CHAPTER 15

SCANNING THE INNOVATION HORIZON

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Summary

This chapter is dedicated to efforts gathering wide-ranging intelligence to identify new signs of emerging issues, trends and challenges for the future. It describes in detail the practice of horizon scanning, which can be seen as the basic groundwork of foresight projects, or as an important strategic function in its own right.

It presents the European Commission's latest research and innovation (R&I) foresight exercises which are essential in the context of the increasing emphasis being placed by the EU's R&I policy on directionality, in particular towards sustainable development. The need for informed policy priorities results in demand for more systematic, continuous and comprehensive scans to feed into decision-making processes.

1. Introduction

The European Union makes substantial investments in research, science, technology and innovation, aiming at lowering technical and commercial risks associated with innovation to make its economy more competitive and to enable its society to achieve goals such as prosperity, sustainability and quality of life. European strength in science, technology and industry is necessary to ensure that Europe is able to achieve its objectives. To be competitive, Europe needs to maximise the value and productivity of its investments in R&I, and this requires appropriate intelligence and coordination between relevant policies and strategies at EU, national and regional levels. These investments may follow Europe's strengths or weaknesses and concentrate on areas where the greatest impacts can be expected and where the most benefits would lie. A good understanding of capacities and aspirations for future innovations is an invaluable basis for reflection and debate on potential impacts of different investment decisions, and on the normative and strategic considerations that should guide those investment decisions.

This paper presents a brief overview of how horizon scanning took hold in EU efforts to improve priority-setting in science and technology. It begins with the history of the development of priority setting in R&I policy and the analytical methodologies used to support it, showing the hand-in-hand evolution of political and analytical developments. Despite being practised for many years, especially in Japan, horizon scanning in science and technology (S&T) really took off with the publication of the Chinese Roadmaps for 2050. The close coupling between understanding the horizon, the policy goals and the commitment to achieving them that seemed to drive the modernisation of China incentivised other governments to undertake R&I horizon scanning, and to use it in priority setting. The paper reviews some key national projects before describing the European Commission's experience with horizon scanning. Its conclusions simply appraise this experience and point at questions and possible improvements that could determine whether horizon scanning becomes a regular part of the EU policymaking toolbox or remains an experiment from which lessons are applied elsewhere.

2. Horizon scanning in R&I policy

A great deal of modern S&T has its roots in the efforts to sustain the technological leadership of the US military and the commercial advantages these generated for US firms (Bush, 1945; McDougall, 1985; Gholz, 2011; Mazzucato, 2011). The EU's R&I efforts originated in an effort to catch up with the USA in certain fields of S&T (EC 1970, 1985; Patel and Pavitt, 1987; Sharp, 1989). The EU was not alone in this effort. Japan, the Soviet Union and, increasingly, other parts of the world began to invest heavily in R&D and to seek to compete with the USA in S&T. During the 1980s, it became clear that no country could afford to be the world leader in all fields of S&T and strategic R&I programming became prominent.

Japan led the way with the launch of the Very large-scale integration (VLSI) programme in 1976. The ALVEY Programme in the UK and the ESPRIT programme in the European Community were reactions to Japan's VLSI. More and more countries set off to develop capacities in key technologies (Rothwel and Zegveld, 1985), which 'when effectively controlled, offer keys to economic success' (Revermann and Sonntag, 1989, p. 1). The effort to devise priorities led to the development of disciplines such as scientometrics (De Sola Price, 1978), technometrics (Sahal, 1985) and to the application of foresight in S&T (Martin and Irvine, 1984, 1989; Urashima, Yokoo and Nagano, 2012). The foundations of these disciplines lie in the belief that priority-setting in S&T can benefit from on an informed understanding of capabilities and aspirations, which can be revealed by the study of expert communities and their communication.

The practice of horizon scanning evolved in this context and can be seen either as the basic groundwork of foresight projects, or as an important strategic function in its own right. It signifies an effort to gather wide-ranging intelligence that goes beyond the normal intelligence practice, to identify new signals of emerging issues, trends and challenges that could help preparedness for the future (Cuhls, van der Giessen and Toivanen, 2015). In S&T, horizon scanning provides intelligence about capacities and aspirations which could push forward the frontiers of knowledge and innovation. For contemporary R&I policymaking, this intelligence is an essential part of the strategic context of policy decisions. It allows informed evaluations of expected costs, benefits, challenges and opportunities associated with particular R&I policy options and directions (ibid.). Again, Japan led the way. Regular foresight studies in science and technology, with a broad horizon scan, began in the 1970s, and since 1996 they have been integrated into the revision of the Basic Plan, the basis of Japanese S&T policy that is reviewed every five years (Urashima, Yokoo and Nagano, 2012).

The need for a more strategic approach to R&I policy underpins the European Commission's recent efforts to develop a more systematic understanding of the innovation horizon. These efforts build on two foundations: the first is the development of strategic foresight in the EU's R&I policy during Horizon 2020 (EFFLA 2013; Burgelman et al., 2014; Kastrinos, 2018). In the practice of strategic foresight, some of the most powerful context is provided by megatrends[1] (Gore, 2013; EEA 2010, 2015; OECD 2016; ESPAS 2015, 2019), described as inescapably powerful forces). However, in their content megatrends invariably resemble significant debates about the future rather than determined historical destinies. The interplay between determinism and strategies to change the future requires foresight to decompose megatrends, to juxtapose established trends with emerging

1 In 2018, the JRC developed an online megatrends hub: https://ec.europa.eu/knowledge4policy/foresight/about_en and a set of methodologies for using it as the context for decision-making games.

trends, and to debate the significance of different phenomena. Scanning the horizon for signals of new trends is a way of compensating for the power of megatrend discourses over both likely and unlikely alternative futures.

