From Science to Society: The Open Science and Innovation and Network Approach

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Abstract Public investment in fundamental scientific research generates societal benefits (Mazzucato in Public Aff, 2018 [1]; Barrett et al. in Why basic science matters for economic growth. Public investment in basic research will pay for itself. International Monetary Fund Blog, 2011 [2]; Zuniga and Wunsch-Vincent in Harnessing the benefits of publicly-funded research. WIPO Magazine, 2012 [3]; Adams in Calif Manage Rev 48(1):29–51, 2005 [4]; European Physical Society in Physics and the economy. Report. Centre for Economics and Business Research, 2019 [5]). At first sight it seems counterintuitive that public funding of a curiosity driven activity that does not address immediate societal challenges or urgent needs can produce wealth and be even long-term sustainable. We are rather tempted to argue that on the contrary, only applied research and targeted investments such as for instance addressing climate change, advancing microelectronics, increasing the effectiveness of battery-based energy storage or the developments of space technologies can satisfy this criterion. It is important to engage both, public and private funds to address such challenges, but science is a key ingredient to come up with the truly disruptive solutions. The funds required to address grand challenges call for globally concerted approaches over several decades with effects that will become only visible after several generations. Funding alone will, however, not be sufficient to effectively respond to societal challenges. Looking at the private sector, it turns out that a significant share of high-tech companies are ultimately results of initial public funding for curiosity driven scientific research.

Keywords Research infrastructures · Fundamental science · Basic research · CERN · Socio-economic benefits · Government funding

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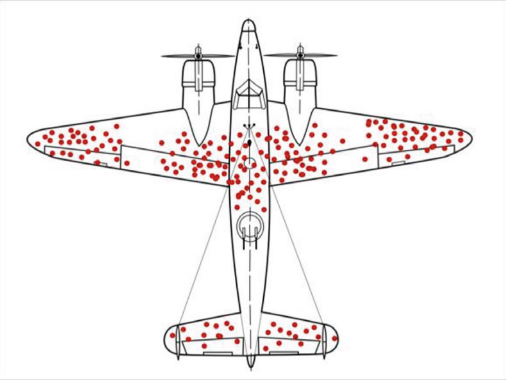
1 Introduction

Public investment in fundamental scientific research generates societal benefits [1–6]. At first sight it seems counterintuitive that public funding of a curiosity driven activity that does not address immediate societal challenges or urgent needs can produce wealth and be even long-term sustainable. We are rather tempted to argue that on the contrary, only applied research and targeted investments such as for instance addressing climate change, advancing microelectronics, increasing the effectiveness of battery-based energy storage or the developments of space technologies can satisfy this criterion. It is important to engage both, public and private funds to address such challenges, but science is a key ingredient to come up with the truly disruptive solutions. The funds required to address grand challenges call for globally concerted approaches over several decades with effects that will become only visible after several generations. Funding alone will, however, not be sufficient to effectively respond to societal challenges. Looking at the private sector, it turns out that a significant share of high-tech companies are ultimately results of initial public funding for curiosity driven scientific research. Among the most visible cases of the numerous companies in the US "Silicon Valley" [4] that have their origins in publicly funded science research is Google [7]. Xerox [8], funded by physicists C. F. Carlson, is another well-known case that throughout its existence and from the beginning on profited from publicly funded research. A recent example for this process would be company BioNTech who produced one of the first effective vaccines against COVID-19 that is funded on fundamental scientific research of the messenger RNA technology [9, 10]. Another prominent case is that of private company Epic Games, generating annually a revenue between 5 and 6 billion dollars [11]. This business would be unthinkable without the publicly funded advancements in computing sciences related to fundamental algorithms and programming languages, computer graphics, multi-user operating systems, parallel processing, distributed computing and a plethora of other developments. A less known example is that of TTech, spin-off of by the Vienna University of Technology in Austria professor Hermann Kopetz, a company whose integrated real-time system [12, 13] is the communication backbone of well-known car brands (Audi, BMW, Volvo and more through the cooperation with Samsung), space rockets (Ariane 6, NASA Artemis mission) and recently in wind turbines (Vestas). Another less known, but highly impacting company is Advanced Accelerator Applications, now a subsidiary of the Novartis Group, funded by former CERN physicist Stefano Buono, exploiting a patent from the organisation [14].

Countless cases show that the underlying science may also differ substantially from the innovation result and is not limited to the primary subject matter [15, 16]. However, gradually gained knowledge through publicly funded scientific research is always at the origin of technology development and eventually also leads to disruptive developments or discoveries. Innovation quantum leaps also happen because of the development and application of novel methodological approaches that are not at all related to the specific challenge (see Box 1 on the development of a new scientific method to overcome biases during the second World War).

In this article we present the Open Science and Innovation and Network approach that revolves around lasting core science missions to generate socio-economic value throughout their entire life cycles. This methodological approach fosters the creation of durable webs between the private, the public and the third sector, also engaging laypeople, not necessarily directly involving them in the scientific research. This leads to an increase of the vertical and horizontal integration of the society that is driven by visionary and positively forward-looking science missions that satisfy human curiosity, an element to which every member of the society at any age can relate to. In the frame of this paradigm, socio-economic benefit generation is not claimed to derive directly from the science for which the mission is conceived. The science may lead to disruptive advancements, but there is no guarantee when and in which ways this can happen. The societal benefits are predominantly incremental, i.e. in addition to the science that works for knowledge gain, mostly generated in the periphery of the science mission, through the activation of intersectoral collaboration projects that aim at making the scientific core mission feasible and long-term sustainable.

Box 1: An Example of Cross Fertilization Between Scientific Research and Innovation with Tangible Effects on Lives of People and Leading to the Emergence of a New Science Domain



During World War II, returning surviving aircraft showed hit patterns that triggered army engineers to re-inforce the damaged parts of the plane (see image above[1]). Mathematician Wald [17] applied fundamental mathematics to show that it is impossible to determine the probability of survival from hits of returning planes only and that the survival of returned planes does not depend on the number and distribution of hits already received. Developments in mathematical methods were used to proof that a hit in one of a few critical locations such as the engine and the cockpit areas is decisive for a plane to be downed and that returning planes do not show hits in those locations. As a matter of fact, the method demonstrated that the vulnerability of a hit on a plane part is the complementary of the probability of a hit on that part ($P[Ci,Bj] = 1 - q[Ci,Bj]$ in the original text). As a result of this purely scientific investigation, the most vulnerable areas identified are the ones where no hits were found on returning planes were re-inforced! The work resulted in significant savings of lives, cost savings, increased military performance. In addition, it led to the foundations and methods of an entirely new science discipline that impacted entire industrial sectors: operation sciences.

2 Motivation

We claim that key technologies on which our society relies and continues to prosper have their roots in either publicly funded science or in the education of innovators that builds on the long-term acquisition of scientific knowledge and the creation of sound scientific principles and methodologies. Several historic examples illustrate this pattern.

One example for such a key technology is semiconductors. Silicon was isolated in 1824 by Swedish chemist J. J. Berzelius who is considered together with R. Boyle, J. Dalton and A. Lavoisier a founder of modern chemistry. Theoretical physicist and Nobel laureate K. F. Braun discovered its rectifying capabilities in 1874 and built the first cathode-ray tube in 1897. Indeed, it was Lavoisier who founded quantitative and experiment-based chemistry from which numerous modern scientific methodologies emerged. To fund his research activity, he conceived the concept of the “Ferme générale” (English: “general farm”), a “tax farming” enterprise, which was an outsourcing of customs, excise and indirect tax operation, collecting duties on behalf of the king and using the fees of the tax collection as source of income for full-time scientific research and to contribute financially to “*better the community*” [18]. He also opened a dedicated laboratory free of charge to other scientists. In

[1] *Image credits* M. Grandjean (vector), McGeddon (picture), C. Moll (concept). Illustration of hypothetical damage pattern on a WW2 bomber. Based on a not-illustrated report by Abraham Wald (1943), a picture concept by C. Moll (2005), new version by McGeddon based on a Lockheed PV-1 Ventura drawing (2016), vector file by Martin Grandjean (2021). CC BY-SA 4.0, 21 March 2021.

addition, he reinforced teaching science and scientific methods in public education, founding also the “Lycée” for secondary education until the age of 18.

