and is mainly based on CEO’s priorities. The work published by Frost and Sullivans, with a timeframe of a few years, relies on the assessment of the maturity (readiness level) of technology from technology experts. Studies looking to long-timeframes, such as Bohemia or PREFET, based their methodology also on the interaction with a large panel of experts from different fields.

In principle, horizon scanning activities of public institutions tend to adopt a time frame of decades while private operators tend to reason in a few years frame. The results are therefore quite different, though not radically. In fact, the pace of innovation makes any predictions very challenging. Regarding the horizon scanning of emerging technologies, even for foresight exercises with a long-term approach, most of the reasoning is on technologies already around and not about completely new, unexpected developments. This explains why the list with long-term vision compared with short-term vision is not that different. This also explains why in the same list, "5G networks", a range of services already on the market, is beside DNA digital data storage, an area of research still in its infancy. Again, broad families like *Solar energy technologies* and *Solar radiation management*, refer to technologies to come but also to mature products barely seen as "emerging disruptive technologies ".

- **The granularity of technologies** is related to the level of specificity of the analysis, and the way technologies and their applications are described and clustered together.

Machine learning is different from Deep Learning, Strong AI is not the same as Weak AI but there are reports where all these disciplines go under the broader term of Artificial Intelligence. This shows that even within a list using the same disciplinary approach, differences can be found in the granularity. This is understandable, granularity is a choice that mainly depends on the purpose and goal, and the type of analysis but eventually this difference in granularity makes it hard to compare different sources.

- **Taxonomy:** it is about the way technologies are searched, named, and classified.

Different approaches can be used to identify and describe the object of the analysis, depending on goals, target audience and focus of the exercise. Examples of taxonomy choices include the keywords for the desk analysis search, the way the analysis is presented to experts to get their feedback, the use of novel terms to describe a specific technology development, the clustering of the results (e.g., in terms of technologies, scenarios, applications, sectors, trends, etc.). As most horizon scan exercises are qualitative, these choices can lead to completely different outcomes.

Taxonomies are essential in science. By classifying objects or phenomena, they facilitate understanding the results for comparison and decision-making purposes. The issue has been broadly recognized in many fields (Epting S., 2021; Motejlek J. and Alpay E., 2021; Mwilu, 2015; Gkoumas, K. and Tsakalidis, A., 2019). However, a taxonomy to name and describe technologies seems missing, at least looking at the resources analysed in section 3. There are striking differences both in the items in the types of technologies and the way they are searched, described, and clustered. This makes it difficult, if not in some cases impossible, to compare results of different resources, and in some cases even between outcomes of the same study but published in different years.

4.5 Boundary conditions

Other elements influence the horizon scan, including choices in terms of the level of analysis of impacts and trends of technology development and constraints regarding the uncertainty of foresight exercises:

- **Socio-economic impacts**

Most of the resources start from the assumption that emerging technologies present a high component of economic and social disruptiveness. They did not perform a systematic evaluation of the social-economic impact of technologies, rather they identify "weak" signals and factors of debate on those technologies that might shape our future. They focus more on thematic trends (or mega-trends), instead of impacts, and then look at how technology development could contribute to these trends.

One of the most interesting examples is the PREFET project. In their work they "implemented a process moving from manually identified "trend seeds" to Intelligence-Augmented desktop research supported with text-mining, data-mining and machine-learning. "Weak signals" were detected, and trends were "informed" (insight generation), resulting in a list of "45 Pre-validated Trends".

Other studies refer to Sustainable Development Goals (SDGs) and provide a qualitative indication of technologies, innovations, and applications that can contribute to them.

Industrial and economic impact are in some cases analysed more in-depth, in particular by businesses and consultants. However, most assessments are qualitative and based on experts' judgments (e.g., interviews with industry players). Quantitative data are generally provided only on specific short-term, technologies. They hardly can be used to compare the impact of different technologies and applications on a medium to long term horizon.

- **Trends and factors**

Though impacts analysis received limited attention in the horizon scan resources selected, there is a vast literature, formal and grey, devoted to the analysis of mega-trends (a few examples are provided in section 3). A variety of factors drive changes in society, from political and environmental factors to issues associated with societal values; technological drivers are one among these others and they influence each other. In the last decade, the role of innovation in shaping the changes in social life appears to be much bigger than before but still is only part of the game. Therefore, several studies work to identify "strategic trends" which represent a sort of boundary of conditions for technology development.

A vivid representation of this lies in the present debate on climate change: the SDGs, the EU agenda on sustainability and the broad societal support to environmental policies which are steering the technology development.

Trends (and so-called mega-trends) could work at the same time as a starting point for a horizon scan exercise (identify technologies that contribute to a trend), or the results of the exercise (identify trends induced by technology development). Several horizon scanning exercises used societal trends to set the goals, and the technology focus of their analysis.

The final goal of analysing trends is not to offer a specific prediction of the world in the future, but to help stakeholders see what may lie beyond the horizon and prepare for an array of plausible futures. As such, trends are helpful to better understand the potential socio-economic impact of technologies.

- **Uncertainties, reliability of results**

High uncertainty is somehow intrinsic in all types of foresight activities, as these are about reflecting on possible futures. There are different factors influencing the reliability (or the level of uncertainty) of results: on the one hand, the methods and tools used, such as the resources selected, the number and type of experts involved, the type of information collected (qualitative, quantitative), the level of the analysis; on the other hand, the complexity of the foresight exercise, for example, whether it looks at completely new topics, or explores a well-known field, the level of granularity of the analysis and the time horizon.

The huge variety of future emerging technologies identified by the resources analysed in section 3 provides an example of the complexity of the exercise. This is even more evident looking at results provided by a specific resource (thus applying the same methodology) in different years, with technologies disappearing and new ones popping up from one year to the other.

Broadly speaking, all reports analysed gave a significant role in the future to digital, biological, materials technology fields. They also pin-point the relevance of some specific technologies, also looking at the persistence of some techs in different editions of the same report, in some cases in the last 5-10 years (e.g., artificial intelligence, quantum technologies, neurotechnologies and others).

Considering the factors, constraints and choices identified in this section, TechEthos searched for converging and elements across these reports and translated them into a set of technology families and a description of their potential applications, and socio-economic impacts. A reflection on the TechEthos approach is proposed in section 5. The identified technology families are in section 6.

5. The TechEthos approach: combining horizon scan and impact analysis

5.1 The TechEthos horizon scan

The TechEthos horizon scan aims to carry out a thorough scanning of the technology horizon to identify a set of different emerging technologies or technology families with a high socio-economic impact and significant ethics dimensions.

The methodology was based on an iterative process combining desk analysis, and consultation of a multi-disciplinary panel of experts (from the fields of technology assessment, ethics, policy, engineering, sociology and social studies and socio-economic sciences).

The Multi-criteria decision analysis (MCDA) approach inspired the comparison, assessment, and selection of technologies, based on a set of impact assessment criteria refined and improved during the analysis. It is meant as an initial assessment, while a more in-depth evaluation of ethics, legal and public impacts is planned in the subsequent phases of the project,

In this section, we reflect on the specific assumptions, constraints and choices considered in the TechEthos horizon scan exercise, based on the methodological areas identified in section 4, and we focus on key elements that we think are important to perform ethics and social-driven horizon scan.

Note that a detailed description of the TechEthos multidimensional horizon scan and impact assessment method and results are provided in deliverables 1.1 and 1.2.

5.2 Conditions and choice

The initial assumptions, constraints and challenges that led to specific choices in designing and performing the TechEthos horizon scan, are summarized in this section following the areas discussed in the previous section (goals, target audience, tools & methods, focus, boundary conditions):

5.2.1 Goals & target audience:

Assumptions:

- Perform a horizon scan to identify and gather information on the evolution of technologies and analyse their potential impacts, to select a portfolio of technologies that will be used as case studies for the development of operational ethics guidelines for technology development.
- Focus on policy and society-relevant technologies, which are more likely to have short to medium-term impacts
- Consider as the main target the stakeholders involved in the TechEthos project: project partners (practitioners on ethical, legal, and social aspects of technology development), researchers, policy makers, ethics committees, and the public.

Constrains/challenges:

- Perform a comprehensive analysis of possible future technologies
- Identify high socio-economic impact technologies
- Select a few of them to include in the TechEthos technology portfolio, providing representative and interesting examples for the ethical analysis foreseen by the project. In the selection, avoid overlaps with previous exercises related to the ethics analysis of new and emerging technologies, to ensure TechEthos work will provide new and useful insights

Choices:

- Consider policy and decision-makers, and researchers (ethics, social sciences), as the primary target audience
- Set the goal to perform an analysis-oriented toward **selecting specific technologies evolution pathways** (more than of depicting future applications and scenarios)
- Collect **resources on both technology and trends and impacts** of technology development
- **Use the ethics criteria as the most relevant** in the final choice of technologies to include in the TechEthos technology portfolio.

