Science Policy Reports

Johannes Gutleber
Panagiotis Charitos *Editors*

The Economics of Big Science 2.0

Essays by Leading Scientists and Policymakers

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Foreword

As Chair of the European Strategic Forum on Research Infrastructures, it is my pleasure to welcome the works compiled by this book, which constitutes a valuable contribution to the efforts to measure the broader impact of Research Infrastructures. ESFRI has carried out significant work over the years on developing indicators for the scientific, social, and economic impact of RIs; one of its main findings is that the impact assessment process should be tailored for each Research Infrastructure and performed continuously over time. A holistic impact assessment is essential for policymakers to decide on investments. A sound methodology must take into account the diversity of Big Science installations and rely on qualified expertise to collect and analyse data along the entire RI lifecycle.

This book is published as part of the EU-funded project FCCIS, which contributes to the international collaboration carrying out a feasibility study for a future circular collider (FCC) at the CERN site. The concept and technical design of the FCC have included from the earliest stage considerations on environmental sustainability and broader socio-economic impact, which is the way forward for all Big Science installations. Science does not exist in isolation; the potential of Big Science to communicate the value of research and to generate social and economic benefits must not be overlooked and should be integrated from the very initial steps of every large Research Infrastructure project.

The workshops that led to the papers in this book created a space for scientists, managers of Research Infrastructures, funding agencies, and economists to discuss best practices to enhance the impact of Big Science. I hope this collaborative work will continue and pave the way for stronger societies, where the value of science is understood and harnessed for everyone's benefit.

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José Luis Martínez Peña research career includes positions such as Research Professor at Instituto de Ciencia de Materiales (CSIC), Scientific Staff of the ILL (France), Research Assistant and BNL (USA). From 2007 to 2012, he was Associate Director of the ILL in Grenoble (France) and from 2014 to 2017, he was Executive Director of ESS-Bilbao, also member from 2017 of the "Commission nationale d'évaluation (CNE2) of the l'Office parlementaire d'évaluation des choix scientifiques et technologiques (OPECST)", and Delegate representing Spain at ESFRI since 2013 and presently chair of ESFRI.

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About the Editors

Dr. Johannes Gutleber develops strategies and sustainable implementation scenarios for future Research Infrastructure projects at CERN. He coordinates CERN's implementation studies with its host states, France and Switzerland. In the frame of this work, he leads socio-economic studies, an integral part of CERN's future project developments, to identify new tools for measuring and optimizing the different types of societal benefits that stem from investments in large-scale research infrastructures.

Before the launch of the FCC study in 2014, he conceived and managed the implementation of a number of key systems for the MedAustron particle-accelerator-based cancer treatment facility. The project was developed as a cooperation between Austria and CERN. It is considered as an example of knowledge transfer from fundamental scientific research to societal applications. Between 1997 and 2008, he developed the online software systems of the Compact Muon Solenoid (CMS), one of the two large experiments at the Large Hadron Collider (LHC). This was one of the mission-critical subsystems of the experiment that enabled scientists to carry out their scientific research that led to the experimental verification of the Higgs boson. He holds a doctorate degree and a diploma engineering degree from the Technical University Vienna, Austria, in technical sciences and in computer science.

Panos Charitos holds a bachelor in Physics and a master degree in Astrophysics from Imperial College London and a M.Sc. in Media and Communications from the London School of Economics. His studies in media and sociology led him to study for a MA and a Ph.D. in Social Sciences. He joined CERN in 2011 as a member of the ALICE experiment. Since 2013 he has served as co-editor of CERN's Physics Department. In 2015, Panos was appointed Chairperson of the Future Circular Collider communication network and Chief-Editor for Accelerating News and CERN's EP Newsletter. In 2020, he was appointed member of the Editorial Board of the *Journal of Cultural Analysis and Social Change*. Previously, Panos had worked for major media outlets in Greece and the UK. In parallel, his extensive experience in the publishing industry led to the foundation of ROPI Publications, a niche publishing house specializing in the history and philosophy of science.

About the Authors

Leslie Alix After completing an economics and business preparatory class, I joined the Grande Ecole programme at Skema Business School. Concurrently, I pursued a double master's degree in international relations and affairs at Science Po Aix, while working on a work-study scheme as a territorial studies analyst at Bpifrance. Subsequently, I joined CNRS for two years as a socio-economic studies analyst at a local level for the FCC project, and I have continued in this role at CERN for the last year.