Another example of purely curiosity driven scientific research based on the observation of nature is the work of Gregor Mendel [19]. Today considered as “the father of modern genetics” he was a science interested physics teacher and a monk. This environment permitted him to study variations of plants in the monastery’s experimental garden. His work and discoveries were only recognised about forty years later, when his results were reproduced. Only almost one hundred years later, the combination of Mendelian genetics with Darwin’s theory of natural selection permitted to found modern evolutionary biology. 200 years later, the work is an integral part of any high-school curriculum and the cornerstone of all we know about genetics and heredity, and it forms the foundation of modern agronomy and continued advances in personalised medicine that determine our everyday life.

A more recent example is the Internet [20] as we know it today. It was pioneered by the Advanced Research Projects Agency (ARPA), the publicly funded US defense R&D organisation, as of 1966 and the protocols were conceived by Universities of Los Angeles, Utah and SRI, a nonprofit scientific research institute in California that was established by the trustees of Stanford University. Eventually, the World Wide Web [21] was developed at CERN in 1989 to enable information sharing over the Internet in a user-friendly way and was provided to the entire world free of charge.

Public funding of company directed research and development and innovation is at the origin of the business development. Ultimately, the operation of a company is paid by the consumers on one hand through their tax contributions and on the other hand by the consumption of the goods the company produces. However, the wealth generated from this activity is for the benefit of a restricted circle of company stakeholders only. Where the business is organised as a cooperative the wealth spreads to more people, but still not beyond the members of the cooperative. We also saw the advent of non-R&D government subsidies of private technology companies, for instance in the form of limited duration subsidies [22] for purchasing electric vehicles [23, 24] and the creation of renewable energy sources [25]. The intent is not only to accelerate the energy transition by making key technologies artificially more affordable, but also to initiate a consumer driven technology advancement process [26]. Evidence for the positive effects [27] and it is more effective if the subsidies can be linked to conditions of R&D investments [28]. In addition, effective constraint-based incentives, such as for instance including the environmental cost of energy in the price of goods and services and the targeted funding of fundamental technology advancements in the renewable energy sector, exist [29, 30].

We re-iterate therefore our claim that public investment into fundamental, purely curiosity motivated science generates wealth and benefits for everyone over long time periods. But how can we argue in times of multiple threats to nature, economy, peace and free societies that taxpayers’ money should continue to be allocated to non-applied, non-business oriented, apparently non-directed knowledge generation with little probability for short term returns and without guarantees for even long-term benefits for individuals?

The discovery of the semi-metal "Silicium" is evidence that fundamental scientific research driven by human curiosity to understand the basic principles of how nature and the universe work generate impact in the long run, even if this research has not any immediate short-term use in everyday life. It is the driving force of humankind to advance their lives that eventually leverages the knowledge gained for their benefits. As soon as human beings were able to set spare energy in their daily struggle aside, they devoted available free time to apparently non-solution directed activities such as arts and science. Freud [31] explains that "*Life, as we find it, is too hard for us. […] 'We cannot do without auxiliary constructions'. […] There are perhaps three such measures: powerful deflections […], substitutive satisfactions […] and intoxicating substances […]. Voltaire has deflections in mind when he ends Candide with the advice to cultivate one's garden; and scientific activity is a deflection of this kind, too*".

The anecdotic historic observations show that so far, public investments in fundamental science have indeed paid off, but there is no way to be able to predict what, when and in which ways tangible societal benefit is created from the curiosity driven science. "*Prediction is very difficult, especially about the future*", is a quote attributed to Niels Bohr to warn about creating forecasting models based on samples, even when using the out-of-sample approach. There exists no guarantee about the level of success of the Open Science and Innovation process. It is an illusion, however, that other approaches and domains can do better. No financial wealth manager can guarantee a return of the invested funds, no engineer would make promises about the market adoption and value of an emerging technology. The dynamics of societal and market developments depend too much on external and complex (in the sense of "unpredictable emerging behaviour") factors that are not in the realm of control of any single entity to make firm statements about whether an opportunity will eventually materialise and become a tangible societal benefit. Some examples for such unpredictable, beyond fact-based technology developments and adoptions are:

(1) The domination of alternating current (AC) over direct current (DC) electricity generation following the advancements of understanding electricity in physics research [32].
(2) The domination of combustion-based vehicles and the artificial push of Diesel-powered vehicles over electric vehicles.
(3) The success of nuclear energy over energy production from renewable wind and solar sources.
(4) The widespread adoption of electron beam-based cancer treatment rather than light-ions.
(5) The world-wide adoption of VHS over Betamax for video recording [33].

The societal benefit generation process associated with fundamental science seems to be characterised by serendipity and dominated by external constraints that are not "in control". Cost is a determining factor for widespread societal adoption of technology. The Open Science and Innovation and Network approach presented in this article aims at a gradual transition towards a defined and repeatable process through gradual culture change. The method presented in the next chapter is a catalyser to

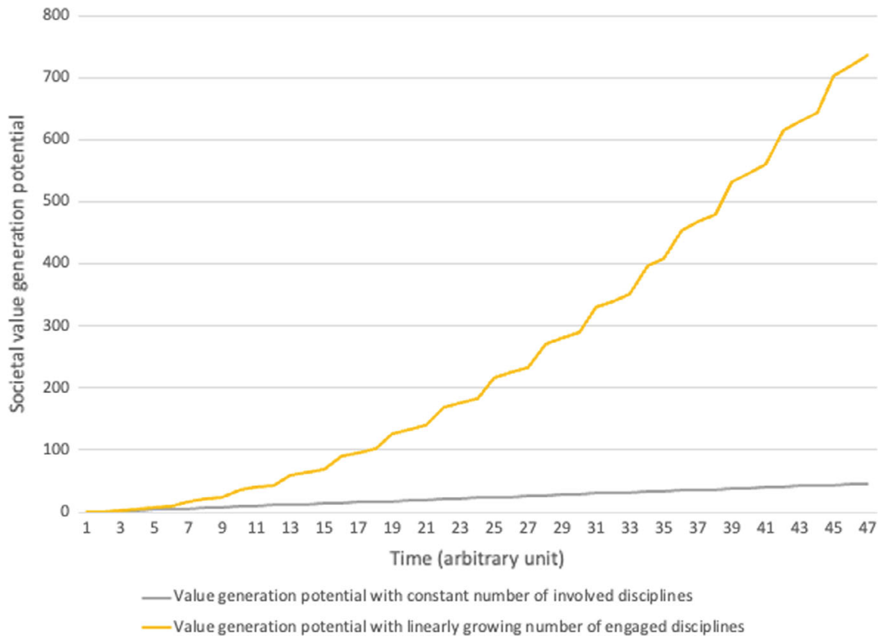


Fig. 1 Figure of the potential to generate societal value over time on arbitrary scale time (x) and value (y) axes. Societal value generation potential is a product of time invested and the number of engaged sectors to contribute with knowledge and to pick up knowledge created. Consequently, the value potential increases exponentially (orange line) with a linearly growing number of knowledge domains that are integrated in a science mission. A constant number of engaged knowledge domains leads only to a linear increase of the societal value generation potentials

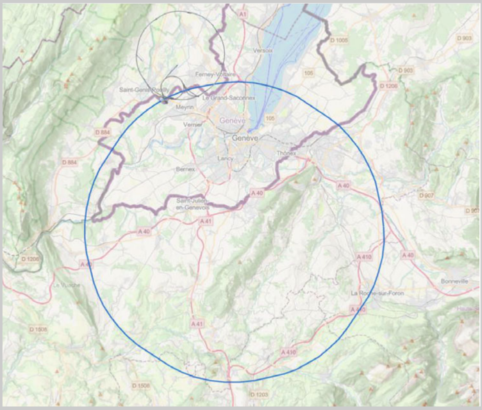
increase the probability for the creation of societal benefit emerging from the results of public investments in fundamental, curiosity driven science (Fig. 1).

3 The Method

We conceived a process that integrates Open Science and Innovation with an Open Network environment to support a collaborative science mission development in the frame of the Future Circular Collider study (see Box 2). The integrated Open Science and Innovation and Network process acts upon three levers to generate societal benefits:

(1) a promoter process represented by a visionary science mission,
(2) concurrent iterative advancement of knowledge in multiple disciplines,
(3) the increase of the probability to generate societal value by multiplying the number of people engaged from diverse and complementary disciplines over sustained periods of time.