5.2.2 Tools & Methods:

Assumptions

- Use desk analysis, from available horizon scanning exercise (secondary sources), as time and resource constraints, would not allow an original analysis of primary sources (e.g., peer-review articles, in-depth analysis of the specific technologies, technology and business experts, etc.)
- Engage experts through a limited set of interviews and an online survey
- Integrate qualitative data with available and representative quantitative data. Perform a multi-dimensional assessment of the socio-economic impacts of the technologies
- The use of automated search systems was not foreseen, as the focus was on short to medium term technologies (and not on the analysis of weak trends and signals to detect potential long term or unexpected future developments)

Constraints/challenges:

- **The wide range and diversity of results of the selected resources** (in terms of technologies and applications)
- **The limitations in retrieving and comparing quantitative or semi-quantitative data**. We looked at patents and cooperative projects, using a set of keywords related to the specific technologies identified (see Deliverable 1.2 for details). The activity showed how complex, uncertain, and time-consuming is to retrieve these data for such a diverse and broad range of technologies.
- **The limitations in terms of expertise and competencies available** (from the project team and external experts) to assess and make a judgment on such a broad range of different techs. This includes the risk of confusion and/or bias in the assessment and comparison of technologies performed by experts, due to both competencies and the way in which the project chose to classify and describe technologies. It is worth noting that finding qualified experts having knowledge on both new and emerging technologies and ethical thinking it is generally difficult (a detailed description of the recruitment and selection process of experts is provided in deliverable d1.2 of TechEthos).
- **The challenge in assessing and comparing impacts of different technologies**, even from a qualitative point of view, given their enabling character and the diversity in terms of areas, sectors and contexts of applications (e.g., how to compare economic impacts of internet of things and virtual reality, as they are closely interconnected, and with an impact on entire value chains? Or how to compare impact of quantum technologies with regenerative medicine, as one is applied in many sectors, including medicine, the other just in one specific sector, but with huge potential?)

Choices

- **Cluster the wide range of technology families** identified in literature, considering their functions, scientific working principles, applications, concern and trends addressed[2]
- **Provide a concise and non-technical description** of the technology families, accessible to experts with different backgrounds (factsheets)
- **Develop our own set of criteria for socio-economic impact assessment**
- **Extensively use expertise of partners and consultation of experts to assess the criteria**, as complete and reliable information on impacts missing from literature
- **Use an iterative approach,** combining several steps of analysis, consultation and review (see deliverable D1.2)

5.2.3 Technology Focus:

Assumptions

- Focus on technologies which are more likely to have short to medium-term impacts because these technologies have more information available, and awareness of stakeholders is potentially higher, allowing for a more reliable evaluation of their socio-economic impact and more critical debate with stakeholders
- Ensure selection of case studies for the ethical analysis that could have a general interest and relevance

Constraints/challenges

- **The different characteristics of the technologies identified**, in terms of time horizon, level of granularity, terminology used to describe them within each of the resources analysed
- **The constraints given by the different time horizons of the technologies identified**, and thus the different level of information and timescale on which to assess the technologies. This includes consideration of the time horizon on which to evaluate impacts
- **The choice of the appropriate level of granularity**, as a trade-off between the need to develop ethics guidelines covering broad areas of technology development, and the need to focus on specific sectors and application to ensure concreteness and practical implementation of the case studies (this will be a focus in the next phase of TechEthos)
- **The focus on technologies (instead of scenarios or trends)** required clustering elements with similar characteristics. This approach has the risk of missing trends toward convergence of technologies (e.g., analysing future applications enabled by the convergence of bio, digital and cognitive technologies)

Choices

- **Development of own classification and categorisation**. The focus has been given to technology features (instead of sectors, or societal trends) 3. This was instrumental for the purpose of the project, as the goal of the horizon scan was to select technologies. Moreover, the project plans to develop, after the horizon scan, its own application scenarios, including societal trends and factors

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[2] In TechEthos, technologies have been classified within a family if they are characterised by one or more of the following aspects: they perform similar functions, are based on similar (scientific) working principles, or address similar goals/concerns/trendsgà

[3] a mix of different approaches has been used to classify technologies, including descriptions that are sectoral-oriented (e.g., precision farming), concerns-related (e.g., climate technologies, threat detection and response), application-based (mobility), and technology-based (e.g., quantum technologies, synthetic biotechnologies).

- **Identify broad categories of technology families** (coarse granularity) and include within each family a set of more specific technologies and applications. This would leave the appropriate level of flexibility and possibility for generalisation in the next phase of the project
- In the selection of the TechEthos technology portfolio, consider that in most if not all the horizon scan resources, the **digital, biological, materials technology fields all are expected to play a relevant role** in the future

5.2.4 Boundary conditions:

Assumptions

- Perform a multi-dimensional assessment of the socio-economic impacts of the technologies

Constraints/challenges

- **The limits given by the enabling character, the level of development, and the uncertainties** connected to innovation process, making it not possible to foresee all potential applications of a new and emerging technology (thus also limiting the identification of impacts)
- **The wide differences in the type and level of information collected** on both the technology families and the criteria for the assessment, according to the specific technology.
- **The challenges given by a multi-dimensional assessment**, combining both data and expertise (partners, and experts) from different disciplines. Differences in experiences, perspectives, and competences made difficult to find a common language and ensure the same level of understanding of the topic (on the other hand, this has been one of the added values of our analysis, as discussed in the next session)
- **The challenge to identify suitable criteria** to assess such a wide number of technologies from different sectors and fields, in particular concerning ethics impacts (a core aspect for the project
- **The difficulties in judging the reliability of the foresight analysis**, given the diversity of methodologies and the limited information available within the reports, and the uncertainties intrinsic in any foresight exercise

Choices

- **Accept a certain level of heterogeneity in the description of technologies**, including possible overlaps in terms of scientific areas, disciplines, technical solutions, applications, trends and global challenges.
- **Accept the limits of this classification**, as the enabling character and trends toward convergence of emerging technologies would justify also different ways of clustering and organising them.
- **Accept that the assessment of the technology families is qualitative** and relies on partners' and experts' experience and judgment.
- **Formulate a set of ethics assessment criteria broad enough and still relevant and sufficiently sharp to enable selection**, inspired on an 'ethics by design' approach (see the list of impact assessment criteria in annex). These included:
    - A list of values and principles that lead to ethical tensions or problems in many technologies' fields
    - The use of two different categories to assess these values and principles: "impact on" and "concerns over". The first corresponds to established or easily foreseeable effects, while the second reflects a more speculative approach regarding new and emerging technologies.

  This approach allowed the consideration of the variability in the readiness of the different technologies, and different levels of certainty and time horizons in the ethical assessment of new and emerging technologies.and different levels of certainty and time horizons in the ethical assessment of new and emerging technologies.

- Use strategic trends and megatrends identified in literature (see section 3) to guide the identification of technologies with an expected significant socio-economic impact and to inspire the definition of the impact assessment criteria
- **Perform a very qualitative and indicative assessment of impacts**, with the only purpose of doing a comparative analysis to spot major, showcase differences across technology families. Each of families would deserve an in-depth analysis to identify and evaluate with some degree of confidence the diverse range of their potential impacts.
- A set of additional criteria were considered as a supplement of the impact assessment criteria, to prioritise, and finalise the selection of technologies for the TechEthos portfolio. These take into account short term policy priorities, potential added value for TechEthos, and expertise, and potential interest of the project partners on the specific technologies.

5.3 Results

TechEthos developed specific elements that could work as initial models for future ethics and social driven exercise. These elements can support the setting of the focus of the analysis (such as the taxonomy issue) and the socio-economic impact analysis. In particular

- **A clustering of 35 technology families**, based on the list of technologies of over 150 single technologies resulting from the horizon scan exercises as described in section 3. The technologies families were grouped based on similarities in disciplines and application areas of the specific technologies identified. The list of 35 technology families were subsequently reduced to a list of 16 family of technologies (see Table 4). In Table 9 (annex section) is shown the rest of technologies (the excluded technologies).
- **Factsheets about the 16 technology families**. These factsheets were structured to gather a set of minimum information for each of the technology families, including a description of the technology and its applications, and indicative information on the impact assessment criteria.
- **A set of criteria for impact assessment**, following the five dimensions requested by the project (industrial, economic, ethics, legal, policy).
- A **Multi-criteria Impact Assessment matrix** to summarise results of the impact assessment, and support decision-making
- **A "triage" approach** to make a final selection of technology families for the TechEthos portfolio (see Table 5), based on three criteria (2.2: need for guidance on ethical aspects, 1.3: level of interest by industry and investors and 3.1: impact on societal challenges, see annex section 8.3) considered very relevant for the purposes of TechEthos (see Deliverable 1.2 for more details).

6. Key Disruptive Future Technologies

6.1 Short list of technology families

As a result of the TechEthos horizon scanning exercise, a list of high socio-economic impact technology families was developed (see Table 4). This short list of technology families was the product of a thorough analysis of the resources presented in this report. In a first round of analysis, a list of 35 technology families, with a significant socio-economic impact, was initially produced. Subsequent analysis and reflections on the identified technology families, based on a qualitative assessment of social-economic impact following specific criteria (see Table 7 in Annex section), led to the short list of 16 family of technologies. The remaining (excluded) 19 technology families are:

- *Bioproducts, Human enhancement, Advanced computing, Artificial intelligence, Cybersecurity techs, Human behaviour technologies, Human-machine interfaces, Genetic Technologies, Personalised medicine, Advanced materials, Critical infrastructure technologies, Energy storage and production technologies, Industrial automation, Materials and production systems for the circular economy, Military, defence, security technologies, Molecular engineering, Nanotechnologies and nanomaterials, Robotics and Sensing and imaging technologies.*

A short description of the reasons for excluding these 19 technology families is displayed in Annex 6, Table 9. The description of the overall processes to select the different families can be found in Deliverable 1.1 (steps to reach the list of 16 technology families) and Deliverable 1.2 (steps to reach the TechEthos portfolio of three technology families).

The 16 families have been grouped in research and innovation fields, broadly identified based on scientific disciplines and European policy fields. Each of the 16 technology families had a factsheet presenting, in a synthetic way, examples of key industrial applications and indicators about socio-economic and ethics impacts intended to provide an easy look about technology family future potential. Such as factsheets can be found in Deliverable 1.1, nevertheless, a brief description of them is presented in Annex 1 - Model of a technology family factsheets.