Trends are sequences of events in time that imply an underlying cause. The horizon is scanned for 'signals'. These are significant observations (events) which may or may not signify a trend. Horizon scanning relates such observations to one another to develop 'signposts". Signposts are conditions that could signify a trend within underlying causal theories. By accumulating signposts, trends become more visible and different causal theories build and lose predictive value. And as we begin to discern trends, the future becomes more predictable.

The second foundation of the European Commission's horizon-scanning effort lies with the international experience that is demonstrating more and more clearly the feasibility of scanning that is useful for policy. Studies aiming to produce representations of the scientific and technological frontier began in the 1980s (Sahal, 1985; Callon et al., 1983; Callon, Rip and Law, 1986) but really took off in the 21st century with the growing importance of the internet and the development of text-mining algorithms (Porter, Kongthon, Lu, 2002; Kostoff, 2012; Kim and Chen, 2015). Early studies built on the framework of the key technologies of the 1980s: ICT, biotechnology, industrial technology and new materials and energy technologies (Revermann and Sonntag, 1989). Later, the frameworks became more elaborate. Two phenomena probably played a role: the first is technological convergence and cross-fertilisation (Roco and Bainbridge, 2003). An important part of convergence was tied to what they saw as the unification of S&T:

'The sciences have reached a watershed at which they must unify if they are to continue to advance rapidly. Convergence of the sciences can initiate a new renaissance, embodying a holistic view of technology based on transformative tools, the mathematics of complex systems, and unified cause-and-effect understanding of the physical world from the nanoscale to the planetary scale' (ibid. p. x).

R&I policies have gradually moved from discipline-based work towards a systems-oriented policy. In the EU, key technologies and key application areas continued to be the framework (see Cahil and Scapolo, 1999) until the Fifth Framework Programme (FP5) put its focus on key actions for particular socio-economic systems, such as the cities of the future, industry, etc. Whilst this was very well received, evaluation of FP5 centred around the EU's relative inability to coordinate national R&D policies:

'Our panel is convinced that the required changes need to be conceived within an overall strategy for Europe, articulated at the level of the EU and supported by all the Member States' (Majo et al., 2000 p. i).

The ability of the Union to coordinate national programmes and policies became a key political issue of the decade, with the European Research Area (Kastrinos, 2010), whilst the thematic structure of the framework programme remained stable.

3. Horizons and roadmaps

In 2010, the Chinese Academy of Sciences published a Roadmap for Science and Technology in China to 2050 (Lu, 2010). This signalled China's resolution to move from imitation to innovation with Chinese characteristics, rooted in domestic efforts and integrating global innovation resources. The roadmap was based on an analysis of key systems for China's socio-economic development and strategic capabilities, which framed its priority-setting process. Through this lens, China set out what it saw as the horizon of R&I challenges for the coming 40 years.

Roadmap for Chinese S&T 2050

Strategic systems for China's socio-economic development

a. The system of sustainable energy resources
b. The green system of advanced materials and intelligent manufacturing
c. The system of ecological and high-value agriculture and the biological industry
d. The generally applicable health-assurance system
e. The system of ecological and environmental conservation development
f. The expanded system of space and ocean-exploration capability
g. The national and public security system

S&T initiatives of strategic importance for China's modernisation

1. Six S&T initiatives of strategic importance to international competitiveness:
   a. New principles and technologies of Post-IP Network and its test beds
   b. Green manufacturing of high-quality raw materials
   c. Process engineering of highly efficient, cleaner and recycling utilisation of resources
   d. Ubiquitous sensing-based informationised manufacturing systems
   e. Exa (1018) supercomputing technology
   f. Molecular design of animal and plant strains and products
2. Seven S&T initiatives of strategic importance to China's sustainability:
   a. 4 000-metre transparency underground programme
   b. New renewable energy power systems
   c. Deep geothermal energy power generation
   d. A new nuclear energy system
   e. Marine capacity expansion plan
   f. Stem cells and regenerative medicine
   g. Early diagnosis and systematic intervention of major chronic diseases
3. Two S&T initiatives of strategic importance to China's national and public security:
   a. Space situation awareness network (SSAN)
   b. Social computing and parallel management systems
4. Four basic science initiatives likely to make transformative breakthroughs:
   a. Exploration of dark matter and dark energy
   b. Controlling the structure of matter
   c. Artificial life and synthetic biology
   d. A mechanism of photosynthesis
5. Three emerging initiatives of cross-disciplinary and cutting-edge research:
   a. Nanoscience and technology
   b. Space science and exploration satellite series
   c. Mathematics and complex systems

The defining difference between the Chinese Roadmap and all other priority-setting exercises is its expansionary nature. It was not a plan for the efficient use of resources in a steady state. It was the expansion plan which, over a decade, built the current competitive position of Chinese R&I and its future prospects.