Box 2: The Future Circular Collider—A Science Mission for the Twenty-First Century



The science mission of the "Future Circular Collider" [29] foresees an integrated research programme with two particle colliders that would be operated subsequently in a new, circular underground facility with a circumference of a bit more than 90 km length (see image above of the blue reference scenario trace and the grey, existing CERN particle accelerator and particle collider tunnels in the Geneva area. *Source* CERN (2023)). Initially, an intensity frontier machine, would collide electrons and positrons. This facility serves probing the so called "Standard Model of Particle Physics" with unprecedented precision to gain a deep understanding of the Higgs boson and all associated processes and to search for the tiniest deviations from the predictions of the "Standard Model" in search for answers to observed phenomena that cannot be explained with that model so far [27, 28]. The second machine collides protons and heavy ions to be able to directly observe new particles and processes for which the first collider indicates the energy scales. The integrated programme provides a global community of about 15,000–20,000 physicists with a platform to carry out their scientific research until the end of the twenty-first century. The concept for this new research infrastructure is currently being developed in the frame of the international, open and collaborative study that is hosted by CERN, an international research organisation founded in 1954, straddling the Swiss French border region in the Geneva area.

First, **a scientific mission with a sufficient interest must exist to act as a "promoter process"** to attract a relevant community of scientists for a sustained period of time (see Fig. 2). The formation of a critical mass of potential participants in the mission is the pre-condition for the further two levers to work. It can take decades until this critical mass is reached, and the sustainability of the science mission may suffer from a lengthy community capacity building process. Therefore, it makes sense to incubate selected fundamental science cases based on a strategy development process that is driven by science experts. This is a challenging feat, requiring in depth knowledge about scientific disciplines, visionary forward looking thinking, the ability for unbiased scrutiny and the possibility for independent judgement with a right to err. Altogether, it relies on "freedom and independence of science", a state that is not to be taken for granted.

Second, it leverages that fact that new **knowledge is always gained incrementally and this process requires concurrent advancement and integration of multiple disciplines**. An iterative increase of understanding of the world around us with a wide and open horizon is needed to advance the core science mission along its lifecycle and to develop applications for everyone and to continuously solve the problems of everyday life.

Third, through **engaging persons with diverse knowledge and complementary needs** in the Open Science and Innovation and Network process the potential pathways for societal benefit generation are multiplied in space (application domains and locations) and in time (at any time along the lifecycle of the core project). Bi-directional openness of the scientific core mission is a pre-requisite for the process to work. The creation of a closed science mission and science community and even the unidirectional intent to foster technology transfer from science to industry is counteracting the process due to the absence of mutual understanding of needs, capabilities, risks, opportunities and cultures.

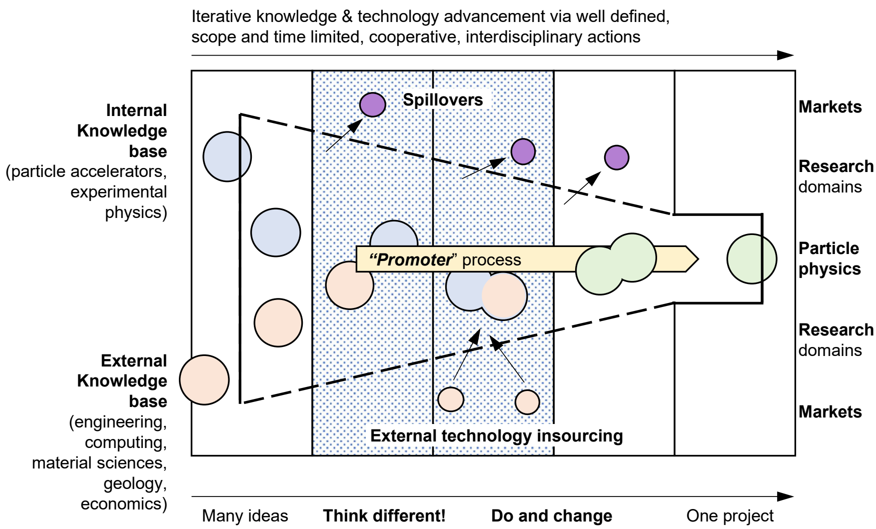


Fig. 2 Open Science and Innovation and Network process that revolves around a core science mission, engaging interdisciplinary actors for scope and time limited actions to iteratively advance knowledge and technologies throughout the entire life cycle of the science mission from the onset

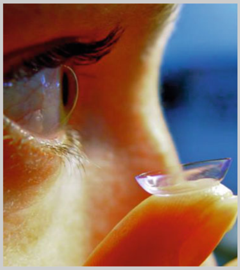
Together, the three levers act on one fundamental principle: the fact that advancing knowledge beyond the current state of science compulsory requires new technologies and processes, either because they do not yet exist or because they are not sufficiently sustainable to advance the knowledge gain. Both causes require either conceiving entirely new approaches or conceiving ways to significantly improve the performance of an existing approach.

This is best achieved by opening up the scientific research process to seek involvement of complementary, frequently not at all domain-related persons to develop solutions to surmount the challenges to answer the scientific questions, i.e. either to be able to carry out the science or to perform the scientific research in a sustainable way. This is the mechanism to make investments in fundamental science pay off for the society and to significantly reduce the time between the investment and the return.

We can observe that such processes historically occurred, but at limited scale and rather randomly. At most, actions were tactically planned, but not systematically integrated in the scientific research activity as a fundamental, strategic concept. One past success story of the approach occurred in astronomy. In the seventeenth century scientists started to team with artisan lens makers to produce better telescopes [34]. This led eventually to the industrialisation of high-quality eyewear and optical instruments as an affordable good for everyone (see Box 3). In that case the opening of the science can on one side be traced to the fact that skilled precision work, which takes a lot of time that astronomers could not afford to invest, was needed. On the other side, the cost of uniquely created precision lenses was prohibitive for the scientists and thus more affordable, automated processes needed to be invented. Jointly this led to a shift from a manual to a mechanised process with integrated quality management. The development of measurement concepts and instruments is another societal benefit that emerged from the continuous need of scientific research and the accompanying technology developments to advance. Eventually, the developments led to a societal wide adoption in a diverse set of application domains beyond astronomy and eventually for every member of the society.

Box 3: Astronomy Opens the Eyes of People

Astronomy with optical instruments really took off in Europe in the late sixteenth century with the works of J. Kepler, C. Huygens, I. Newton and further well-known names. However, these scientists did not actually produce the lenses. They rather specified the required characteristics and designed the entire telescopes [3] through support by the advances in optics by W. Snellius and R. Descartes. Probably the first known relevant attempt to patent telescope technology can be associated to Dutch spectacle-makers H. Lipperhey in 1608 and the first patent was obtained by lens grinder J. Metius the same year. G. Gallilei improved the design in the following year and I. Newton constructed the first functional reflecting telescope in 1668. An immediate transfer of the newly developed principles of optics and the craftsmen skills acquisition to construct scientific instruments to societal applications took place. Primitive hand-operated lathes to form lenses had soon to be abandoned to be able to meet the scientists' stringent requirements, formulated by the mathematicians and physicists that worked with the astronomers or which were astronomers themselves. Since then, this intersectoral and complementary symbioses remained, extending to scientists who had the need to explore the microcosm with microscopes. It resulted in today's optics industry including spectacles, contact lenses, microscopes, telescopes, photo and film cameras, chirurgical vision correction. Science still drives the domain by developing optical instruments beyond the use of visible light.

 Replica of Newton's first telescope, The Science Museum UK, CC BY 4.0	 World's largest optical lens (5.1 ft.) built for the 3.2 gigapixel camera of the Vera C. Rubin Observatory, first light expected in 2025 (https://gallery.lsst.org), CC BY 4.0	 Contact lens, Wikipedia, Etan J, CC BY 3.0 Wikipedia, https://commons.wikimedia.org/wiki/File:Contact_Lens_Ayala.jpg

More recent evidence for the effectiveness of the approach from the second half of the twentieth century onwards revolves around information and computing technologies. Mathematicians, chemists, meteorologists, physicists, physicians and numerous others brought in computer scientists and electrical engineers to provide them with ever more performing hardware and software to make their scientific research more effective, faster and ultimately more sustainable. This process brought us supercomputers, minicomputers, later workstations leading to personal computers, cluster computing, networks, ever more versatile programming languages, software libraries and components, middleware, protocols, advances in human computer interface and ultimately the World Wide Web (see also Box 4). The web [21] was conceived based on the explicit demand of particle and high-energy physicists to be able to rapidly exchange the descriptions, settings and results of their scientific experiments to assure that shortcomings could be eliminated as early as possible, that the experimental equipment and processes can be transparently compared to verify the results and to combine the results of the same scientific research carried out with different equipment at a global level in the frame of a world-wide scientific collaboration. The need to break through a sustainability barrier in fundamental physics research caused eventually a disruption on how humans exchange information, for professional reasons and for leisure. Today, the entertainment business dominates the use of the web. The need of purely publicly funded fundamental scientific research is at the origin of a more than ten trillion-dollar annual business that is made possible by the web [35] and gives many members of our society easy access to uncountable services to cope with the everyday tasks of their daily lives. The amount of money that every taxpayer has invested in the development of this technology is truly marginal and without doubt worth it. Our recent studies in cooperation with economics researchers revealed the continued willingness to financially contribute to the fundamental physics research with particle accelerators that are at the origin of the World Wide Web, since they feel that this type of scientific research is worth it, even without a guarantee that developments eventually lead to societal applications [36, 37].