Dr. Ennio Capria is the Deputy Head of Business Development at the ESRF. In his research career he worked on the development of electrochemical nanobiosensors, nanocomposites and optoelectronic devices and particularly their characterisation with synchrotron light. At the ESRF, he is coordinating the participation of the ESRF in various collaborative initiative with industry, in particular on energy storage applications, additive manufacturing methods and nanosciences. Since 2020 Ennio is Director of the Platform of Advanced Characterisation of the Technological Research Institute Nanoelec.

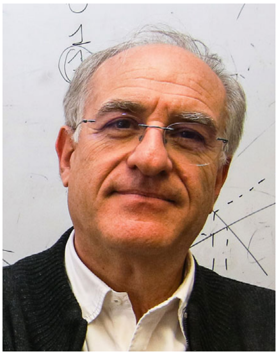
Gelsomina Catalano (senior researcher at CSIL since 2008) has an extensive experience in socio-economic impact assessment for large research infrastructures. She has collaborated with various institutions (e.g. the Italian Space Agency, CERN, ALBA synchrotrons, Elixir, Diamond) to assess different types of impacts. Also, she has contributed to shaping models for cost-benefit analysis and identifying impact pathways of RIs. She is currently leading the development of a CBA framework (in the frame of **PathOS project**) specifically tailored to assess the impacts of open science practices.

Riccardo Crescenzi is a Professor of Economic Geography at the London School of Economics and a former European Research Council (ERC) grant holder. He leads research on foreign direct investment, global value chains, and their innovation impacts worldwide. Currently, he is the Principal Investigator for a UKRI-funded project on global inequalities. Riccardo has advised numerous international organizations, served as Rapporteur for the European Commissioner's High-Level Expert Group on Innovative Cities, and as a Jury Member for the European Innovation Council's European Capital of Innovation.

Dr. Erica Delugas (senior researcher at CSIL since 2022) conducts applied research in industrial, research and innovation policies, and small business economics. She carries out literature and documentary reviews, statistics and econometric analysis.

Erica is currently involved in the Horizon Europe project PathOS, contributing to developing a CBA framework tailored to open science practices and in the H2020 FCCIS project, developing a model for the socioeconomic impact of the CERN Future Circular Collider. She is researching human capital and education activities at CERN.

Erika Susan Dietrichson is a Ph.D. candidate at the Technical University of Denmark's Centre for Technology Entrepreneurship. Her research explores the innovation impact of Big Science Organizations, focusing on conditions, interactions, and knowledge spillover within the ecosystem. Erika's work contributes to understanding how these organizations influence technological advancement and economic growth. She has formal prior experience with the European Spallation Source ERIC, enhancing her insights into science-industry collaborations.



Massimo Florio is Professor of Public Economics at University of Milan. He has been involved in several research and evaluation projects for the European Commission, European Parliament, EIB, OECD, World Bank, CERN, ASI, ESA. His main research interests are in applied welfare economics, cost-benefit analysis, industrial and regional policies, privatization, public enterprise and socio-economic impact of research infrastructures. His books on have been published by The MIT Press, Oxford University Press, Routledge and others. Among his latest publication there is "The Privatisation of Knowledge: A New Policy Agenda for Health, Energy, and Data Governance", edited by Routledge (2023).

Irene del Rosario Crespo Garrido obtained her degree in Economics at the University of Vigo (Spain). While studying for a Master of Business Administration, she worked as a business administration responsible and marketing officer in the automotive industry until 2016. Since 2017, she worked as an economist researcher, studying the socio-economic impact of CERN. Her work has helped her to further develop her profile with a master's in executive business management and with a specific course focused on the Cost-benefit analysis of investment projects at the University of Milano. Currently, she is working as Project Monitoring & Control Officer of the Hi-Lumi project at CERN, waiting to present her PhD at CERN. The topic of the research thesis is the analysis of the "Socio-Economic Impact of Open Data and Software developed for the LHC scientific program".

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Stephan Haid studied Business Administration, focusing on international and strategic management. Since January 2024 he is the Head of Administration and Technical Services at the Max Planck Institute for Structure and Dynamics of Matter in Hamburg. From 2020 to 2023 he was the Director of Administration of the Cherenkov Telescope Array Observatory (CTAO) in Bologna. From 2013 to 2020, he was the Head of Organizational Development at the Deutsches Elektronen-Synchrotron (DESY), where he held various administrative positions since 2008.