Soon after the Chinese Roadmap was published, the Parliament of Finland launched the project '100 opportunities for Finland and the world' (Linturi, Kuusi and Alqvist, 2014), and the Russian prime minister launched the project 'Russia 2030: Science and Technology Foresight' (Gokhberg, 2016). Both projects benchmarked national capabilities in S&T in relation to key areas which were identified through some form of horizon scanning. The Russian study used a literature-based approach to its horizon scanning, whilst the Finnish one used an expert conversation-based methodology. The Russian study presented its findings in seven categories. The first three were the traditional generic technologies of the 1980s: ICT, biotechnology, and new materials (and nanotechnology), whilst the other four were application areas: healthcare and medicine, environmental management, transport and space systems, and energy efficiency and energy savings. In those four categories, the report catalogues about 200 important research areas, characterising Russian S&T as world class in a very small number of them (a handful of areas in medicine and energy, one area in space and one area in materials). However, the report made no case for the need for Russia to be world class in some areas. It simply developed an assessment on which government agencies and public and private companies could base their decisions about what they wanted to achieve.

The Finnish study explicitly took the view that Finland would have to adapt to whatever the world economy becomes. Thus, it defined future global value networks in which Finland would have to play a role if it were to sustain its standard of living. The study carried out a broad expert consultation on trends in S&T that would affect the global value networks and evaluated the importance of those trends in relation to their potential effects on such networks. The 100 trends with the biggest potential impact were labelled 100 opportunities for Finland and the world and were used by the study to benchmark the capacity of Finland in relation to the world standard. The Finnish study was revisited during 2017 with a similar methodology and was published under the title Societal Transformation 2018-2037 (Linturi and Kuusi, 2019). There were a few changes between the two studies. The global value networks terminology became more austere and some of the areas identified changed. The earlier study defined sensors, functional materials and intelligent goods as emerging global value chains, while the later work emphasised more social areas related to work, education and meaningful life. There was also some change in the framing of areas of innovation that constitute breakthroughs, as can be seen in the box below.

The figure below traces the evolution of the view on future global value networks of interest to Finland.

Figure 15-1 **Horizon scanning of the Parliament of Finland: global value networks and areas of technological breakthroughs**[2]

100 opportunities for Finland and the world (published in 2014)	Societal transformation 2018-2037 (published in 2019)
Global value networks	
Automation of passenger-vehicle traffic	Passenger transport
Automation of commodity transport	Logistics
Manufacturing close to customers	Manufacturing of goods
Virtualisation of retail trade and services	Exchange
Local or functional food	Sustenance
Distance presence and remote control of tools	Remote impact
Individualisation of learning and guidance	Acquiring information
Self-care based and personalised healthcare	Healthcare
New capabilities for those who have lost their functional health	Redressing disabilities
Sustainable energy technologies	Energy supply
Raw materials from untapped areas of the earth and space	Materials
Participatory forms of entertainment, culture and influence	Producing experiences
National defence and anti-terrorism	Safety and security
Functionalisation of spaces and structures	Built environment
Operation models for self-organising communities	Collaboration and trust
Virtualisation of identities and social structures	Existential meaning
Democracy, freedom and social cohesion	Power structures
Equipment that increases awareness of the environment	*Automation of work*
Functional materials and new material technologies	*Work and income*
Functional added value of intelligent goods	*Proficiency and its proof*
Areas of technological breakthroughs	
Control of metabolisms of human beings and other organisms	Biotechnology and pharmacology
Social innovations	Digital crowdsourcing platforms
Algorithms and systemic solutions based on IT	Artificial intelligence and algorithmic reduction
Measurement and picturing	Digitisation of sensory data and processing
Moving and transportation	Transport, mobility and logistics
Robotics	Production of products and services
Key enabling materials and industrial raw materials	Material technology
Energy technology	Energy technology
Messaging technologies and protocols	Instrumentation and telecommunication
Human machine interface technologies	*Globalising technology interfaces*
Imitation of nature and cyborgs	

Science, research and innovation performance of the EU 2020

Source: Author's elaboration based on Linturi at al., 2014; Linturi and Kuusi, 2019

Note: The placing of areas next to each other indicates the continuity from one report to the other, unless in italics, which indicates discontinuities.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter15/figure_15-1.xlsx

2 The placement of areas next to each other indicates the continuity from one report to the other, unless in italics, which indicates discontinuities.

4. Horizon scanning in the European Commission: the Radical Innovation Breakthrough Inquirer

The European Commission's Radical Innovation Breakthrough Inquirer (RIBRI) project was inspired by the Finnish study in two ways. First, having realised the importance of values in foresight and R&I policy (Remotti et al., 2016; Webber et al., 2018), the Commission came to appreciate the Finnish study's emphasis on values and the concomitant interest in social innovation. Second, the idea of using values as a means of evaluating the potential impact of radical innovations was consistent with the rising emphasis on directionality in EU R&I policy, in particular towards the Sustainable Development Goals in the UN Agenda 2030.

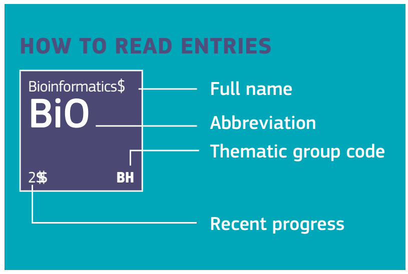
The RIBRI study used a mixed approach to identify radical innovation breakthroughs. For the most part, a massive bibliometric study used specially trained algorithms to mine scientific and technical publications for emerging concepts. Signals identified by the algorithms went through expert refereeing, after which they were written up as Radical Innovation Breakthroughs (RIBs). These were compared to and enhanced with other RIBs identified by other recent foresight studies, including surveys of social innovations. The 100 most important ones were selected through expert assessment procedures for their potential for widespread use by 2038, their level of maturity, and the EU's relative position in patents and publications.