Box 4: Science Drives Interactive and High-Performance Computing

Digital Equipment Corporation (DEC) founders Olsen and Anderson worked at the MIT Lincoln Laboratory on federally funded defense and national security research projects [38]. Their work resulted in the concept of "interactive computing", i.e. a programmable computer with graphical output capabilities, user input and real-time input/output processing capabilities (image above, PDP-1 with Type 30 CRT display used with a light pen in 1963, Courtesy of the Computer History Museum (Copyright Computer History Museum, All rights reserved)). Their concept of "digital modules" permitted "composing" computers that could be tailored to the performance and capability requirements of their users. The approach originating from and targeted to science applications [39] was rapidly picked up by the community, satisfying a wide range of data and signal processing needs and permitting to balance performance, capabilities and cost. The companies PDP and VAX series became synonym for the "minicomputer", much smaller and less costly than mainframes, but more powerful and versatile than much later appearing microcomputers. DEC also introduced the concept of "clusters", networking multiple computers together to share resources such as storage systems and peripherals, thus permitting to scale up the system and making the system available to a larger number of concurrent users in time-sharing mode as opposed to buying a more powerful machine. C. G. Bell oversaw the development of the VAX computer systems. It made DEC the second largest computer company in the world, making the system comprising various kinds of hardware, operating system, software libraries, programming languages and numerous peripherals the de-facto standard in sciences, engineering and research with subsequent significant and lasting influence on modern processor and computer architectures. The technology enabled generations of scientists to carry out their calculations, analyze data, and perform simulations. This facilitated breakthroughs in various fields, including physics, chemistry, biology, and climate science.

As science projects scaled up over time, complementary science and engineering disciplines were involved in the activities of the core missions. This happened primarily out of the need to make the science missions initially feasible, to carry them out successfully and sustainably. This approach was and is, however, still today not a planned strategy that is included from the onset. Among the "Big Science" endeavours of their times that exhibited such inclusive patterns we can exemplary cite some:

Exploratory expeditions, for instance the "Beagle" [40], most famous for the participation of Charles Darwin that led to the development of the theory of evolution also developed systematic data gathering processes, the development of precision barometers and the establishment of the "Beaufort" wind scale.

Radiotelescopy, for instance the Arecibo infrastructure, ALMA, EVLA, GBT, VLBA, NRAO, SKA and others lead to precision timing systems such as rubidium-based clocks, low-noise amplifiers and filters, distributed software systems for data analysis (@Home technologies), advances in ultra-low temperature cryogenics refrigeration technologies [41, 42].

Planetary exploration [43–46] led to the advancement of global and interplanetary networking technologies, the development of autonomous systems and fault tolerant systems, the development of radiation hard and tolerant electronics, portable chemical analysers, wireless devices, solar power units, quartz clocks, food safety processes, insulated body wear, wearable body function monitors, thin air cushion heavy lifting systems, Teflon-based appliances, novel fabrics, novel wires, fire resistant cloths, water purification systems and a plethora of further societal applications.

Particle and high-energy physics with large particle colliders such as the Tevatron that required low-temperature superconducting high-field magnets at industrial scale directly led to the establishment of MRI as a today standard medical diagnosis tool (see Box 5). Before this project and its successor, the Large Hadron Collider (LHC), the production of superconducting Niobium–Titanium wire required for such devices was insignificant and unaffordable for deployment at large [47].

Box 5: Superconducting Particle Accelerators Induce Wide-Spread and Affordable Advanced Medical Imaging and Material Analysis

Driven by the need to find a disruptive solution to lower the electricity bill of ever larger circular particle accelerators and the need to make US Fermilab's new particle collider called Tevatron actually sustainable, the laboratory made in 1974 an initial purchase of superconducting niobium–titanium (NbTi) wire to build the required superconducting accelerator magnets [48]. The procured amounts represented 95% of the material ever produced. Fermilab teamed up with material scientists and manufacturers in a collaboration to advance this technology that eventually would become a multi-billion per year world market created by magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) analysis [49]. All knowledge gained about the material mining, processing, wire creation and building of high field magnets were freely made available in the form of a "kit" to the companies with whom Fermilab cooperated. The Tevatron collider caused a thousand-fold increase in the world NbTi production, triggering new ways to mine the ore needed for this superconducting wire. The businesses further expanded in the wake of the even larger Large Hadron Collider, built by CERN in the late 1990s and both MRI and NMR based on high-field superconducting magnets became key technologies that are prevalent in numerous societal applications. It is likely that the same effect is induced with the construction of an even more powerful particle collider that would rely on high-temperature superconductors (HTS). These elusive materials permit achieving higher magnetic fields with less cryogenic refrigeration, lowering further the electricity bill and decreasing technical infrastructure requirements. The image shows an example of an innovative open MRI system that is based on superconducting technology developed as cooperative R&D for future particle accelerators at CERN (Picture by courtesy of ASG Superconductors (Copyright ASG Superconductors, All rights reserved)). HTS are today only little used due to their price and limited mining. They are a key technology for the society in numerous domains such as renewable energy production, fusion technology, energy transmission and storage, medical imaging, materials analysis, life sciences, novel microelectronics, computing and communication technologies.

We do not explicitly include in the enumeration the Gemini and Apollo manned space exploration programmes [50, 51], two sequential but inseparable technology endeavours, carried out by a single nation only, because the original driver was not scientific research, but political competition of two nations in a post-war effort to establish a new world order. Nevertheless, this gigantic and so far unmatched activity can probably be seen as the most prominent example of publicly funded Open Science and Innovation and Network with countless tangible and proven evidence for societal impacts at large [52] that found their way into the everyday life of people.

Citing DARPA and NASA programmes, critics may argue that societal benefits are not limited to publicly funded fundamental scientific research. Public investments in all kinds of projects and programmes that are simply too risky for private investors can pay off for the society at large. The objection is partially true if the concept of Open Science and Innovation and Network is built into the programme or project from the onset. DARPA is indeed a lighthouse example for the benefits of public investments in activities that pursue defense-related missions. As a member of a post-war international scientific research organisation that committed to peaceful missions only (CERN constitution [53], Article II), I argue that the same effects can be achieved without the need to pursue defense objectives. Publicly funded research infrastructures pursuing fundamental science missions can be demonstrators and field laboratories to optimise and fine tune this methodological approach and serve as blueprints for the Open Science and Innovation and Network approach.

In the frame of the Future Circular Collider study, we analysed the value-adding potentials of a scientific physics research infrastructure in terms of job-creation effects. The investigation [54] revealed that indeed any public infrastructure investment would lead to comparable value added and job creation, but the long-term sustained effects on domains that define societal evolution beyond purely investment-shock induced economic impacts would be marginal. Hence, the investment effect would lead to limited duration and limited perimeter economic effects, but it would not lead to creation of relevant knowledge and technological progress that are needed for establishing a long-term sustained effect including deep societal effects due to the high job mobility that science projects tend to exhibit. Typical key elements that are absent in conventional publicly-funded infrastructure projects are the creation of "knowledge jobs" that are connected to a lifetime salary premium [55] due to the participation in international and collaborative scientific research programmes, the horizontal and vertical societal integration leading to increased societal coherence and resilience, reinforced cultural integration and language training that fosters societal performance and increased market access for participating companies and the accelerated market penetration of companies due to their experience advantage over competitors.

In addition to publicly funded defense and conventional infrastructure programmes and projects, tourism and cultural productions play important roles for large-scale scientific research. In the frame of socio-economic impact analysis of the Future Circular Collider we saw that this impact pathway [56, 57] acts at least along two axes: it represents a relevant and sustainable economic activity embracing all the forementioned opportunities (e.g. job creation, salary premium of early career professionals, culture exchange, language training, market extension and increase of competitiveness) and it also facilitates the visibility of the scientific research and thus helps the societal acceptance. The latter example helps to understand the origin of the sustained economic effects of public investment in scientific research. The underlying cause for the substantial difference between the effects of public investment in large-scale scientific research infrastructures and conventional infrastructures can be traced to the differences of the activated sectors. While common infrastructure projects are characterised by the goal to deliver a "state-of-the-art" service to a subset of members of the society, commonly limited to the residents of a particular region, for a budget "as low as possible", a research infrastructure targeting fundamental science aims at delivering services "beyond the current-state-of-science" to as many users as possible, ideally at global scale, under the pre-conditions of societal acceptance and controlled, sustainable cost for all its stakeholders.