María Loureiro García is Professor of Economics at the University of Santiago de Compostela (USC) since 2017. She joined the USC with the Ramón y Cajal Program in 2004 designed to insert international scholars into the Spanish university system.

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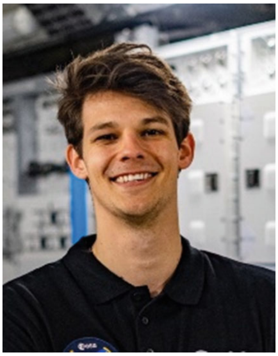
Charlotte Mathieu is the Head of the Industrial Policy and Space Economy Division at the European Space Agency (ESA). She worked for ESA in 2003-04 and again since 2008, when she was seconded at the European Space Policy Institute (ESPI). She then joined ESA's Director General's Policy Office, the Director General's Office for Relations with the European Union, the Directorate of Telecommunications and Integrated Applications and now she works in the Directorate of Commercialisation, Industry and Competitiveness. She holds Master's Degrees in Aerospace Engineering and in Technology Policy, as well as a Degree in Economics.



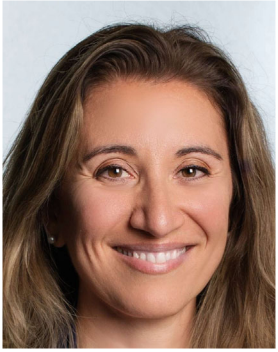
Jakob Peters is a proficient economist with a secondary degree in physics. He has a comprehensive background in economic analysis of large-scale science projects, having worked for the European Space Agency, where he co-authored two papers on measuring the space economy in cooperation with the OECD, European Commission, and US Bureau of Economic Analysis. Peters currently advances his research at the German Research Centre for Fundamental Science (DESY). His unique expertise bridges the gap between economic theory and practical applications in the sectors of space and fundamental physics.

Gabriele Piazza is a Ph.D. candidate in Economic Geography at the London School of Economics and Political Science (LSE). His research focuses on the economic effects of investing in Big Science Projects. Before joining LSE, Gabriele worked as an Economist at the Greater London Authority and the think tank Centre for Cities.

Luca Secci, former CEO of Eumetra International SA, is a Global Account Director with over 30 years of experience in consumer insight and brand strategy. He has held numerous positions of increasing responsibility within major market research networks, covering many industries and many countries worldwide. He specialises in large-scale surveys to understand individuals' social change and consumer behaviour. He has been involved in sustainability since 2008.

Gerhard Streicher is Senior Economist at WIFO, which he joined in 2011. Since 2001 (after a lengthy excursion into experimental hydraulic engineering), his research interests focus on multiregional input-output modelling. Projects that he has worked on in recent years range from impact studies for companies to the potential effects of the bio-based economy as well as the economic effects of carbon pricing, customs duties or economic sanctions.

Dr. Adrian Tiplady is the Deputy Managing Director for Strategy & Partnerships at the South African Radio Astronomy Observatory (SARAO), a National Facility of South Africa's National Research Foundation. For two decades, he has been involved in South Africa's participation in the international SKA project – from working towards realisation of the SKA Observatory as an inter-governmental treaty organisation, to ensuring establishment of a legally protected radio astronomy reserve in South Africa to host the future SKA MID radio telescope, and SARAO's MeerKAT telescope. He has a diverse range of technical and non-technical expertise, and is currently interested in the realisation of a 'social license to operate' as a critical success factor for next-generation research infrastructures.



Silvia Vignetti (senior researcher at CSIL) is an economist with more than 20 years of experience evaluating EU policies, specialising in research and innovation programs. She collaborates with research institutions such as CERN, CNAO, ALBA, ELIXIR, E-RIHS and others, assessing socio-economic impacts. Currently engaged in the Horizon Europe PathOS project, Silvia previously contributed to H2020 RI-PATHS project aimed at developing a comprehensive framework describing the socio-economic impact of research infrastructures. She is an expert in social cost-benefit analysis.