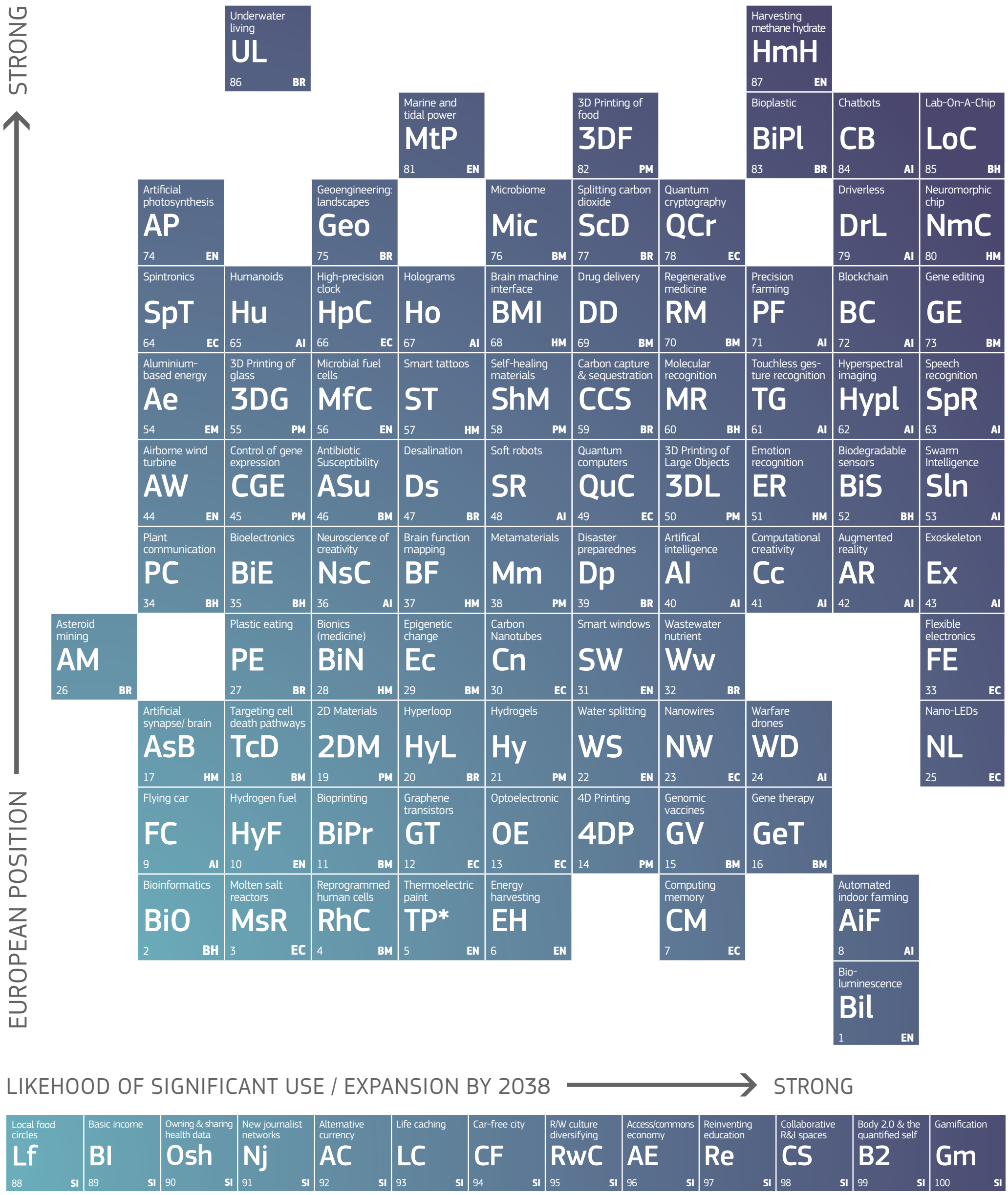
The 100 RIBs were clustered ex post into nine areas: Artificial Intelligence and robotics (AI&R); electronics and computing (E&C); bio-medicine (BM); human-machine interaction and biomimetics (HMI&B); printing and materials (P&M); resource boundaries (RB); energy (E); bio-hybrids (BH); and social innovations (SI). In all areas other than social innovations, the collections include mature topics that have been around for a while (breakthroughs waiting to happen) and emerging new areas of fundamental research (high potential – high uncertainty breakthroughs). All social innovations depicted are areas of existing social activity and thus of considerable maturity. Having ranked the RIBs in terms of their potential for significant use in 20 years and the current relative strength of the EU in the global system, the RIBs can be portrayed as presented in the figure below:

Figure 15-2 Table of radical innovation breakthroughs

TABLE OF RADICAL INNOVATIONS BREAKTHROUGHS

A dashboard of 100 emerging developments offering strong impact on global value creation and potential solutions to societal needs





THEMATIC GROUPS

AI	Artificial Intelligence and Robots	BH	Biohybrids	BR	Breaking Resource Boundaries
HM	Human-Machine Interaction & Biomimetics	BM	Biomedicine	EN	Energy
EC	Electronics & Computing	PM	Printing & Materials	SI	Social Innovations