4 The Open Science and Innovation and Network Platform and Process

Historic evidence, the quantitative socio-economic analysis of CERN's LHC [58] and HL-LHC programmes [59] and a set of socio-economic impact analysis in the frame of the Future Circular Collider study [60] showed us that an Open Science and Innovation and Network process is at the origin of sustainable incremental socio-economic impact generation of fundamental science missions. The mechanics works at all phases of the mission, from the onset of vision definition, over the concept definition, throughout the design and technology R&D phase, during the scientific research carried out at the research infrastructure, as well as at the retirement phase. Having identified the key elements of the pattern permit us to devise ways to move out of a state in which serendipity determines the outcome of the approach.

We understood that a catalyzer for the process is needed. The Open Science and Innovation process needs an Open Network platform on which it can thrive (see Fig. 3). It assures that diverse and complementary stakeholders can be efficiently engaged in a planned matter and in sustainable ways. That integrating approach permits creating societal benefits already from the onset, before the new research infrastructure for the science mission is even designed, before its construction and before the actual scientific research begins.

A feature that comes with the pattern is the direct feedback of stakeholders to the science mission definition that can have an impact on the design of the research infrastructure. The process fosters the establishment of requirements that can help that

(1) scientific excellence,
(2) societal feasibility and,
(3) understanding and management of risks,

are built into the science mission from the onset.

The need to verify that the objectives are met through an iterative process supports that the research infrastructure will exhibit sufficiently high scientific performance to attract a relevant user community for sustained periods of time, that the proposed scenario is acceptable for the society and that it can be implemented and operated with acceptable risks. This anticipating approach foresees the design for societal benefit generation and thus raises the probability that incremental benefits will eventually be generated in addition to the potential impacts of the science gained with the core mission.

The iterative process is best implemented according to the classical "Plan-Do-Check-Act" steps [61]. In addition, the Open Network Environment requires a lean legal framework that permits partners from as many as possible organisations to participate in the mission according to the mutual needs and interests.

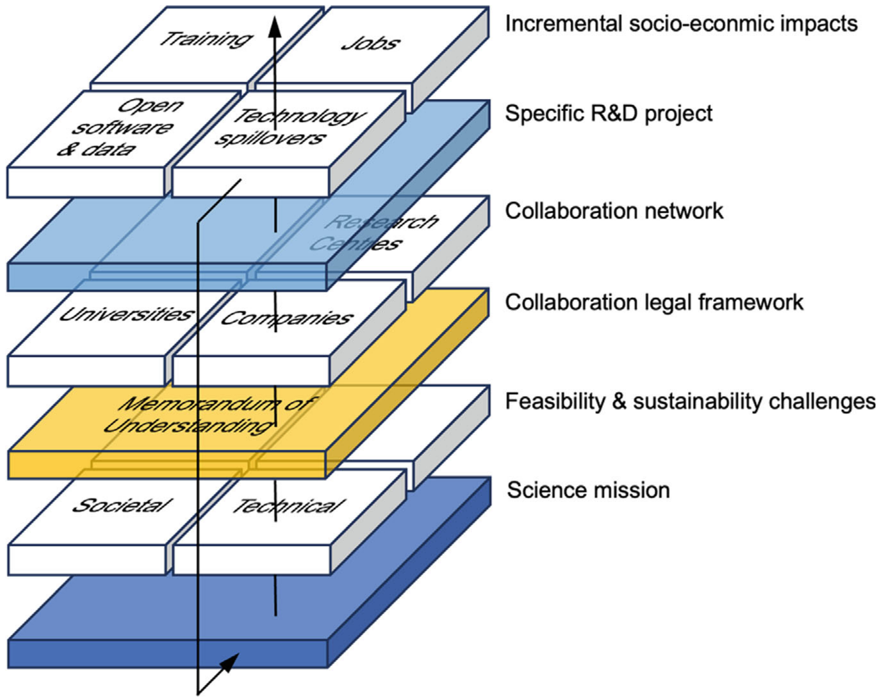


Fig. 3 The integrated Open Science and Innovation and Network architecture

Together these three elements create a "platform", "*a business model that creates value by facilitating exchanges between two or more interdependent groups. To make these exchanges happen, platforms harness and create large, scalable networks of users and resources that can be accessed on demand. Platforms create communities and markets with network effects that allow users to interact and transact*" [62].

The process needs to start by identifying the mission's main constraints by establishing a risk registry (see Table 1 for an example of the structure). This step makes it possible to prioritise the key technical challenges that determinate the feasibility of the science mission that can be covered with science and innovation actions.

Next, the mission's or project's coordinators need to conceive collaborative projects, leveraging a network of partners that remains open for new participants throughout the entire science mission. It federates potential stakeholders from the following domains:

1. Companies from the private sector,
2. Research organisations from the private, public and third sector,
3. Universities and comparable higher education institutions,
4. Schools,
5. Citizens and
6. Funding agencies.

Table 1 Key elements of the risk registry

Domain	Indicates in which segment of the mission or project the risk is identified, e.g. governance, management, technology, environment, society, stakeholders, funding, regulatory
Mode	Describes the specific manner or way by which the materialised risk leads to a failure, e.g. incompatibility with climate protection laws
Cause	Describes the root of the mode, e.g. high electricity consumption of the research infrastructure leads to significant carbon footprint
Consequences	Describes what happens if the risk materialises, e.g. failure to obtain the authorisation to build the research infrastructure
Likelihood	Indicates a probability that the risk materialises. A scale, typically 1–5, needs to be calibrated for each project, e.g. "probable"
Severity	Indicates the level of impact on the project if the risk materialises. A scale, typically 1–5, needs to be calibrated for each project, e.g. "critical"
Risk index	(Likelihood × severity) yields a risk level, typically one of "intolerable", "undesirable", "tolerable", "negligible". This prioritisation permits identifying those risks that need to be addressed and guides the mitigation action development
Required action	Describes based on the risk index, which general types of action needs to be foreseen, e.g. an action is needed such as avoid, reduce, compensate
Proposed mitigation	The specific measure to reduce either the likelihood, the severity or both
Residual likelihood	The likelihood of the risk to materialise after the mitigation measure
Residual severity	The severity of the risk to materialise after the mitigation measure
Residual risk index	Residual likelihood × severity, which needs to be at an acceptable scale

The specific goal of the Open Network Environment is to federate participants according to a geographically distributed and topically complementary approach. Clusters addressing specific challenges related to the mission or the project can also form regionally and locally everywhere in the world. The platform aims at forming a resilient pole of world-wide scientific attraction, generating opportunities for industrial partners to grow and raise their competitiveness and engaging a wide range of people for vertical and horizontal integration of the society to produce added values for everyone by leveraging excellence through a visionary core mission.

As challenges and potentials are gradually identified and tackled, stakeholders are added to the Open Network Environment via the legal framework and are engaged in Open Science and Innovation actions. It is essential to stress and always keep in mind that the core mission must always drive the entire process (the engagement of collaboration partners and the definition of research and innovation actions) and that it remains at all times the primary goal.

Additional societal stakeholders associated to the mission contribute with their domain specific expertise. However, they do not directly contribute to the science and they are never solicited or constrained to financially or otherwise participate to the scientific exploration. They engage to make the mission feasible, sustainable and resilient and they can profit from the knowledge gained and the technologies developed in this process through targeted interaction and cooperation with other, complementary stakeholders that are associated to the mission. They are considered key feasibility enablers of the science mission.

In the frame of the Future Circular Collider that is legally represented by CERN, an international research organisation, we conceived a lean and structured legal framework [63] as part of the platform to carry out the targeted science and innovation projects in a network of collaboration partners. It is based on a multi-lateral "Memorandum of Understanding" that is established with the partner organisations before research and innovation actions take place. The community of partners having signed the document forms the "FCC collaboration". It remains open throughout the entire science mission, permitting organisations to join as needed and based on mutual interest. It makes them partners in the scientific core mission and assures that the collaborative nature, the sharing of knowledge and resources, the openly making available of knowledge gained and the voluntary engagement of resources on a best effort basis are understood and accepted by the participants. The memorandum exists in two forms: one for non-profit organisations such as universities and schools and one for for-profit organisations, typically companies. Third-sector organisations such as applied research centres and cooperatives may choose to engage with one or the other text. This Memorandum is typically signed by the companies' CEOs or CTOs, by the rectors of the universities, the directors of the schools or the chairs of the boards of the funding agencies. For citizen involvement no such formal engagement takes place, since it occurs typically via the other participants.