In naming and describing the technology families and the individual technologies, in some cases, widely acknowledged terms were adopted. In others, new terms have been used for the purpose of this analysis. Note that in selecting the 16 technology families, one of the most important criteria has been the need for additional guidance in dealing with ethical aspects of a technology family (criteria 2.2 in Table 7, Annex 3), as a specific requirement of the TechEthos project is to complement the work on ethics analysis done by other initiatives[4].

[4] See in particular the Sienna and Sherpa projects at www.sienna-project.eu and www.project-sherpa.eu, dealing with ethical analysis of the following technology domains: human genomics & enhancement, robotics, artificial intelligence, human genomics, and human enhancement.

Table 4: The 16 high-socio economic impact technologies identified by TechEthos.

R&I	No	Technology families	Specific technologies
Bio and environment	1	**Environmental & climate technologies**	Geoengineering technologies (e.g., solar geoengineering); Carbon capture, usage and storage (CCUS) technologies; carbon dioxide splitting technologies; Energy storage technologies (e.g., next generation batteries and green hydrogen); Splitting carbon dioxide; water splitting; artificial photosynthesis; Algae and microorganisms against climate change; wastewater treatment technologies (e.g., for nutrient recovery);Advanced sensing technologies (e.g., quantum sensors, IoT); digital techs for monitoring and traceability (e.g., blockchain for resources traceability, weather tracking technologies, satellites, robots and drones).
	2	**Bioengineering & industrial biotech (excluding healthcare)**	Biologically inspired engineering, including biohybrids; Bionics and exoskeleton; Bio-inspired materials (e.g., smart biomaterials), bio-inspired electronic systems (e.g., biological-computer interfaces and parts), bio-inspired computing architectures, such as massive parallelism or swarm computational intelligence; Bioinformatics & AI in 'omics' data to understand industrial biological processes.
	3	**Synthetic biology**	Synthetic food; Alternative proteins (in vitro meat); Artificial photosynthesis; Plant communication, Genome synthesis; DNA synthesis machines.
Digital	4	**Data processing technologies (excluding quantum techs)**	Edge and exascale computing (huge calculation/processing power); distributed cloud, serverless computing (data based on as-used needs not by a fixed bandwidth); neuromorphic computing, distributed ledger technologies and blockchain (digital structural design to process and transmit data encrypted in a decentralized system); chem-putting and 3D printing of molecules.
	5	**Quantum technologies**	Quantum computing, Quantum Internet, Quantum sensors.
	6	**Internet of things (IoT)**	Advanced sensing technologies; processors and actuators; Advanced IC technologies (e.g., 5G), data processing and data analysis technologies.
	7	**Cognitive and behavioural technologies**	Chatbots and smart assistant; Data mining; pattern recognition; Artificial Intelligence techs (speech recognition; Gesture recognition; Natural language processing, rules-based AI systems); Human-machine interfaces.
	8	**Virtual/Augmented reality**	Software technologies: computer and algorithms for coding/modelling, such as Virtual Reality Modelling Language (VRML) or Augmented Reality Markup Language (ARML). Hardware technologies, such as headsets, smart glasses; contact lenses, projection mapping, motion sensors, tracking, control; haptics devices: wired gloves, 3D mice, optical sensors, speech and gesture recognition.
Health	9	**Regenerative medicine**	Tissue engineering and biomaterials; cells therapies; medical devices and artificial grown tissues and organs
	10	**Artificial human/neurotechnologies**	Artificial uterus; artificial synapse; artificial brain; wearable organs; (direct) brain-machine interfaces; neuromorphic engineering; neuromorphic chips and computing; the neuroscience of creativity; bionics; neurostimulation.
Materials and manufacturin	11	**Additive, advanced manufacturing technologies**	3D printing of food, glass, large objects and buildings, organs; microfluidic platforms, optical devices; metal and ceramic parts.
	12	**Autonomous systems**	Autonomous vehicles (car, aircraft, drones); autonomous industrial machines and robots; adaptive assurance of autonomous systems; hyper-automation.

	13	**Threat detection and response technologies**	Combined development and use of multi-sensor technologies, software, and IC technologies; unmanned monitoring and surveillance systems (e.g., drones, robots); centralized data management and analytics; decontamination management; doppler radar; disaster resilient materials and electricity resistant measuring techniques (geological investigations). All these will benefit by combination with AI.
	14	**Precision farming**	Pervasive automation by large-scale robotic and microrobots, soil and water sensors; weather tracking; satellite imaging; minichromosomal technology; vertical farming; genetic and synthetic biology methods for multiple purposes (e.g., plants modification, in vitro meat).
	15	**Mobility technologies**	Combined development of different emerging technologies, such as smart sensors, IoT, connectivity, blockchain, big data, digital platforms, artificial intelligence; autonomous vehicles, electric vehicles, flying vehicles, etc.
	16	**Space technologies**	Combined development of robotics, AI, sensors, ultralight and adaptive materials and structures; advanced systems for integration; ICT, storage and distribution of energy.

6.2 TechEthos technology portfolio

An iterative process, based on use of the impact assessment criteria and experts consultation, led to the refinement and selection of final list of three technology families (**The TechEthos technology portfolio**): Climate Engineering, Extended Digital Reality, and Neuro-technologies. These three technology families will be used for TechEthos project as models to explore the interaction of technologies with the planet, the digital world, and the human body looking to develop operative ethics-by-design guidelines for researchers and innovators.

The list of the three families of technologies and the motivations that led to that choice, following the TechEthos methodology, are reported in Table 5 and Table 6, respectively.

Table 5: The 3 technology families selected for the TechEthos Technology Portfolio.

Technology	Description	Specific technologies
Climate Engineering	Climate engineering is a family of technologies that enables the modification of natural processes and human activities looking to detect, mitigate and respond to global threats due to climate change crisis locally and globally.	Geoengineering technologies (e.g., solar geoengineering); Carbon capture, usage, and storage (CCUS) technologies; carbon dioxide splitting technologies; Algae and microorganisms against climate change; artificial photosynthesis.
Digital Extended Reality	Extended Reality refers to AI-powered digital technologies (hardware and software) capable of perceiving and processing human sensorial outputs, e.g., voice, gestures, language, movement, emotions, and other elements of human communication). By processing such human-related data, extended or mixed virtual scenarios (e.g., visual, audio, linguistic or haptic) can be tailor-made or "customized" based on the user interest and behaviour. These technologies can be used to profile, model, predict, discriminate, and influence the user's behaviour or nudge their choices.	**Data analysis and software:** virtual, augmented, and mixed reality systems; human digital twins (avatars); nudge and affective computing; applied behavioural analysis and engineering; people profiling; user nudging; biometric and behavioural recognition; AI-based technologies for speech, pattern, and gesture recognition; Natural Language Processing (NLP). **Hardware and data processing**: headsets, contact lenses and glasses; projection mapping; motion sensors; distributed cloud; edge and exa-scale computing; serverless computing (data as-used needs).

Neurotechnologies	Health technologies that aim at affecting and emulating human-brain capabilities and functions through artificial replacements or add-ons in a two-way interaction between the brain and the external environment or systems.	Human-brain-machine interaction: artificial synapses; artificial brain; (direct) brain-machine interfaces

Table 6: Key motivations for the final selection of the 3 technology families to focus the TechEthos work.

Impact	Key motivations
Overall	• Introduce transformations in the access and use of natural resources (energy and environment) by regions, industrial processes, and society at large. • Influence people's daily habits, the organisation of work, jobs, industrial and business models and cultural, policy and political behaviour, throughout our economies and society. • Influence personhood and the way we perceive humans. It could disrupt existing practices
Ethics	• Potential for irreversible transformation, access and inequalities across regions and economies • Potential for human supervision and control, human rights, privacy and data protection, surveillance, misuse, and digital divide • Potential for infringement of human rights, irreversibility; integrity and responsibility; equal access • Impact on people's health and safety
Industrial and Economic	• Significant investment by sectorial players • Impact on both local and national economies, at both global and local level • Impact on highly valuable sectors, enable innovation in other sectors.
Public	• Potential large impact on the environment • Potential large impact on people’s lives, individuals and communities • Potential large impact on people's healthcare, safety and jobs • High impact on Societal challenge
Policy	• High to very high public and policy priority at the national, regional and international level
Legal	• Require adaptation and possibly also significant changes in existing legal frameworks • Requires adaptations and harmonization across international frameworks
TechEthos portfolio	• Relevant example for broader fields of application • Work on tangible, existing medium to long term applications and as well some long-term applications (opportunity to shape their development) • Specific competencies available in the consortia

7. Final reflection and outlook

"Don't think that Horizon Scanning is about predicting the future – this is a common misconception. The value of Horizon Scanning is in using it to change mind-sets, challenge assumptions and provide more options" - Carney, 2018

Horizon scanning is typically carried out to think about possible futures scenarios, more than guessing the future, and to provide insight to the stakeholders in their choices. Thus, the sections up to now provide:

- A review of horizon scan studies performed by research, businesses, and policy organisations
- A structured list of "future" technologies expected to have significant ethics and socio-economic impacts
- A comparative analysis of these studies, structured around five analytical areas: target audiences, goals, tools & methods, technology focus, boundary conditions (trends and social impacts)
- A multidimensional impact assessment inspired by Multi-Criteria Decision-Analysis (MCDA)

On this basis we will summarise our critical reflection of the TechEthos approach in this section, i.e., outlining the merits and limitations of combining horizon scan and impact assessment.

Our analysis shows the variety of approaches used and results achieved by a wide set of horizon scan exercises dealing with new and emerging technologies at international, European, and national level.