1 Glowing plants, Visualization of gene expression
2 Biohybrid
3 Waste-burning with lithiumflouride/thoriumfloride material, Collaborative efforts in Canada, Protoypes in China
4 Destruction of cancer cells, Macrophages to kill the Tuberculosis pathogen
5 (*No value for European position) - Thermoelectric paint, Harvest of electriciy from waste heat
6 Biological motion, Other sources (wind, heat, radio, chemical)
7 In-memory algorithms, Faster phase-shifting computer memory
8 Techno farming in extreme conditions
9 Personal autonomous drones and rockets, Coordinated flying taxi services
10 Production, Storage, Hydrogen-powered vehicles
11 Bones, tissue, skin, blood vessels and other human parts, 3D-printed models
12 Microprocessors, Neuromorphic chips, Next-generation electronics
13 Optical computing, 5D optical data storage, Photonic chips
14 Exposure to heat, Water contact
15 Clinical trials, DNA vaccines for animals, Better delivery pathways
16 Disease areas, Treatments
17 Atomristors, ENODe, Junction-based artificial synaptic device, epiRAM
18 Targeting new pathways to trigger cell death
19 2D Semiconductors, 2D Magnets, Black phosphorous ink
20 Section of Hyperloop Track finalised in NL, Further tests under way at several sites
21 Regenerative medicine, Soft robots, Biothreat detection devices, Optogenetics
22 New Catalysts, Fertilizers
23 Batteries, Nanosensors, Electrochromic devices, FET, Heat dissipators
24 Intelligence, Fuel autonomy, Microdrones, Defense against drones
25 Multitasking LED displays, Deep UVC, Optical Data Communication
26 Asteroid detection, Examination and mining technologies
27 Plastic-colonizing fungi, Micro-to-macro: plastic-munching worms
28 Exoskeleton, Upper limbs, Internal organs
29 Epigenetic technologies for diagnosis and other technologies
30 Nanotubes with fullerenes, On-chip light sources, Liquid biopsy chip
31 Electrochromic materials, Liquid crystal sandwich, Nanocrystals
32 Nutrient recovery from wastewater, Biological phosphate removal
33 Transistors, Displays, Energy storage, Sensors, Health monitoring, 3D printing
34 Senses of plants, Parasites involved in plant communication
35 Biochip, Biological computer, Biological computer parts, Bio interface
36 Testing and Influencing imagination and creativity
37 Brain electrical activity and biomarker mapping, Improving cognitive functions
38 Cloaking devices, Photovoltaic devices, Medical imaging
39 Submarine (smart-)cable network, Robots & AI emergency response
40 Duelling Networks, Capsule Networks, One Shot Image Recognition
41 Computational Creativity
42 Synchronization with the physical world, Live instructions, Therapy
43 Medical applications, Military applications, Industrial applications
44 Ground- and flying Generator Airborne Energy Systems
45 Epitranscriptomics, Embryo development
46 AST Micro-assay, Lab-on-a-Stick, Microfluidic devices, AST Gadget
47 Nanofiltration, New distillation solutions
48 Pneumatic, Living muscle tissue, Hydrogel, Mechanical
49 Quantum systems, Quasiparticle control
50 Energy: 3D-printed turbine prototype, 3D-printing robots for building
51 Interpreting facial expressions and text, voice, heartbeat, breathing
52 Medical uses, Food/medication tracking, Environmental sensing
53 The Swarm-Organ project, Unmanned Aerial Vehicles
54 Aluminium-ion batteries, Aluminium-air batteries
55 Fused filament fabrication, Stereolitography
56 New catalysts, Cheap material for electrodes, Wearable energy devices
57 Medical technologies, Environmental monitoring, Marketing
58 Civil engineering, Protective clothing, Energy storage, Soft robotics
59 Exploring new storage solutions, New uses for CO_2
60 Portable diagnostic devices, Electrodiagnosis, Screening (medicine)
61 Ultrasonic gesture sensing, Optical cameras and sensors, Gesture decoding equipment
62 Medical imaging, Food quality, Mining, Recycling, Security, Hardware & Software
63 Dedicated chipsets and algorithms, Systems and devices
64 Spin relaxation and spin transport, Combination with Claytronics
65 Mimicking humans, Application demonstrators, Control
66 Attophysics, Ultra-precise time measurement for GPS applications VoIP
67 Acoustic holograms, Touchable/printable holograms
68 Electroencephalography (EEG, ECoG, fNIRS, fMRI)
69 Breaking the Blood-Brain-Barrier, New- and nano-materials, Genetically-engineered devices
70 Cellular therapies, Tissue engineering and artificial tissues or organs
71 Agrobots, Internet of Things in precision farming, In-field devices
72 Trust, Notarization, Smart contracts, Corporate blockchain networks
73 CRISPR as revolution in health, CRISPR in agriculture
74 Drug production, Fuel processing, Renewable energy, Air purification
75 Changing landscapes and climate, Climate Engineering: greenhouse gas removal
76 Gut bacteria and immunotherapy and gene activity, Probiotic bacteria and depression
77 Low-cost carbon dioxide splitting
78 Quantum key distribution from orbit, Faster data rates, Blockchain
79 New-generation sensors, Man-machine synergy, Legislation, Connectivity
80 Neuromorphic chips for object recognition
81 New technologies for tidal and wave energy harvesting
82 Soup with 3D-printed twist, Technology to help people with dysphagia
83 Bioplasics for Skin contact, Wound repair, electronics
84 Unscripted chatbots, Reuse & integration with major platforms, Enterprise & Customer Service Applications
85 Sepsis detection, Lab-on-a-stick, Cheap lab-on-a-chip manufacturing
86 Aquanaut technologies for hotels, Entering a sustainable underwater future
87 Methane Hydrate Gas in China, Energy from methane hydrate gas on a large scale
88 Community and indoor Gardening, Localised Food Systems, Permaculture
89 Unconditional Minimum Basic Income, National Referendum on unconditional basic income
90 Healthbank for Health information, Sharing scientific health data for money
91 Large-scale investigative journalism
92 Crypto-currencies traded world-wide, Giving up cash
93 Live caching as an industry, Scrapbooking
94 Banning cars from cities, New cities without cars
95 Breakdown of established gatekeepers, Ownership disruption
96 Online mediated sharing, Rise of the Commons, Based-peer production
97 Increase in diversity of actors in and forms of education
98 Makerspaces on the rise
99 Tools for tracking common devices, Body 2.0 – monitoring at the workplace
100 Data generation combined with participation via gaming, Physical Education and Health