The activation of the participation of an organisation occurs through the joint development of the specific research and innovation action that is described in a standardised form, the "addendum to the MoU". It captures the project goals and objectives, a structuring into work packages, the definition of milestones and deliverables, the estimated value of the resources that partners intend to engage and the establishment of a commonly agreed schedule. While the Memorandum of Understanding is a multi-lateral agreement that establishes the principle of the collaboration between all partners, the addendum defines a specific project jointly carried out by the science mission carrying research infrastructure and each individual partner in the project on a bi-lateral basis. The involvement of potentially further collaboration members is cited in each addendum established between the science mission and the partner organisation. The research infrastructure and the specific project partner estimate both the values of their involvement in the project. Despite the collaborative nature, the core science mission carrying organisation can decide on a case-by-case basis to contribute to the joint project with a financial engagement that is mutually agreed. This is typically being done, since the mission external collaboration partner contributes to the feasibility and the success of the science mission, engaging not only with its existing knowledge, experience and infrastructures ("background"), but typically also with dedicated additional personnel and resources. It is therefore considered just to re-imburse the partner for such incremental efforts that range typically between 50 and 80% of the total estimated project value.

Specific, need-driven collaborative research actions that are limited in terms of scope, objectives and time permit assessing the effectiveness of the activity and offer a wide range of action potentials at any time, ranging from terminating the project if unsuccessfull over adjusting scope, contents, schedule, engaged resources to continuation and subsequent product development for market entry. In this latter case, the research infrastructure that carries the science mission profits from the fact that the Memorandum of Understanding specifies that all results of the collaborative action ("foreground") will be made available free of charge for the benefit of the science mission. Such, double public funding through taxpayers' contributions to the same development is excluded by design.

To be able to make this Open Research and Innovation and Network Environment an integral part of generating socio-economic value throughout the entire life cycle of the science mission, one fundamental condition applies: A socio-economic value policy must be defined and endorsed by top management, since it forms the foundation to be able to plan, fund, implement, check and act in a process-oriented manner. This in turn means that the science mission needs to foresee an organisation structure and set aside dedicated human resources and budget for the Open Research and Innovation and Network activities.

5 Experience with an Open Science and Innovation and Network at CERN

Our experience in the Future Circular Collider study between 2014 and 2023 shows that the platform based process works because the collaboration actions that revolve around a concrete core mission are "S.M.A.R.T." (specific, measurable, achievable, relevant and time-bound). This setup also permitted obtaining additional funding from the EU's H2020 programme and various national research funding instruments in Europe, the USA and Japan.

We carried out almost one hundred projects (see Fig. 5) over a time frame between 2014 and 2019 in the Future Circular Collider conceptual study phase with more than 70 international collaboration partners from the academic and the company sectors (see Fig. 4).

This permitted us to gather evidence that collaboration partners are more motivated to contribute to a specific mission that defines tangible intermediary objectives linked to individual medium-term project horizons of about one to four years rather than high-level and long-term missions with undefined time frames such as for instance fighting cancer, increasing climate change resilience, regenerating ecosystems and soil.

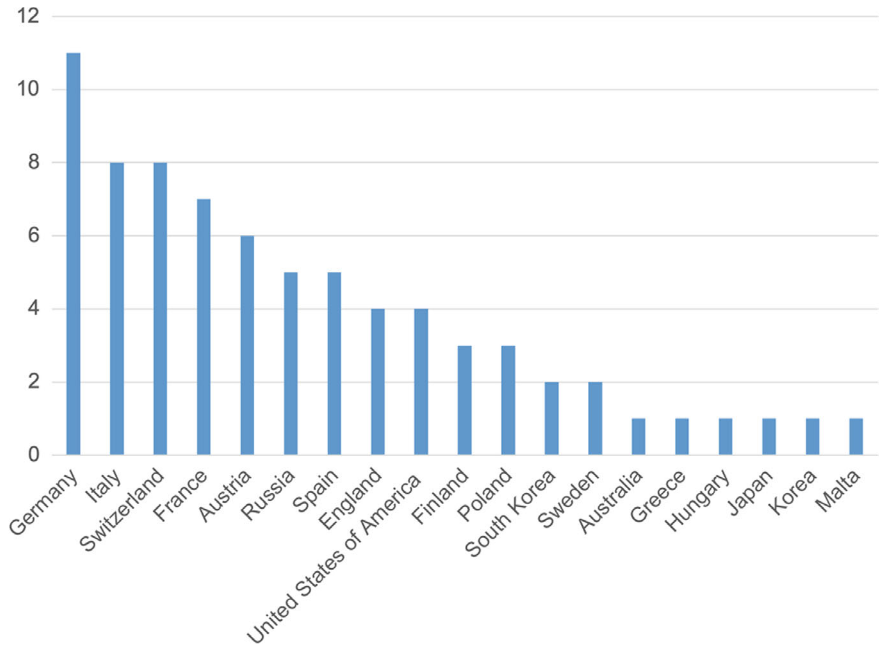


Fig. 4 Number of international collaboration partners by country in the Future Circular Collider conceptual study phase between 2014 and 2019

One specific joint research and innovation action example is the collaborative project to develop agricultural, forestry and renaturation pathways for sterile excavated materials that would be generated during the construction of the Future Circular Collider underground facilities. The developments of soil transformation processes are typically not considered sufficiently rewarding for civil engineering companies who engage in construction contracts in the tens to hundred-million-euro range and that need to be completed under stringent budget and schedule constraints with earnings goals. There is typically no room for new research and development in such contracts. An approximately four-year long investment of about five to ten million euros required to find innovative solutions for re-using excavated materials is considered too high compared to the civil construction contract volumes that companies carry out routinely. Academic institutions do also not easily engage in such a project autonomously, since the required funding, personnel and material resources are considered too high. We also experienced that third party funding sources such as EU H2020 and Horizon Europe research funding programmes and national applied research funds do not typically publish calls in which this type of projects fit without requiring excessive bending that puts the initial project objective in question. Too strong adaptation to existing research funding calls also lowers the efficiency of the

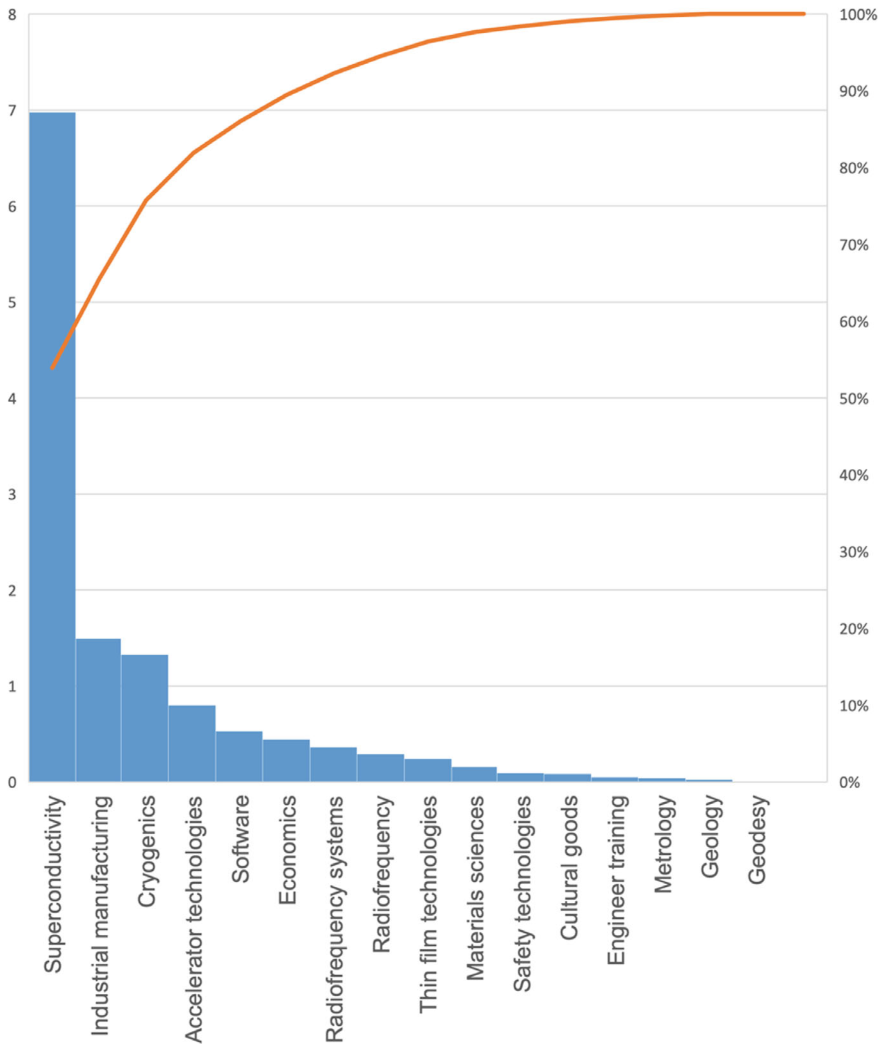


Fig. 5 Intersectoral, collaborative R&D projects carried out during the initial FCC conceptual design phase. The y-axis indicates the cumulative co-funding of the actions in an arbitrary monetary unit. The x-axis indicates the science and engineering domains covered by the R&D projects. Superconductivity was the primary focus in this initial phase to be able to understand the feasibility conditions for the particle collider scenarios