We think the TechEthos exercise has been effective in guiding the review of these secondary resources and in making reasonable choices in a situation of complexity and limitation of knowledge and evidence.

The value of the TechEthos horizon scan has been in the multidimensional character of the analysis, and in the identification of comprehensive qualitative criteria for impact assessment.

The application and use of a qualitative, expert-based approach inspired by MCDA to review horizon scanning results, based on these criteria, is to our knowledge a surprising aspect of the TechEthos experience (as MCDA is more often used in risk and environmental analysis).[5]

We recognize several limits in the analysis:

- The analysis is influenced by the way the technologies are framed in the literature, the resources analysed, and the type and number of experts engaged in the process
- The panel of experts engaged in the process did not cover the full range of disciplines and technologies assessed by the horizon scan
- We mainly focused on studies published in the last 2-3 years
- A more detailed analysis of historical trends (foresight exercises published in the last decade) would have enriched the analysis
- We gave a preference to focussing on a short to medium time horizon. The work could be complemented by an analysis of weak signals and indicators of long-term future trends and technologies, possibly using automated search tools

A further iterative stage to the review of technologies, engaging people with an expertise in each of the 16 families of technologies would have been helpful, to look more in detail at several aspects, such as the applications, and the expected time horizon. This step would also allow for considerations on

[5] See Linkov et al. (2006), , Linkov et al. (2020), Porcari et al. (2021a), Zhang et al. (2021).

the feasibility of the technology developments analysed (as this was not an explicit criteria of our assessment), for example in terms of technical challenges and barriers to enter the market. Economic impact might be analysed in more detail, as quantitative data on at least some specific technologies might be found with a detailed analysis of primary resources. However, this action was not possible given the resource and time plan of the TechEthos horizon scan.

The use of different sets of representations of the families of technologies, within the same exercise, could be interesting to further analyse results. For example, analyse all technologies contributing to a specific sector (e.g., farming), considering all the value chain (raw materials, technologies for products, solutions for end-users) as well as the application of each technology in different sectors (e.g., automation, including its application in farming). This would allow a more in-depth understanding of the potential and value of the technology.

The TechEthos horizon scan provided a broad overview of possible technology evolutions and their potential impacts. Further research is needed to understand the potential implications of these technologies for different type of stakeholders, possibly including consideration on second-order, consequential risks, and long-term consequences on society, as they are the most difficult to anticipate.

Outlook: results of the horizon scan (deliverables 1.1,1.2,1.3) will inform all project WPs, including the mapping of the innovation eco- systems and the design of the scenarios (WP3), and the development of wide-purpose and detailed ethics framework and operational guidelines (WP5) that could support the research community both on the specific technologies identified, and more broadly in the development of any new and emerging technologies.

8. Annexes

8.1 Annex 1 - Model of a technology family factsheets

The factsheets are meant to provide a description of the technology families, their most relevant features, and their potential socio-economic impacts. factsheets have been compiled for each of the 16 high socio-economic impact technologies identified by the TechEthos horizon scan (see deliverable D1.1.). In detail, the structure consists of the following elements.

8.1.1 Descriptive fields

These fields are compiled based on a qualitative assessment using desk analysis and review by experts:

- **Name of the technology family**
- **Description** of the characteristics, functions, and uses of the technology
- **Key functions and capabilities** of the technology family, indicating if the family refers to hardware and/or software developments
- **Key industrial sectors** of current and/or potential uses and applications of the technology, considering both traditional and innovative (research-intensive) industrial sectors. A reference list has been developed based on the NACE 2 standard classification for economic sectors and other policy-oriented classifications[6]
- **Examples of specific technologies** clustered within the family. Technologies are classified within a family if they are characterised by one or more of the following aspects: they perform similar functions, are based on similar (scientific) working principles, or address similar goals/concerns/trends
- **Examples of applications** enabled by the technologies within the family. These include current and potential expected uses of the technologies across different industrial sectors, considering both business-to-business and business to consumer applications[7]
- **Time horizon to mass market**[8]**,** considering the following indicative time scale short (1-3 years); medium (3-5 years): long (>5 years). The assessment refers to at least one of the specific technologies of the family (e.g., short indicate that at least one specific technology is close or already on the market).

8.1.2 Impact assessment fields

These fields are compiled based on a qualitative assessment of the technologies within the family against the impact assessment criteria:

- **Key ethical issues** identified considering the functions and capabilities, technologies, applications listed in the descriptive field, and criterium 2.1 and the guidance provided in annex 8.3.

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[6] The one from the European Commission area Internal Market, Industry, Entrepreneurship and SMEs: https://ec.europa.eu/growth/sectors_en

[7] This field is intended to provide few representative examples of use of technologies, for the purpose of better describing them. However, it cannot be in anyway considered complete. The enabling character, the level of development, and the uncertainties connected to any innovation process, make not possible to foresee all potential applications of a new and emerging technology.

[8] The time to market has been preferred compared to the technology readiness level, as the evaluation of the latter for the wide range of technology analysis was much more difficult and uncertain, based on available resources.

- **Expected industrial and economic impact**, concerning the key industrial sectors, technologies and applications listed in the descriptive part, and the criteria 1.1 and 1.2 and 1.3.
- **Expected public impact** concerning criteria 3.1 and 3.2 and the guidance provided in annex 8.3.
- **Expected policy impact** concerning the specific technologies and applications listed in the descriptive part, and criterium 4.1.
- **Expected legal impact** concerning criterium 5.1 and the guidance provided in annex 8.3.

8.2 Annex 2 - Indicators for quantitative data on impacts

In addition to the qualitative fields, a set of quantitative indicators have also been identified to complement the impact assessment. A desk analysis process was followed and provided the search strategies to identify and quantify these indicators, using keywords identified for each technology family and related to the specific applications within the family. Patents (number, growth, share) and industry participation in EU Framework Programmes (EU-FP) related to a technology family have been used as indicators for the industrial and economic impact. The number and growth of EU-FP projects related to a technology family have been used as indicators for the policy impact. A 3-points Likert scale (low, medium, high) has been used to qualify such indicators. The quantitative assessment was limited by the set of keywords and the data available. The quantitative indicators have been used to support the qualitative assessment and final selection of technology families, considering the limitations of the analysis.

Expected industrial and economic impact (quantitative indicators)

- **Number of patents**: For 2014-18 period, absolute number of patent applications filed for a specific technology family relative to those filed for the full sample of technological families included in the TechEthos project. Deemed representative of a technological family's industrial R&D strength.
- **Growth of patents:** For 2007-13 and 2014-18 periods, growth in patent applications filed for a specific technology family relative to growth in filings for all patents. Deemed representative of a technological family's industrial R&D growth.
- **Share of Europe in patents**: For 2014-18 period, share of patents with inventors located in Europe within the technology family relative to the total share of inventors located in Europe in all patents. Deemed representative of the relevance of Europe in global industrial R&D for the technology family.
- **Industry participation in EU-FP projects**: For 2014-18 (H2020 projects), share industry participation in the technology family relative to industry participation in all EU-FP projects. Deemed representative of a) degree of industry participation in publicly funded R&D and b) technological readiness level of the technology family (based on the assumption of low industry participation in basic research).

Expected policy impact (quantitative indicators)

- **Number of EU-FP projects:** For 2014-18 (H2020 projects), absolute number of technology-family-related EU-FP projects relative to the total number of EU-FP projects for all TechEthos technology families. Deemed representative of technology family's prominence among EU policy priorities.
- **Growth of EU-FP projects**: For 2007-13 (FP7 projects) to 2014-18 (H2020 projects) periods, growth in related EU-FP projects for a technology family, relative to growth in all EU-FP projects. Deemed representative of a technology family's growth in prominence among EU policy priorities.

8.3 Annex 3 - Impact Assessment Criteria

Table 7: Impact Assessment Criteria table.

Impact dimensions & criteria		Data Source
1	**INDUSTRIAL AND ECONOMIC IMPACT**	
1.1	**New and emerging:** the level of novelty of the technology family is… *Low: Mostly incremental innovations technologies driven by minor improvements compared to existing technologies* *High: Mostly radical or disruptive technological development, transforming products, services or processes*	Desk research Interview
1.2	**Enabling:** the degree of cross-sectorial and systemic relevance of the technology family across economic sectors is… *Low: Enables innovation in few industrial and economic sectors* *High: Enables innovation in most industrial and economic sectors*	Desk research Interview
1.3	The level of **interest by industry and investors** in the technology family is... *Low: Low interest is indicated by stagnating job growth or job loss, low investments, low profitability expectations, lack of sector-wide effects, etc.* *High: High interest is indicated by significant job growth, high investments, high profitability expectations, potential for sector-wide transformations, etc.* *Note: for industrial R&D strength see quantitative data in the factsheets*	Desk research Interview Quantitative analysis Survey(Q1)*
2	**ETHICAL IMPACT**	
2.1	The potential of the technology family to significantly affect or engage **ethical principles and values** is… *Low: The advance of the technology family has limited or no effects on ethical principles and values.* *High: The advance of the technology family has big effects on ethical principles and values.* *Note: Ethical principles and values include e.g. equality, privacy and data protection, autonomy as well as specific concerns related to health, environment and human interactions*	Desk research Interview Survey(Q4)* Workshop
2.2	The need for **additional guidance** in dealing with **ethical aspects** of a technology family (e.g., not covered by existing guides, standards, regulations) is… *Low: The ethical implications of the technology family could be managed with existing guidelines, standards and regulations.* *High: The ethical implications of the technology family will need new guidelines, standards and regulations.*	Survey(Q5)* Workshop
3	**PUBLIC IMPACT**	
3.1	The potential of the technology family to have a significant impact on **societal challenges** (e.g. Sustainable Development Goals, principles of the European Pillar of Social Rights) is… *Low: The technology family has little or no impact on societal challenges (opportunities, threats).* *High: The technology family has a large impact on societal challenges (opportunities, threats).*	Desk research Survey(Q3)* Workshop
3.2	The potential impact of the technology family on **people's lives** (also considering minority and vulnerable populations) is… *Low: A relatively small impact on people's lives, e.g., how people work, move, transport, interact.* *High: A relatively high impact on people's lives, e.g., how people work, move, transport, interact.*	Desk research Survey (Q2)* Workshop
4	**POLICY IMPACT**	
4.1	The **policy** level of focus on the technology family within government/policy strategies, action plans, foresight exercises at national, EU and global level (s) is… *Low: no or very limited policy activities such as strategies, action plans, foresight exercises.* *High: many / prioritised policy activities such as strategies, action plans, foresight exercises.* Note: for EU policy priorities see e.g. quantitative data in the factsheets Note: has an overlap with "additional guidance" see above 2.2	Desk research Interview Quantitative analysis Workshop
5	**LEGAL IMPACT**	
5.1	The potential of the technology to significantly affect **existing legal frameworks** is... *Low: no or very limited changes in existing legal framework* *High: significant changes in existing legal framework (e.g. creating new laws; establishing new legal bodies)*	Desk research