Source: European Commission, DG Research and Innovation based on Warnke, P et al., 2019
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter15/figure_15-2.xlsx

Comparing the extremes of the different distributions provides the following highlights:

1. The AI and robotics revolution

AI&R form a cluster of innovations that will have a huge impact on the future world economy and society. It is the most populous cluster of RIBs identified and the one with the highest average potential for significant use in 20 years' time.

Emotion recognition

Emotion recognition has been about applying advanced image-processing algorithms to images (or videos) of the human face. Recent developments have extended the field to include other means of gauging emotions (text analysis, tone of voice, heartbeat and breathing patterns, etc.) and even extending them to other species. Applications cover areas such as marketing (detecting minute, subconscious reactions to advertising or products), smart devices that adapt to our mood, and law enforcement (improved lie detectors).

In some areas of the AI&R cluster, such as chatbots, Europe is strong while in other areas, like computing memory, Europe's capacities are relatively weak. Consolidating the application pathways emerging from the surge of innovations in algorithms and hardware in sectors such as mobility, health, education and food seems at least as important as fostering the further emergence of upcoming innovations. It is vital for Europe to pursue trajectories that unlock the potential of these technologies to support better solutions able to meet citizens' needs.

2. Fast-emerging innovations

The results include 45 RIBs currently at a low level of maturity which are expected to develop quickly and find important use in the coming 20 years. Among these, seven RIBs are expected to be particularly fast moving:

- Neuromorphic chip
- Biodegradable sensors
- Hyperspectral imaging
- Warfare drones
- Harvesting methane hydrate
- Thermoelectric paint
- Neuroscience of creativity and imagination
- 4D printing

Neuromorphic chip

Modelled on biological brains, neuromorphic chips are less flexible and powerful than the best general-purpose chips, but highly efficient for specialised tasks. They can boost the development of AI-based systems for specific purposes such as object recognition, voice and gesture recognition, emotion analytics, health analytics or robot motion, and can moderate their power consumption.

Among the 45 potentially fast-moving RIBs, relative weaknesses in Europe were found in the following:

- 4D printing
- Bioluminescence
- Automated indoor farming
- Water splitting
- Computing memory
- Molten salt reactors
- Graphene transistors
- Energy harvesting
- Hyperloop

4D printing

4D printing adds an additional element of time to 3D printing/additive manufacturing. 4D-printed objects can change shape or self-assemble over time if exposed to a stimulus – heat, light, water, magnetic field or another form of energy – which activates the process of change. Among the ground-breaking applications foreseen are drug devices reacting to heat changes in the body, shape-memory materials enabling solar panels to auto-rotate towards the sun, and self-repairing infrastructures.

Amongst the 45 potentially fast-growing RIBs, relative strengths in Europe were found in:

- Harvesting methane hydrate
- Underwater living
- Bioplastics
- 3D printing of food
- Lab-on-a-chip
- Chatbots
- Quantum cryptography
- Marine and tidal-power technologies

Interestingly, in the field of quantum cryptography, the EU leads in terms of patents but China is the leader in publications.

Lab-on-a-chip

A lab-on-a-chip integrates laboratory functions into a single device of small dimensions. It promises better and faster diagnostics, especially in areas with poor healthcare infrastructure, a more active role for patients in monitoring their own health, as well as enabling citizens to engage in environmental monitoring.

3. Highly speculative areas

The following highly speculative topics made it into the 100 RIBs:

- Neuromorphic chip
- Neuroscience of creativity and imagination
- Plant communication
- Spintronics
- Bioelectronics
- Aluminium-based energy
- Airborne wind turbine
- Artificial photosynthesis
- *4D printing*
- *Asteroid mining*
- *Thermoelectric paint*
- *Artificial synapse/brain*
- *Flying car*

Bioelectronics

Bioelectronics is the use of biological materials and architectures inspired by biological systems to design and build information-processing machinery and related devices. Researchers hope to develop bio-inspired materials (e.g. capable of self-assembly or self-repair) and bio-inspired hardware architectures (e.g. massive parallelism) to be used in new sensors, actuators and information-processing systems that are smaller, work faster/better and require less power.

In the first eight RIBs on this list, Europe has noteworthy capacities. In the other five (indicated in italics) its position is either unclear or weak as regards maintaining and further advancing its position as a pioneering actor in newly emerging technologies. The neuromorphic chip also deserves special attention because, in spite of its low maturity, expectations on its widespread use in 2038 are very high.

4. Mature, yet radical

Some of the RIBs identified are quite mature – they have been known for a while and have been subjects of R&D and patenting. At the same time, they have a great deal of unexploited growth potential in the perspective of 2038. Their relative technological maturity places them at the junction between R&I policy and industry policy concerns. Such RIBs are found, for example, in the area of nanotechnology (nano-LEDs, nanowires, carbon nanotubes). Hydrogels and holograms also fall into this category. Their further development is not so much a matter of R&I policy but more a subject for industry policy or other policies concerned with the respective domains. Given their potential, it is worth asking whether appropriate regulatory frameworks are in place and if complementary social innovations are needed for the successful and beneficial exploitation of these RIBs, or whether an industry policy is required to strengthen Europe's position in the areas of carbon nanotubes, nanowires and hydrogels, where currently it is not world-leading.