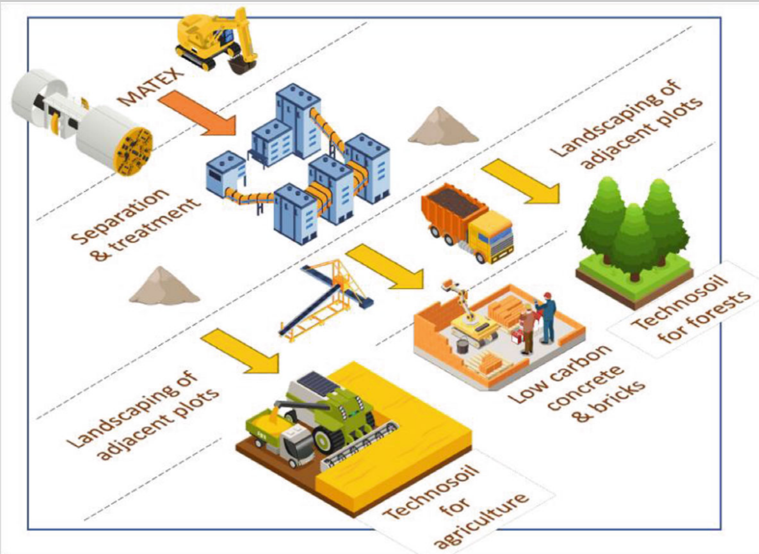
research action due to the need of integrating non-core activities and additional partners that are not related to the objective. This results in a lose-lose situation for the researcher and funding agency, which is a situation to be avoided.

The design of a multi-billion subsurface engineering project required to carry out a science mission with particle colliders, however, justifies such investment, since a successful materials re-use process can lead to savings in the hundreds of million-euro range, will advance soil and agronomy sciences and provide civil construction companies with a portfolio of technologies that can be deployed in small and medium scale projects across Europe. In addition, it also attracts interest of other relevant infrastructure projects such as in the case of the Future Circular Collider project the Lyon-Turin tunnel project across France and Italy and the Metro Lausanne project in Switzerland.

We experienced that setting up such a project as a procurement action for contracted research with an individual company or a university has little chance to work, since the intersectoral composition of a geographically distributed team with a wide-angle view of the challenge and the tight binding to the core mission are missing. Also, pure company R&D can lack a certain openness and out-of-the-box thinking and university only R&D risks remaining at an academic level, disregarding the requirements for industrialisation and economic relevance.

Our Open Science and Innovation and Network led to the creation of a "challenge-based international competition" that invited consortia of companies and scientists to propose credible solutions for the transformation of sterile soil with project relevance, TRL level range, time scale and economic impact estimates (see Box 6).

Box 6: Mining the Future®—An International Challenge-Based Competition



The civil works of the Future Circular Collider (FCC) would generate in the order of 7 million m^3 of excavated materials (in situ). A large quantity of these materials is “molasse”, a heterogeneous, sedimentary rock frequently found in the Geneva basin.[2] Today, no industrial scale re-use technology for this type of materials is known. Therefore, an international, challenge-based competition (miningthefuture.web.cern.ch) has been launched to identify credible means for the innovative re-use of the molasse, to help reduce the amount of excavated material that has to be disposed in landfills, reducing at the same time nuisances and the carbon footprint of the construction works. The winner of the competition has been awarded financial assistance for services required to advance the technology readiness level of the proposed technologies. The consortium led to the development of a novel integrated materials treatment and re-use concept (see image above. *Source* CERN (Copyright CERN, All rights reserved)): It comprises conveyor-belt mounted on-line characterisation of the materials during the tunnelling process using a complementary set of sensor technologies and artificial intelligence machine learning. The surface site features a newly conceived modular separation plant that can be scaled to the civil construction project and be adapted to the different re-use pathways. An innovative concept to incubate the sterile rock to generate fertile soil for agriculture, forestry and renaturation has been identified as the most promising and effective re-use pathway. Because of the competition, CERN has launched dedicated follow up research and innovation actions in the open network environment to demonstrate the three key ingredients: the on-line materials characterisation, the modular separation plant and the fertile-soil production. Eventually, the process aims at bringing the new product, service or process to market to address the challenge of the FCC project with benefits for the entire European construction industry.

The system leads to successful advancements, but of course there is no guarantee for success. For instance, out of four collaborations with institutes to produce a 16 T strong superconducting particle accelerator short model magnet, two yielded results that corresponded to the established goals. Out of three projects to advance superconducting Nb_3Sn wire performance, one led to the established performance goals and one resulted in significant advancement of the technology. This pattern is, however, not surprising since all the research activities are high-risk endeavors at low TRL, developments that companies would not even engage out of free initiative. For the participating universities and research centres pursuing such developments alone is also not attractive due to the necessary efforts and resources required that can only be leveraged in the frame of a multi-partner setup. In particular, the actions that did not meet the required research goals were essential, since they helped to exclude the

[2] For an overview of the molasse basin in the European alps, providing evidence for the relevance of generating socio-economic impact at a large scale with solutions to re-use this type of materials, see https://en.wikipedia.org/wiki/Molasse_basin.

unpromising paths at an early stage, before potentially significant financial and human resource efforts were invested. A collaborative setup serves as an effective cushion for the materialisation of risks. Successes and failures shared help all participants to pursue the work according to the most promising paths.

6 Challenges Related to the Open Network Environment

We experienced that the collaboration approach is initially difficult to grasp and accept for some potential participants, irrespective if they belong to the for-profit or non-profit sector. We observed that the main reasons are the absence of previous exposure to intersectoral, collaborative work in an international setup and the distribution of project, budget and personnel management and across several participating organisations without necessarily a single authority. In fact, the system calls for autonomy and assuming responsibilities at different levels ranging from organisation to individuals. The science mission organisation's unconditional acceptance of the collaboration project outcome, irrespective of success of failure, is frequently seen with suspicion since this diverges from conventional business relations and contracted research projects. We also experienced that companies and university legal services sometimes request adding clauses to the collaboration agreements to resolve situations in which the project diverges from initially established schedules and deliverable contents, despite the fundamental collaboration agreement referring to a "contribution to the mission on a best effort basis". To safeguard against such situation, individual technical collaboration partners suggest usually phrasing milestones and deliverable contents in generic terms and linking them to formal conditions such as the production of a report, rather than contents-related conditions such as the delivery of analysis, feasibility assessments and demonstrated concepts and designs. The contents shall, however, always remain the focus of the interest since it is the aim of the collaborative work. As gradually a culture of curiosity driven and high-level solution-oriented work towards a core mission and a realm of trust among the cooperation partners are established, such concerns tend to move to the background. Once it becomes clear that schedules, milestones and deliverables can be adjusted based on intermediary results and that research and innovation actions can be split into phases that can be engaged based on gate conditions, cooperation is typically advancing well. We experienced this "collaboration culture learning process" across all sectors, including universities, public and private research centres and non-profit research organisations.