8.4 Annex 4 - Guidance on impact assessment criteria

Further parameters in assessing the relevance of each technology were ethical, legal, and public impact.

ETHICAL IMPACTS
Fundamental principles:

1. Impact on: human rights, freedom, autonomy, integrity, responsibility, privacy, security, inclusivity.
2. Potential for: harm, dual-use/misuse, novelty/radical, blurring fundamental legal and moral categories, human supervision/control, irreversibility.

Applied/specific concerns:

3. Impact on: health, safety, privacy and data protection, environment, sustainability, human cells, tissues, embryos, animals and plants, human interaction, human reproduction.
4. Concerns over: scientific integrity, overstretched promises, preventive measures, equal access.

LEGAL IMPACTS:
List of fundamental principles of democracy & rule of law:

5. Non-derogable fundamental rights: right to life; right to be free from torture and CID; right to be free from retroactive application of penal law
6. Definition of personhood
7. Transparency and accountability of governments
8. Access to legal redress mechanisms
9. Equality before the law and rights of minority groups
10. Fairness/non-discrimination under the law
11. Free and fair elections

List of legal domains for the assessment of legal impact:

12. Human beings, human cells or tissues, human embryos & foetuses (conduct of research law), research on animals (animal law), privacy, data protection, IPR, criminal law/criminal procedure, contracts law, environmental and natural resources law, health law (including drug and devices testing and approvals), labour law, family law, ICT law, outer space law, corporate/tax law, trade/customs law, immigration law, int'l law (humanitarian, law of armed conflict), products liability, insurance law, dispute resolution/judicial systems.

PUBLIC IMPACT:

13. Sustainable Development Goals:

1. No poverty; 2. zero hunger ; 3. good health and well-being; 4. quality education; 5. gender equality; 6. clean water and sanitation; 7. affordable and clean energy; 8. decent work and economic growth; 9. industry, innovation and infrastructure; 10. reduced inequalities; 11. sustainable cities and communities; 12. responsible consumption and production; 13. climate action; 14. life below water; 15. life on land; 16. peace, justice and strong institutions; 17. partnerships for the goals.

14. 20 principles of the European Pillar of Social Rights:

1. Education, training and life-long learning; 2. gender equality; 3. equal opportunities; 4. active support to employment; 5. secure and adaptable employment; 6. wages; 7. information about employment conditions and protection in case of dismissals; 8. social dialogue and involvement of workers; 9. work-life balance; 10. healthy, safe and well-adapted work environment and data protection; 11. childcare and support to children; 12. social protection; 13. unemployment benefits; 14. minimum income; 15. old age income and pensions; 16. health care; 17. inclusion of people with disabilities; 18. long-term care; 19. housing and assistance for the homeless; 20. access to essential services.

8.5 Annex 5 - Impact evaluation matrix

Table 8: Example of the Multi-Criteria Decision Analysis impact assessment matrix with TechEthos impact dimensions.

	Industrial & economic impact	Ethical impact	Public impact	Policy impact	Legal impact
Technology family 1	High	Very high	Low	Medium	Very low
Technology family 2	Low	Very low	Medium	Very high	High
Technology family n	Very high	Medium	High	Very low	Very high

8.6 Annex 6 - TechEthos List of technology families (excluded)

Table 9: List of merged or excluded technology families.

R&I Field	No	Technology family	Reason for exclusion or merging with others
Bio & Environment	17	Bioproducts	Excluded: novelty and ethics impact limited (criteria 1.1, 2.1); at least partially covered by existing ethics guidance (criteria 2.2)
	18	Human enhancement	Excluded: already covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2)
Digital techs	19	Advanced computing	Merged with the Data processing technology family
	20	Artificial intelligence	Excluded: partially covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2). Specific uses and applications integrated in different technology families.
	21	Cybersecurity techs	Merged with the Data processing technology family
	22	Human behaviour technologies	Partially covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2). Elements merged in Cognitive and behavioural techs
	23	Human-machine interfaces	Partially covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2). Elements merged in Cognitive and behavioural techs and other technology families
Health	24	Genetic Technologies	Excluded: already covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2)
	25	Personalised medicine	Excluded: sectorial (not enabling across sectors, criteria 1.2); partially covered by existing ethics guidance (criteria 2.2)

Materials and manufacturing, techs	26	Advanced materials	Excluded: too broad definition, and ethics impact limited (criteria 2.1). Relevant elements integrated into the technology families within the Materials and manufacturing field
	27	Critical infrastructure technologies	Excluded: sectorial (not enabling across sectors, criteria 1.2); ethics impact limited (criteria 2.1); relevant elements integrated into the Threats detection and response technology family
	28	Energy storage and production technologies	Merged with the Environmental and climate technology family
	29	Industrial automation	Merged with the Autonomous systems technology family
	30	Materials and production systems for the circular economy	Merged with the Environmental and climate technology family
	31	Military, defence, security technologies	Excluded: out of the scope of the project (all EU framework program funded research must have an exclusive focus on civil applications, thus excluding military and defence applications, but including issues of civil security)
	32	Molecular engineering	Excluded: ethics impact limited (criteria 2.1)
	33	Nanotechnologies and nanomaterials	Excluded: partially covered by existing ethics guidance (criteria 2.2)
	34	Robotics	Excluded: partially covered by existing ethics guidance, such as guidelines from Sienna and Sherpa project (criteria 2.2). Specific uses and applications integrated into the Autonomous systems technology family
	35	Sensing and imaging technologies	Partially merged with the Threats detection and response technology family

8.7 Annex 7 - Collection of specific technologies from literature

8.7.1 Airi – Italian Association for the Industrial Research

Table 10: The technologies selected in the 2020 Airi report: The Innovation of the Near Future: Key technologies for the industry.

<table>
<tr><th colspan="4">Advanced Manufacturing</th></tr>
<tr><td colspan="2">Eco-sustainable intelligent production machines and systems developed according to the Smart-Factory/Industry 4.0 paradigm.
Knowledge based design: new tools with a high knowledge content for the design, simulation, and production of advanced products.
Production systems management: Methods and standards for the automation and integration of complex production systems.</td><td colspan="2">Logistics and distribution: Internet-based ICT methods and technologies for real-time integration of the players in the supply chain from retail to producers, to suppliers.
Components and subsystems for improving effectiveness, efficiency, and environmental sustainability.
Additive techniques for the manufacture of advanced products
Biological Transformation in the Manufacturing Industry.</td></tr>
<tr><th colspan="2">Digital technologies</th><th colspan="2">Health and Biotech</th></tr>
<tr><td>Cloud Computing.
Internet of Things (IoT).
Big data and Data Science.
Artificial Intelligence.
Machine Learning and Deep Learning.
Immersive technologies: virtual reality and augmented reality.</td><td>Digital ecosystems.
Mobile Radio Networks and Services.
Internet and its security.
Technologies for "Online Contents".</td><td>New approaches to omics technologies.
Innovative technologies for drug discovery.
The new in vitro diagnostics.
Production of biopharmaceuticals and vaccines.</td><td>Molecular Imaging.
Nanomedicine.
Medical devices and minimally invasive technologies.
Advanced therapies and gene editing.</td></tr>
<tr><th colspan="2">Environment</th><th colspan="2">Chemistry</th></tr>
<tr><td>Eco-techs for the recycling and reuse of hard plastics.
Environmental robotics.
Integrated approach to closing the WEEE cycle.
Technologies for eco-friendly uses of tires.
Selective recovery of supernatant from groundwater.
Passive samplers for component monitoring.</td><td>Volatile (VOC) of environmental matrices.
Innovative methods to characterize contaminated areas.
Isotopic and molecular techniques.
Robotics for monitoring aquatic environments.
New generation bio refineries.</td><td>Chemical conversion of raw/waste lignocellulosic biomass.
Strategies for the valorisation of paper mill sludge.
Use of food waste in the tanning industry technology.
Varnishes and paints from bio-renewable raw materials.</td><td>Valorisation of biomasses and their reuse.
Synthesis of ethyl diazoacetate in flux.
Additive manufacturing and material development.
Production of acrylic acid and acrylonitrile from biomass.</td></tr>
<tr><th colspan="2">Microelectronics and semiconductors</th><th colspan="2">Transportation</th></tr>
<tr><td>Integration of electronic systems on silicon.
Embedded-non-volatile-memory integration on silicon.
Optoelectronic and photonic components.
Photonic components based on quantum technologies.
Protocols for the transmission of quantum information.</td><td>Technologies for chemical sensors.
Smart materials and 3D printing for microsystems.
Electronic artificial olfactory systems (e-nose).
Synchrotron light and free electron lasers.
Development of new materials for microelectronics.
Technologies for smart systems.</td><td>Fuels.
Powertrain systems.
Integrated security.
Innovative materials.
Connected car for better, ecological and safe mobility.
Technologies for human-machine interaction (HMI).
Energy efficiency.
The Pirelli IoT solution for the fleet business.</td><td>.
Traceability and diagnostics of freight wagons.
Development of energy-efficient rail vehicles.
Improving energy efficiency on board.
Digitization, communication and connectivity on board.
Promotion of complete ship automation.</td></tr>
</table>