Hydrogels

These natural or synthetic polymeric networks are capable of holding large volumes of water that can replicate the dynamic signalling involved in biological processes, such as cell/tissue development. In the near future, hydrogels will provide the basis for first-aid kits and innovative drug-development concepts. In the longer term, we can imagine curative soft robots performing surgery at microscopic and sub-microscopic levels, and hydrogels in mobile-phone screens sensing environmental pollutants and informing an app.

5. A view from Europe's Research and Technology Organisations (RTOs)

During a workshop entitled 'Future technology for prosperity – horizon scanning' in Oslo on 2-3 July 2019[3], we asked a number of Europe's RTOs and funding bodies[4] the question: 'What are the next emerging technologies Europe should invest in?'. The workshop was part of a wide public consultation on the draft strategic plan for the next EU Research and Innovation Programme, Horizon Europe.

RTOs play a very important role in the European Innovation system, intermediating between science, technology, industry and government. Based on their special position, we asked the directors of participating RTOs and funding bodies to single out the technology they thought was the most important for future prosperity.

Current policy debate in the EU already focuses a lot on information and communication technologies, including AI, the digital transformation[5] and Industry 4.0[6]. Participants were asked to focus on areas 'other than digital only'.

The result was a collection of emerging technologies considered to have particularly strong potential, in their opinion, to create prosperity, including economic growth and broader benefits. An essential factor was the contribution of the technologies to society and the transition towards sustainability.

The technologies presented can be clustered into five areas, technological frameworks: biological transformation; smart materials; marine technologies; low-energy data transmission; and 'power to X'.

1. **Biological transformation** includes the increasing exploitation of biological knowledge as well as the increasing spread of biomimetic design. Biological transformation brings together the basic disciplines of biotechnology, engineering and information technology. Methods of adaptive data processing (machine-learning algorithms) are just as important as biotechnological production processes. Their combination and intelligent networking, including biological components and principles for their optimisation were considered key to a bio-intelligent economy that enables prosperity and healthy and sustainable (qualitative rather than quantitative) growth. The areas discussed in the workshop included Human-Machine Interaction, smart farming, gene technology and neuro-technologies.

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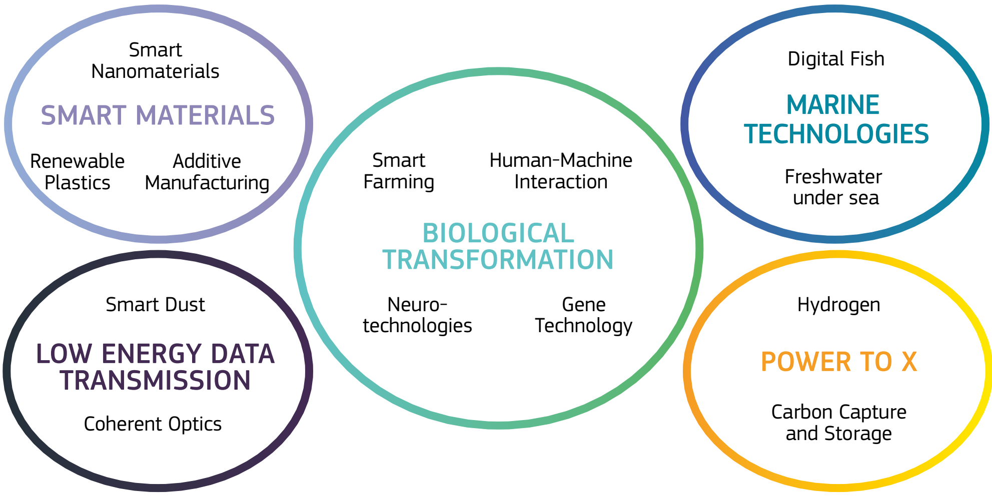
3 The workshop was organised by the Directorate for Prosperity in the European Commission's Directorate-General for Research and Innovation and the Research Council of Norway. https://ec.europa.eu/info/sites/info/files/research_and_innovation/ki-03-19-551-en-n.pdf

4 Organisations represented: Agency for Higher Education, Science and Innovation Funding in Romania; Austrian Institute of Technology; CEA Tech; Cenate AS; CSEM; Enterprise Ireland; European Commission Directorate-General Research & Innovation and the Joint Research Centre; Firda AS; European Association of Research & Technology Organisations; Flanders Make vzw; Fraunhofer Gesellschaft; International Iberian Nanotechnology Laboratory; Innovate UK; J. Stefan Institute; Luxembourg Institute of Science and Technology; Łukasiewicz Research Network; National Research Council of Italy; Norwegian Research Centre; Norwegian Biotechnology Advisory Board; Research Council of Norway; Research Institutes of Sweden; Research Institute on Computer Science and Control at the Hungarian Academy of Sciences; SINTEF; State Secretary to the Minister of Research and Higher Education of Norway; Technology Agency of Czechia; Tecnalia Research & Innovation; TNO; University of Malta; University of Applied Sciences Salzburg; VTT Ltd.