Another challenge we faced in the frame of establishing a collaborative network is to explain the big picture of the science mission to the potentially engaging researchers and engineers and to motivate their engagement: Why should, for instance, a university of applied sciences for agronomy team up with a tunnel boring company and material scientists in a science mission that eventually wants to find answers that relate to the inner workings of fundamental particles and the forces that govern our Universe? Should this underlying storyline not simply be set aside and the specific activity could be carried out in a conventional technology R&D project? It could indeed be done, but not integrating the science mission could increase the risk of failure to comply with the core mission's needs and constraints that govern the work and that should be clearly understood by all participants. Typical misunderstandings revolve around the long-time scales of the mission, the financial boundary conditions, the required large-scale technology industrialisation processes, legal and regulatory frameworks that constrain technical choices and the international governance of the science mission. Consequently, a lack of the understanding of the fundamental mission needs affects the likelihood to be able to procure eventually the developed required technologies when needed, the impact of the technologies on the mission that need to be advanced beyond the current state-of-the-art. Failure to right-scale the requirements and constraints typically leads either to under- or overspecifications that lead to inadequate solutions or abandoning a potentially sufficiently suitable approach.

The fact that the science mission drives the process, establishes and enlarges the collaboration network over a sustained period of time, activates network participants when and as required and assures that the process remains focused on the initially stated needs. It permits adapting the participant configurations for individual actions as required.

We saw also that the approach helps engaging laypeople easier, creating naturally a mutual understanding about the science goals and the values generated for the society throughout the mission. Rather than artificially constructing cases for citizen science and public engagement in a mission that builds on fundamental physics that is even difficult for the seasoned scientist to put in words, public engagements in Open Science and Innovation and Network actions that revolve around the core mission, are easier to define in the periphery of the mission. A concrete example is the involvement of pupils and residents of communes that are affected by a Future Circular Collider in the establishment of initial fauna and flora inventories, required to capture the environmental aspects. The activity is required for the research infrastructure to implement the avoid, reduce and compensate approach that is a fundamental building block of developing a societally acceptable project scenario. At the same time, it establishes a relation of trust between the scientists that promote their mission and project and the population in which the research infrastructure is embedded, assuring that also their needs, fears and interests are heard. The research infrastructure promoters also get their chance of explaining in small steps the reasons for their choices, the constraints that guide choices and solution developments and how they integrate the population's requirements. Eventually this approach helps introducing the science missions iteratively, one step at a time, through a mutual culture understanding process.

7 Concluding Thoughts and Remarks

In this article we tackled the question, if public investment in a fundamental science mission is a sustainable investment scenario. We outlined traditionally serendipity-induced effects of generating societal value based on historic examples and derived from these observations the basic validity of the Open Science and Innovation and Network concept. We presented the case of the currently ongoing Future Circular Collider study hosted by CERN that builds on this paradigm from the onset to build socio-economic benefit generation into the science mission. The approach relies on a mission with well-defined goals and a long-term vision so that it is attractive for a research community that can act as a promoter. The mission must offer specific challenges that permit engaging a broad intersectoral community from the private, public and third sectors in the periphery of the science domain. The mission may initially not be feasible with state-of-the-art technologies and processes, but it must be possible to demonstrate a credible roadmap towards feasibility, leveraging the Open Science and Innovation and Network approach. Advancing the state-of-the-art and even the state-of-science to render the mission feasible and long-term sustainable are motivation factors for the collaboration participants. Therefore, making each participant a stakeholder with a sense of ownership and responsibility is a key to the success of the approach. The stakeholders' interests are diverse, need to be identified and have to be considered in the collaboration agreements for each joint research and development on a case-by-case basis. The agreements must make sure that the achievement of the science mission remains at all times the primary goal and driver. We presented the lean collaboration framework that was put in place for the Future Circular Collider study in 2014 for this purpose. It turned out to be essential for the success of the presented approach.

We outlined examples for the generation of societal value that emerged from the Future Circular Collider mission already during its early concept phase, before the research infrastructure required for the science mission is designed in detail, constructed and put in operation. We also showed that it is necessary to accept that a fraction of the collaborative actions in the frame of such a project do not lead to the expected results. Science and engineering are iterative processes that rely on the principle of discarding ineffective and unsuccessful solution pathways. Fear of failure and sunk-costs are fundamental barriers to knowledge and technology advancement in the privately funded and application-oriented research. Only sufficiently visionary and long-lasting science missions with large user communities and with challenges that require solutions beyond the current state-of-the-art or even beyond the current state-of-science can exhibit the required resilience for this approach. Despite the investment risks, the probability for valuable returns for the society are high. The likelihood of generating socio-economic benefits through a science mission is a function of the number of intersectoral collaboration actions carried out and the duration of the science mission. It is therefore important to be able to establish an open network that is based on geographically distributed and topically complementary involvements of partners throughout the entire lifecycle of the mission from the onset. We therefore advocate that the Open Science and Innovation paradigm in combination with an Open Network Environment approach should be incorporated into the organisation and structure of every fundamental science mission.

Research infrastructures with fundamental science core missions can be spearheads of this approach beyond their fields. Indeed, the approach could drive even conventional infrastructure projects. Examples include but are not limited to transport projects such as tunnels, railroads and metro lines, airports, power plants, electricity distribution infrastructures, water supply infrastructures and even cultural projects such as the Olympic Games. Leveraging the Open Science and Innovation and Network approach can increase the short-term return of a variety of investment projects.

The approach is also an ideal vehicle to obtain a "social license" for a large-scale project by creating societal returns early, by helping to understand implementation and operation risks, and by anticipating challenges that can jeopardise the investments and render multi-year engagements worthless. All these elements are known to be vital for project success but do regularly not make it in the project organisation. In fact, Open Science and Innovation and Networking can be an effective ingredient for project risk management.

Still, we believe that it is challenging to achieve a wide adoption of the concept without dedicated policies at governmental and inter-governmental levels, without dedicated co-funding lines, tax rewards and other public incentives to promote the approach. Short term solution-oriented and politically motivated decisions are obstacles for the approach that relies on a long-term vision and curiosity driven science and technology development.

8 Policy Recommendations

Based on the thoughts elaborated in the previous section, we conclude by formulating policy recommendations to promote the Open Science and Innovation and Network methodology to support the effective and lasting generation of socio-economic impacts via fundamental science missions:

- The Open Science and Innovation and Network paradigm should be included in all publicly funded science missions from the onset.
- The paradigm must be endorsed by top management who mandates a dedicated group of persons to put the approach in place and to carry it out.
- An appropriate legal collaboration framework must exist to plan and implement the approach.
- A dedicated budget line in the frame of the mission must be put in place, separated from conventional procurement rules and actions, avoiding contradictions with existing procurement and tendering rules. The science mission must have the possibility to co-fund collaborative actions and the co-funding rate should be determined on a case-by-case basis. Ideally, funding agencies involve in the

science mission as stakeholders with dedicated funding lines that according to this scheme will also receive proper re-assurance of the effectiveness of the public funding.
- The science mission core team must be adequately staffed to plan, carry out, check, evaluate and adjust the science and innovation actions.
- The implementation of the concept must be properly planned by identifying the feasibility and sustainability challenges of the science mission upfront, ranking them according to a risk management scheme that is based on a methodological approach.
- For the identified challenges, a methodological investigation of socio-economic impact pathways must be carried out that embraces all environmental aspects of the project and which considers the benefit potentials at an as wide-as-possible societal scale.
- Socio-economic impact potentials identification, quantitative estimation, success monitoring and evaluation must be built into the science mission and must be accompanied by periodic reporting of quantified impact indicators.
- A governance structure must be put in place that has the authority to plan and launch, re-scope and end Open Science and Innovation and Network actions depending on adequately defined performance criteria. This can typically be achieved by a dedicated monitoring, advisory and steering board that is supported by the monitoring and reporting group.
- Mission internal and external communication and stakeholder dialogue must be put in place and carried out. The entire approach will only work well, if the mission participants are informed about the policy and working principles and if a sufficiently large set of external parties from the private, public and third sectors are aware of the opportunities and working principles. This requires the active support and cooperation of all participating institutions and funding agencies. It also requires significant lead time. Hence the approach is most suited for long-term missions.
- Finally, full transparency about the approach is the key to success. Openly accessible documentation about the framework, the mission challenges and risks and opportunities, the results and performance of the collaborative actions, the socio-economic impact potentials and actually evaluated impacts must be made available.

The conclusions and recommendations outlined in this section are already largely part of a common body of managerial knowledge. Science missions are, however, typically dynamically emerging and characterised by a self-organising, organic development. The most important recommendation is therefore that the public funding governance body assure the establishment of a proper mission organisation and structure that incorporates the Open Science and Innovation and Network paradigm as soon as the mission emerges from a pure vision phase and enters a concept phase and no later than the start of the design phase. The earlier the course is set using a methodological approach, the higher is the likelihood that socio-economic impacts are generated.

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