Telecommunication with the advent of graphene.		Predictive diagnostics of autonomous rails and metros. Innovative technologies and materials for the railway	Construction of new marine vehicles: Blue Economy. Improving efficiency and safety in production processes.
Space		**Energy**	
Technologies for gravimetric missions. Technologies for solar exploration. Advanced ultralight and adaptive structures. Robotics and artificial intelligence. Technologies for atmospheric re-entry and exploration. Refuelling, transport and removal of satellites and debris. Technologies and applications for space safety. Technologies for antennas on board satellites. Technologies for miniaturization of equipment. Earth observation radar technologies. High-speed data for future Earth observation missions.	AI for the treatment of radar images. Cybersecurity for the protection of space systems. "Next generation" atomic space clocks. Technologies for space propulsion. Development of new solid propellants. Technologies for accessing space. Next generation tanks for launchers and spacecraft. Additive manufacturing. Flexible telecommunication technologies. Autonomous driving and navigation technologies. Advanced environmental control. Energy storage and distribution. Optics and photonics for space.	Big data and analytics. Robotics in the oil industry. Blockchain technology in demand response. Electrochemical storage and batteries. Chemical storage technologies. Thermal storage systems. Energy storage and monitoring of the electricity service. 2nd and 3rd generation Bio-feedstock. New fermentation processes. Green Refinery. Hydrogen. New generation automotive lubricants. Innovative fuels for CO2 reduction. Elastomeric materials for energy-saving tires.	Algae and use of CO2. CO2 valorisation for advanced materials. Innovative cellular cements with low energy footprint. Advanced materials and process electricity generation. Innovative lubricants for the industrial sector. Advanced and innovative photovoltaic cells. Large scale photovoltaic applications. Concentration and hybridization solar thermal. Luminescent solar collectors and urban photovoltaics. Electrical system in synergy with the gas network. Advanced solutions for geothermal resources.

8.7.2 BOHEMIA Project

Table 11: Overview of top priority R&I directions for the 19 targeted scenarios from BOHEMIA.

Target scenarios	Top priority R&I directions
Assisted Living	E-health solutions, including tele-medicine, measuring health data and transfer
	Research on assistive technologies and the impacts of their application
The Bio-economy	Developing and testing new circular bio-economic processes
Cheap Renewable Energy	Exploration of energy storage solutions, beyond batteries
	Methods, practices and solutions to promote energy saving and reduction of energy consumption
Continuous Cyberwar	Tools for monitoring, evaluation and responding to threats
Defeating Communicable Diseases	Effective public health education about communicable diseases, incl. Prevention, treatments, hygienic questions, disinfection
Emotional Intelligence Online	Developing standards and codes of behaviour concerning the use of individuals' emotions for commercial and public purposes, as well as for emotional data sharing and privacy
	Research and development in cybersecurity, particularly in relation to the online sharing and use of information about individuals' emotions
Human Organ Replacement	Breeding of tissues and organs (theory and practice)
ICT-Based Security and Defence	Understanding the roots causes of security challenges
Low Carbon Economy	Exploitation of new business models for circular economy and promotion of sustainable lifestyles
Material Resource Efficiency	Environmental impact assessment
Nano-to-Macro Integral Manufacturing	Understanding the impact of 3D printing on individual health and safety and on the environment, across various industries
Nature Valued	Building models for a sustainable circular economy based on renewable resources and renewable energy
Precision Medicine	Making use of biotechnologies for personalized medicine
Reframing Work	Research on new variants of entrepreneurship through collaborative research
Smart Sustainable Mobility	Research on battery efficiency, energy storage and recovery technologies
The Electro-sphere of Sensors	Development of new sensors based on a better understanding of the relation between sensing and knowing
Towards a More Diverse Food Supply System	Understanding and managing systems of sustainable agriculture and aquaculture
Towards a New Knowledge System	Adapting educational techniques to online environments, and piloting various solutions (e.g., distributed online courses with tutoring, navigating through the stock of knowledge)

	Devising intellectual property models and practices in open knowledge systems, and experimenting with new forms of IP sharing
	Understanding the neural basis of knowledge acquisition, and the relation of cognition to experience more generally
Ubiquitous Expert Systems	Development of better machine-learning algorithms

8.7.3 Consultants to Governments and Industries - CGI

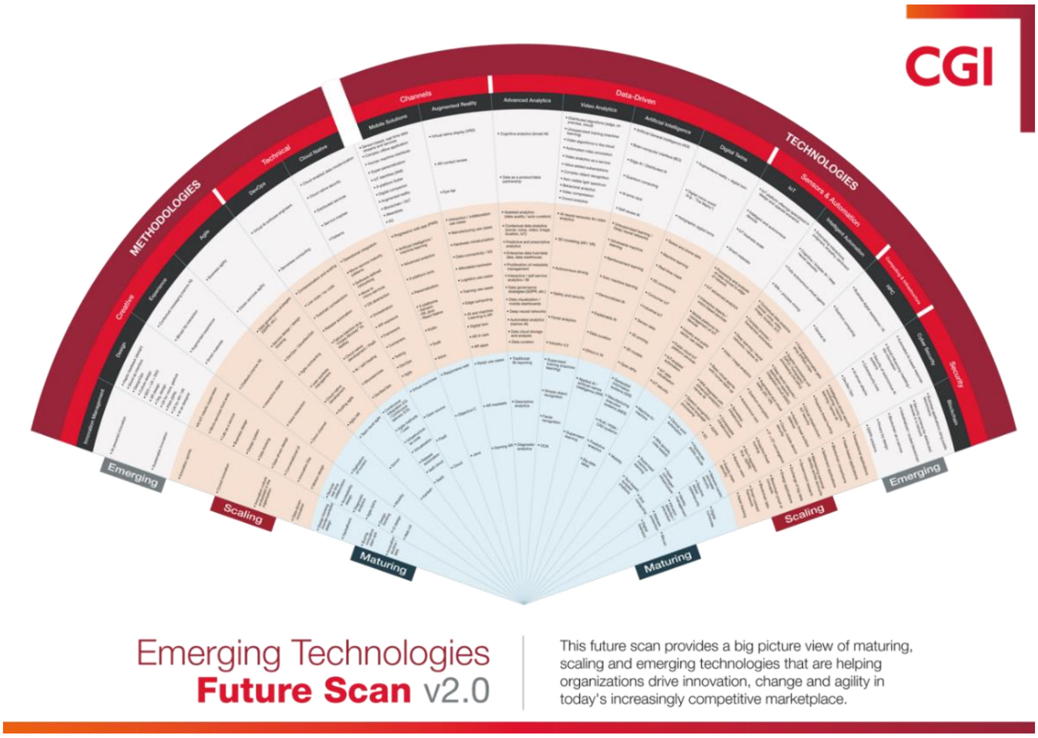

Figure 5: CGI Map of Emerging Technologies. Link to the image: Emerging Technologies Future Scan.

8.7.4 Deloitte

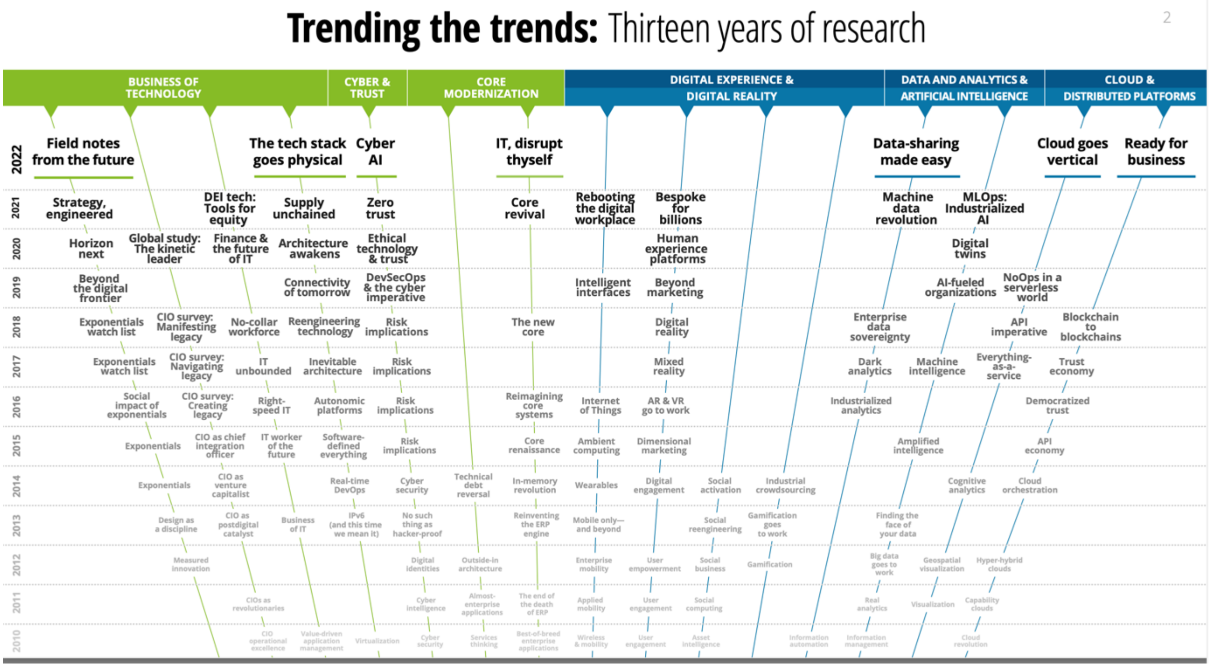

Figure 6: Deloitte Technologies Trends since 2010.