5 https://ec.europa.eu/growth/industry/policy/digital-transformation_en

6 https://www.europarl.europa.eu/RegData/etudes/STUD/2016/570007/IPOL_STU(2016)570007_EN.pdf

Figure 15-3 Overview of technology frameworks and technologies



Science, research and innovation performance of the EU 2020

Source: Müller, J and L Potters (2019) Future technology for prosperity: Horizon scanning by Europe's technology leaders, European Commission

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/partii/chapter15/figure_15-3.xlsx

2. **Smart materials** (e.g. renewable plastics, smart nanomaterials and additive manufacturing) build on technology that provides them with additional functionalities, capacities, and features in bulk and/or at the interface, including adaptability and the capacity to be both sensors and actuators, or to create new structures even on a very small scale. Further development of smart materials can contribute to environmental sustainability (enabling, recycling, repair and self-healing or sensing) and find important uses in healthcare (e.g. thanks to their properties, some smart materials can be used in medical applications that enable better treatment of patients and new forms of therapy) as well as other areas of application.

3. **Low-energy data transmission** will be important as data networks are expected to expand massively in the next few years. The two technologies discussed in the workshop include coherent optics, which allow the transmission of larger volumes of data over longer distances, with lower energy consumption on the existing fibre-optic infrastructure; and smart dust, which is a completely different way of transmitting and receiving data opening up completely different application domains. Smart dust combines systems for ubiquitous Internet of Things (IoT) with ultra-low power consumption or energy autonomy. It encompasses intelligent sensors that are degradable and able to communicate among one another.

4. **Power to X** refers to the electrification of industrial processes and the transition in the way heavy industries, and especially the chemical industry, use power. The two technologies discussed in the workshop are hydrogen and carbon capture and storage. The long-term vision is to turn natural sources of energy, such as sunlight, directly into heat, fuels and further chemical products, which could massively increase the efficiency of the chemical industry through direct power conversion, also closely aligned with carbon capture and storage technologies.

5. **Marine technologies** emphasise the potential of the seas. Digital fish, the monitoring of fish via sensors, enables a digital twin of fish to be created. This enables the lives of fish to be tracked and studied, hunger mitigated, disease stress and further stress factors to reduce diseases, fish mortality to be improved, and the optimisation of feeding processes and fish well-being. The other area discussed concerns the potential to discover and exploit large amounts of fresh water below the ocean surface, often hidden in caves. This water could be used to irrigate regions with low precipitation, for example, for farming or to provide communities with fresh water.

All areas have in common the fact that they relate to societal challenges and have the potential for systemic changes. They involve the need to better understand the underlying systems, a combination of disciplines and collaboration and co-creation of all main actors, with industry taking a leading role in this. The role of policymakers is seen as shaping the conditions for a strong innovation ecosystem whereby all actors in the innovation process are connected and can create value, creating critical mass to tackle strategic economic and societal domains, and to deploy favourable regulation and financial instruments as an impetus for collective innovation. Participants also emphasised active engagement with civil society and citizens from the very start of technology development.

6. In conclusion: waves of change and horizon scanning

Which areas should Europe prioritise? How should strengths and weaknesses be dealt with? Such strategic questions cannot be answered by horizon scanning, although it can inform us about the implications of one or other of the choices. A scan of the horizon at a specific point in time raises our awareness of potentially important areas of R&I and provides for a better-informed R&I strategy. In its simplest form, it enables us to ask ourselves whether or not we need to invest in all these areas and why, and to better understand the opportunity cost of our choices.

While this is an important strategic function, it is also important to note that a complete scan of the horizon is very costly, and the picture of the horizon is a moving one. The Finnish experience with the two successive studies provides some insight into the speed of change. New understandings and experiments change people's views of what is doable and worth doing, while societal values, norms and beliefs also influence the pursuits of scientists and engineers.

The waves of change associated with the functioning of economic expectations have, since the Second World War, combined with notions of technological performance associated with military concerns to drive technological innovation in domains that have massively increased economic productivity. Several authors (Mazzucato and Perez, 2014; Mazzucato, 2018; Perez, 2016) have argued that humanity needs to shift towards different sets of technological aspirations that reflect humanistic ideals and the value of our ecosystem – such as the UN Sustainable Development Goals. The workshop in Oslo related technologies clearly to a 'purpose'. In RIBRI, we see some signs of such waves of change. The most visible innovation drive related to the 'digital revolution' is expected to be followed by a more diverse wave of innovations that address broader concerns of life and the ecosystem. For many (Kastrinos and Vercruysse, 2019; Messerli et al., 2019), and the EU has expressed commitments in this respect, the SDGs will, to a considerable degree, shape the value-creating structures and processes of the future.

However, this is neither a clear case nor a finished battle. Although mining methane hydrate – to use an obvious example of an area where Europe appears to be strong – could solve resource problems, it also poses significant environmental risks. The values of sustainability and environmental performance are not clear-cut. While science, technology, research and innovation can enable and contribute to sustainability pursuits, they cannot alone provide a new green wave. What they can do is to provide answers to those who claim that such a wave is impossible and that sustainability cannot be achieved. They must show that it is doable and provide the tools for achieving it. It is society's duty to decide that it is worth doing.

In this context, it is the duty of horizon scanning to showcase different alternatives and to allow for the continuous assessment of those alternatives as routes towards sustainability. This does not necessarily mean that only the most efficient routes must be followed. Often short-term efficiency is a long-term liability. Priorities and choices must be informed and to achieve that, scans of the horizon need to be systematic, continuous and comprehensive, feeding into decision-making processes that are both engaging and participative, involving broad sets of stakeholders and the concerned public, in a new EU R&I policy that will successfully pave the way to sustainability.

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