Table 12: Time series of Deloitte Technology Trends.

2020	2021	2022
Horizon Next	Bespoke for billions: digital meets physical	Blockchain: Ready for business
Global study: the kinetic leader	Core revival	Cloud goes vertical
Finance & the future of IT	Dei *(Diversity, Equity and Inclusion)* tech: tools for equity	Cyber AI: Real defense
Architecture awakens	Machine data revolution: feeding the machine	Data-sharing made easy
Ethical technology & trust	Mlops: industrialized AI	Field notes from the future
Human experience platforms	Rebooting the digital workplace	IT, disrupt thyself: Automating at scale
Digital twins	Strategy, engineered	The tech stack goes physical
	Supply unchained	
	Zero trust: never trust, always verify	

8.7.5 Digital Platforms

Table 13: Overview of the emerging technologies from the various digital platforms analysed: Analyticis Insight (2020), Comptia (2020/2021), Forbes (2021), The Economist (2021), TechStartups (2021).

Analytics Insight	CompTIA	Forbes	The economist	Techstartups
3D printing or additive manufacturing	3D Printing	5G	3D-printed bone implants	5G
Artificial intelligence	5g in Everyday Life	Automated risk management	3D-printed houses	AI and ML
Blockchain	AI	Chatbots and smart assistants	Artificial meat and fish	AR/VR
Cybersecurity	Blockchain	Digital health tech	Brain interfaces	Internet of things (iot)
Drone	Computer Vision	Edge computing	Container ships with sails	Natural language processing
Internet of things (Iot)	Customer Data Platforms	Embedded sim	Delivery drones	Next-generation cognitive computing –
Robotics	Cybersecurity as Critical Business Function	Hipaa-compliant meeting software	Direct air capture	Quantum computing
Virtual reality and augmented reality	Cybersecurity Mesh	Improved natural language processing	Flying electric taxis	Robotics
	Digital Health	Low-code/no-code	Heat pumps	Sensing and mobility
	Digital Twin	New data prediction models	Hydrogen-powered planes	Serverless and next-generation cloud computing
	Drones	Secure access service edge platforms	Personalised nutrition	
	Edge Computing	Voice pay solutions	Quantum computing	
	IoB (Internet of Behaviors)		Quieter supersonic aircraft	
	IoT		Sleep tech	
	Low-Code Technology		Solar geoengineering	
	Quantum Computing		Space tourism	

	Robotic Process Automation (RPA)		The metaverse	
	Spatial Computing		Vaccines for HIV and malaria	
	Total Experience		Vertical farming	
	Virtual Reality/Augmented Reality		Virtual influencers	
			VR workouts	
			Wearable health trackers	

8.7.6 Future technology for prosperity: horizon scanning by Europe's technology leaders

Table 14: Overview of technology frameworks and technologies from Future technology for prosperity.

Technology	Technological Framework
Gene Tech	Biological transformation
Human-machine interaction	
NeuroTech	
Smart farming	
Coherent optics	Low energy data transmission
Smart dust	
Digital fish	Marine technologies
Fresh water under sea	
Carbon capture and storage	Power to x
Hydrogen	
Additive manufacturing	Smart Materials
Renewable plastics	
Smart nanomaterials	

8.7.7 Future Today Institute

Table 15: List of top emerging technologies from Future Today Institute grouped by clusters.

Artificial Intelligence	Consumer
Deep Learning ML (Machine Learning) Weak and Strong AI	Consumer-grade AI Applications Deepfakes for Fun Personal Digital Twins Ubiquitous Digital Assistants Zero UIs (Zero User Interface)
Creative	**Health, Medicine and Science**
Assisted creativity Automated Versioning Automatic Ambient Noise Dubbing Automatic Voice Cloning and Dubbing Generating Virtual Environments for short videos Generative Algorithms for Content Production	AI First Drug Discovery AI Improves Patient Outcomes Deep Learning Applied to Medical Imaging Diagnostics Without Tests Dream Communication NLP Algorithms Detect Virus Mutations Protein Folding Scenario: Deep Twins in the OR Thought Detection
Enterprise	**Research**
100-Year Software Advanced AI Chipsets AI at the Edge AI in the Cloud Algorithm Marketplaces Artificial Emotional Intelligence Digital Twins GlobAI Rush to Fund AI Intelligent Optical Character Recognition Liability Insurance for AI Low-Code or No-Code ML Manipulating AI Systems for Competitive Advantage Massive Translation Systems Natural Language Processing for ESGs (Environmental, Social and Governance) Predicting Systems and site fAIlures Robotic Process Automation Serverless Computing Simulating Empathy and Emotion Spotting Fakes The Rise of MLOps (Machine Learning Operations) Web-Scale Content Analysis	AI Summarizing Itself Automated ML (AutoML) Closed-Source Code Continuous Learning Cost of Training Models Federated Learning Framework Consolidation General Reinforcement Learning Algorithms GP (Gaussian Processes) Models GPT-3's (AI that generates human-like language) Influence Graph Neural Networks Hybrid Human-Computer Vision Machine Image Completion Machine Reading Comprehension Model free Approaches to RL (Reinforcement Learning) Neuro-Symbolic AI NLP Benchmarks No RetrAIning Required Predictive Models Using Single Images Proliferation of Franken-Algorithms Proprietary, Homegrown AI languages Real-time ML Research Vokenization
Talent	
AI Brain Drain AI for Interviews AI Universities Corporate AI Labs Demand for AI Talent Growing	

8.7.8 Frost & Sullivan

Figure 7: List of Top 50 emerging technologies as selected in 2021 by Frost & Sullivan.

8.7.9 Gartner

Table 16: Gartner list of top emerging technologies in 2021 and 2022

Anywhere operations	Year
Artificial intelligence engineering	2021/2022
Autonomic Systems	2022
Cloud-Native Platforms	2022
Composable Applications	2022
Cybersecurity mesh	2021/2022
Data Fabric	2022
Decision Intelligence	2022
Distributed cloud	2021
Distributed Enterprises	2022
Generative AI	2022
Hyperautomation	2021/2022
Intelligent composable business	2021
Internet of behaviour (iob)	2021
Privacy-Enhancing Computation	2021/2022
Total experience (tx)	2021/2022

8.7.10 Massachusetts Institute of Technology - MIT

Table 17: Time series of MIT list of Technology Breakthroughs.

2001	Brain-Machine Interface	Flexible Transistors	Data Mining	Digital Rights Management	Biometrics	Natural Language Processing	Microphotonics	Untangling Code	Robot Design	Microfluidics
2003	Wireless Sensor Networks	Injectable Tissue Engineering	Nano Solar Cells	Mechatronics	Grid Computing	Molecular Imaging	Nanoimprint Lithography	Software Assurance	Glycomics	Quantum Cryptography
2004	Universal Translation	Synthetic Biology	Nanowires	T-Rays	Distributed Storage	RNAi Interference	Power Grid Control	Microfluidic Optical Fibers	Bayesiam Machine Learning	
2005	Airborne Networks	Quantum Wires	Silicon Photonics	Metabolomics	Magnetic-Resonance Force Microscopy	Universal Memory	Bacterial Factories	Enviromatics	Cell-Phone Viruses	Biomechatronics
2006	Nanomedicine	Nanobiomechanics	Epigenetics	Comparative Interactomics	Diffusion Tensor Imaging	Cognitive Radio	Pervasive Wireless	Universal Authentication	Nuclear Reprogramming	Stretchable Silicon
2007	Peering into Video's Future	Nanocharging Solar	Invisible Revolution, metamaterials	Personalized Medical Monitors	Single-Cell Analysis	A New Focus for Light, DVD	Neuron Control	Nanohealing	Digital Imaging, Reimagined	Augmented Reality
2008	Modeling Surprise	Probabilistic Chips	NanoRadio	Wireless Power	Atomic Magnetometers	Offline Web Applications	Graphene Transistors	Connectomics	Reality Mining	Cellulolytic Enzymes
2009	Intelligent Software Assistant	$100 Genome	Racetrack Memory	Biological Machines	Paper Diagnostics	Liquid Battery	Traveling-Wave Reactor	Nanopiezoelectronics	HashCache	Software-Defined Networking
2010	Real-Time Search	Mobile 3-D	Engineered Stem Cells	Solar Fuel	Light-Trapping Photovoltaics	Social TV	Green Concrete	Implantable Electronics	Dual-Action Antibodies	Cloud Programming
2011	Social Indexing	Smart Transformers	Gestural Interfaces	Cancer Genomics	Solid-State Batteries	Homomorphic Encryption	Cloud Streaming	Crash-Proof Code	Separating Chromosomes	Synthetic Cells

2012	Egg Stem Cells	Ultra-Efficient Solar	Light-Field Photography	Solar Microgrids	3-D Transistors	A Faster Fourier Transform	Nanopore Sequencing	Crowdfunding	High-Speed Materials Discovery	Facebook's Timeline
2013	Smart Watches	Ultra-Efficient Solar Power	Memory Implants	Prenatal DNA Sequencing	Deep Learning	Additive Manufacturing	Big Data from Cheap Phones	Temporary social media	Supergrids	Baxter: The Blue-Collar Robot
2014	Agricultural Drones	Ultraprivate Smartphones	Brain Mapping	Neuromorphic Chips	Genome Editing	Microscale 3-D Printing	Mobile Collaboration	Oculus Rift	Agile Robots	Smart Wind and Solar Power
2015	Magic Leap	Nano-Architecture	Car-to-Car Communication	Project Loon	Liquid Biopsy	Megascale Desalination	Apple Pay	Brain Organoids	Supercharged Photosynthesis	Internet of DNA
2016	Immune Engineering	Precise Gene Editing in Plants	Conversational Interfaces	Reusable Rockets	Robots That Teach Each Other	DNA App Store	SolarCity's Gigafactory	Slack	Tesla Autopilot	Power from the Air
2017	Reversing Paralysis	Self-Driving Trucks	Paying with Your Face	Practical Quantum Computers	The 360-Degree Selfie	Hot Solar Cells	Gene Therapy 2.0	The Cell Atlas	Botnets of Things	Reinforcement Learning
2018	3-D Metal Printing	Artificial Embryos	Sensing City	AI for Everybody	Dueling Neural Networks	Babel-Fish Earbuds	Zero-Carbon Natural Gas	Perfect Online Privacy	Genetic Fortune-Telling	Materials' Quantum Leap
2019	Robot dexterity	New-wave nuclear power	Predicting preemies	Gut probe in a pill	Custom cancer vaccines	The cow-free burger	Carbon dioxide catcher	An ECG on your wrist	Sanitation without sewers	Smooth-talking AI assistants
2020	Anti-aging drugs	Artificial intelligence (tiny)	Artificial Intelligence-discovered molecules	Climate change attribution	Differential privacy	Digital money	Hyper-personalized medicine	Quantum supremacy	Satellite mega-constellations	Unhackable internet
2021	Artificial Intelligence Multi-skilled	Data trust	Digital contact tracing	Gpt-3	Green hydrogen	Lithium-metal batteries	Messenger rna vaccines	Remote everything	Tiktok recommendation algorithms	

8.7.11 The North Atlantic Treaty Organization - NATO

Table 18: The NATO 2020 list of disruptive and emerging technologies

Science and Technology (S&T) trends	Focus areas
Data: Big Data and Advanced Analytics (BDAA)	Disruptive Technologies
Artificial Intelligence (AI)	Disruptive Technologies
Space Technologies (ST)	Disruptive Technologies
Autonomy	Disruptive Technologies
Hypersonic (Weapon Systems) (HWS)	Disruptive Technologies
Quantum (Technologies) (QT)	Emerging Technologies
Bio-(& Human Enhancement) Technologies (BHET)	Emerging Technologies
Novel Materials and Manufacturing (NMM)	Emerging Technologies

8.7.12 PREFET Project

Table 19: PREFET'S List of the top 20 trends in future and emerging technologies.

ICT for an interconnected society	Biotechnology & Health Sciences	Environment, Energy & Climate change
Chemputing & 3D Printing Molecules	Cognitive Augmentation & Intelligence Amplification	Energy Efficient Water Treatments
Adaptive Assurance of Autonomous Systems	Regenerative Medicine s	Algae and Microorganisms Against Climate Change
Neuromorphic Computing (new types of hardware) and Biomimetic AI	Drug discovery & manufacture using AI	High temperature superconductivity & twist electronics
Limits of Quantum Computing: Decoherence and use of Machine Learning	Bioinformatics & ai in 'omics'	Self-healing batteries
Ethically trustworthy ai & anonymous analytics	Cellular senescence & life extension	Net zero concepts & beyond smart grids
Beyond 5g hardware	Bio robotics/bionics	Net zero concepts & beyond smart grids
New approaches to data interoperability in IoT		Zero power sensors & ocean wiring and sensing

8.7.13 PWC

Table 20: The PwC emerging technologies and the converge themes

Building block	Convergence theme
3D printing	Automating trust
Artificial Intelligence	Digital reflection
Augmented Reality (AR)	Extended reality
Blockchain	Hyperconnected networks
Drones	Immersive interfaces
Internet of Things	Working autonomy
Robotics	
Virtual Reality (VR)	

8.7.14 RIBRI Project

Table 21: Overview of the 100 Radical Innovation Breakthroughs (RIBs) grouped by 8 thematic areas.

Artificial Intelligence and Robots		Biohybrids	
Artificial Intelligence Augmented Reality Automated indoor farming Blockchain Chatbots Computational Creativity Driverless Exoskeleton Flying car Holograms	Humanoids Hyperspectral imaging Neuroscience of Creativity and Imagination Precision farming Soft robot Speech Recognition Swarm robotics Touchless gesture recognition Warfare drones	Biodegradable sensors Bioelectronics Bioinformatics Lab-On-A-Chip Molecular recognition Plant communication Antibiotic Susceptibility Testing Bioprinting Control of gene expression	Drug delivery Epigenetic change technology Gene editing Gene Therapy Genomic vaccines Microbiome Regenerative medicine Reprogrammed human cells Targeting cell death pathways
Breaking Resource Boundaries		**Electronics & Computing**	
Asteroid mining Bioplastic Carbon capture and sequestration Desalination Geoengineering: changing landscapes Hyperloop	Plastic Eating Splitting carbon dioxide technology for disaster preparedness Underwater living Wastewater nutrient recovery	Carbon Nanotubes Computing memory Flexible electronics Graphene Transistors High-precision clock Molten Salt Reactors	Nano-LEDs Nanowires Optoelectronics Quantum Computers Quantum Cryptography Spintronics
Energy		**Society**	
Airborne wind turbine Aluminium-based energy Artificial Photosynthesis Bioluminescence Energy Harvesting	Hydrogen fuel Marine and tidal power technology Microbial fuel cells Smart windows	Access Economy Alternative Currency Basic Income Body 2,0 and the Quantified Self	Life Caching Local Food Circles New Journalist Networks Owning and Sharing Health Data

Harvesting Methane Hydrate	Thermoelectric paint Water Splitting	Car-free City Collaborative innovation spaces Gamification	Read/Write Culture Reinventing Education
Printing and Materials		**Human-Machine Interaction & Biomimetics**	
2D Materials 3D Printing of Food 3D Printing of Glass 3D Printing of Large Objects	4D Printing Hydrogels Metamaterials Self-healing materials	Artificial synapse/ brain Bionics in medicine Brain Function Mapping Brain Machine Interface	Emotion recognition Neuromorphic chip Smart Tattoos

8.7.15 SIENNA Project

Table 22: Emerging Disruptive Technologies (Research briefing written for the NWO Gravitation programme) grouped by domains.

Bio-tech		Digital Tech	
3D bioprinting Bioelectronics Bioinformatics Biomaterials Biometrics DNA digital data storage Environmental bio-Tech Food Tech	Genome editing Health monitoring Industrial bioTech Medical bioTech Nano-Bio-Info-Cogno NeuroTech Synthetic biology Tissue engineering	3D Additive manufacturing 5g network Artificial intelligence Augmented reality Autonomous vehicles Big data analytics Blockchain Digital twins Human-machine symbiosis	Internet of Things Machine learning Quantum computing Robotics Sensor Tech Unmanned aerial vehicles Virtual personal assistants Virtual reality
Energy and Environment		**New Materials**	
Biofuels Bioplastics Carbon dioxide removal Energy storage Hydrogen	Smart grids Solar energy Solar radiation management Space vehicles	Biomimicry E-textiles Flexible electronics Materials	Nanomaterials Photonics Smart materials

8.7.16 World Economic Forum - WEF

Table 23: Last 6 years WEF selection of emerging technologies.

2016	2017	2018	2019	2020	2021
Nanosensors and the Internet of Nanothings	Liquid biopsies	Augmented reality	Bioplastics for a Circular Economy	Digital Medicine	Ammonia goes green
Next Generation Batteries	Harvesting clean water from air	Personalised medicine	Social Robots	Electric Aviation	Biomarker devices go wireless
The Blockchain	Deep learning for visual tasks	AI-led molecular design	Tiny Lenses for Miniature Devices	Green Hydrogen	Crops that make their own fertilizer
2D Materials	Liquid fuels from sunshine	More capable digital helpers	Disordered Proteins as Drug Targets	Lower-Carbon Cement	Decarbonization Rises
Autonomous Vehicles	The Human Cell Atlas	Implantable drug-making cells	Smarter Fertilizers Can Reduce Environmental Contamination	Microneedles for Painless Injections and Tests	Diagnosing diseases with a puff of breath
Organs-on-chips	Precision farming	Gene drive	Collaborative Telepresence	Quantum Sensing	Energy from wireless signals
Perovskite Solar Cells	Affordable catalysts for green vehicles	Algorithms for quantum computers	Advanced Food Tracking and Packaging	Spatial Computing	Engineering a longer "healthspan"
Open AI Ecosystem	Genomic vaccines	Plasmonic materials	Safer Nuclear Reactors	Sun-Powered Chemistry	Houses printed with local materials
Optogenetics	Sustainable design of communities	Lab-grown meat	DNA Data Storage	Virtual Patients	Making pharmaceuticals on demand
Systems Metabolic Engineering	Quantum computing	Electroceuticals	Utility-Scale Storage of Renewable Energy	Whole-Genome Synthesis	Space connects the globe

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