Stephanie Willekens works as an economist in the Industrial Policy and Space Economy division at the European Space Agency (ESA). She worked at ESA in 2014-16 as the first Young Graduate Trainee in Space Economy, and then in private consultancies in London and Paris. She joined ESA again in 2020 to develop the Space Economy team, delivering analysis and research on the economic value of the space sector and its impacts on Europe's economy and society. She has led the development of strategic partnerships notably between ESA, the OECD, Eurostat, and the European Commission's Joint Research Centre (JRC) on the topic of Space Economy. She has an academic background in business engineering and economics.

Junhanlu Zhang, an Impact Analyst at the ESRF, Grenoble, holds a bachelor's degree in Anthropology from Durham University and a master's degree in Intercultural Management from the University of Burgundy. With prior roles at the University of Hong Kong and the Pasteur Institute, developing research projects on social entrepreneurship and gender equality, she now specialises in impact assessment within Research Infrastructures (RIs) and Higher Education Institutions (HEIs).

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

Johannes Gutleber

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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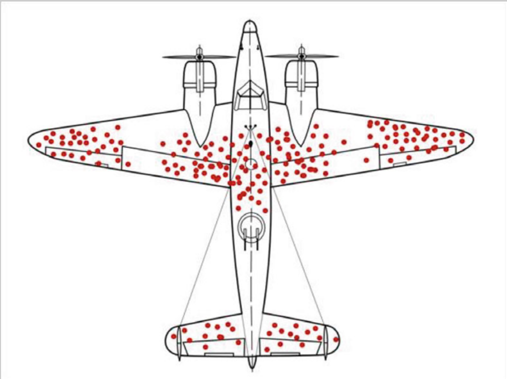
1 Introduction

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

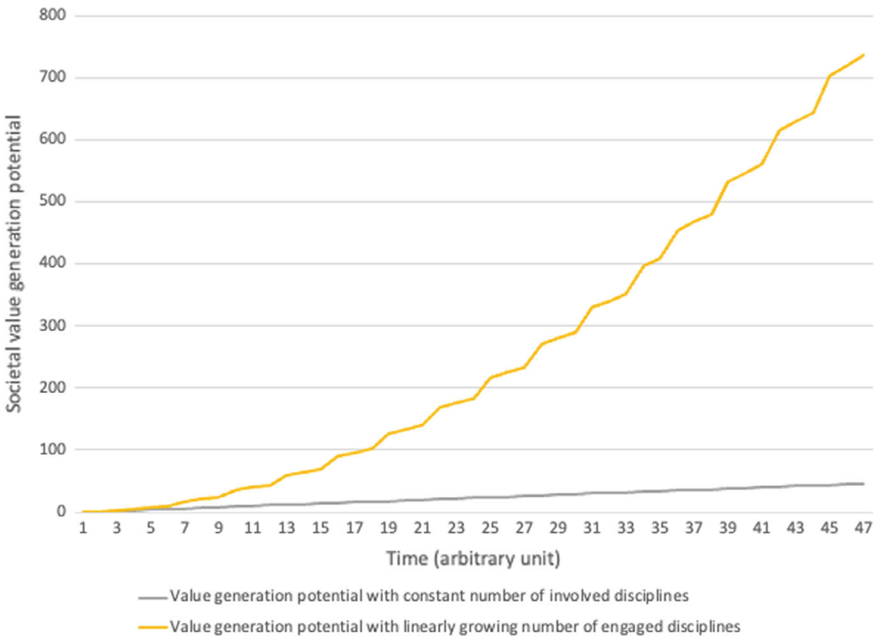


Fig. 1 Figure of the potential to generate societal value over time on arbitrary scale time (x) and value (y) axes. Societal value generation potential is a product of time invested and the number of engaged sectors to contribute with knowledge and to pick up knowledge created. Consequently, the value 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

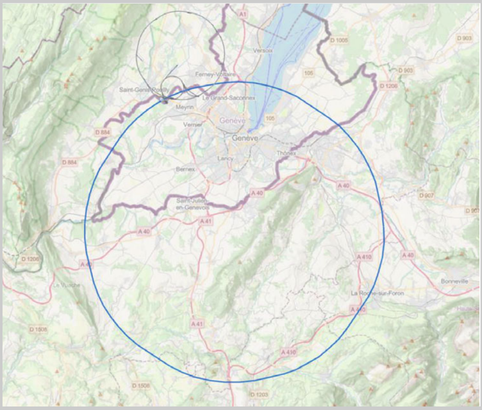
increase the probability for the creation of societal benefit emerging from the results of public investments in fundamental, curiosity driven science (Fig. 1).

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.

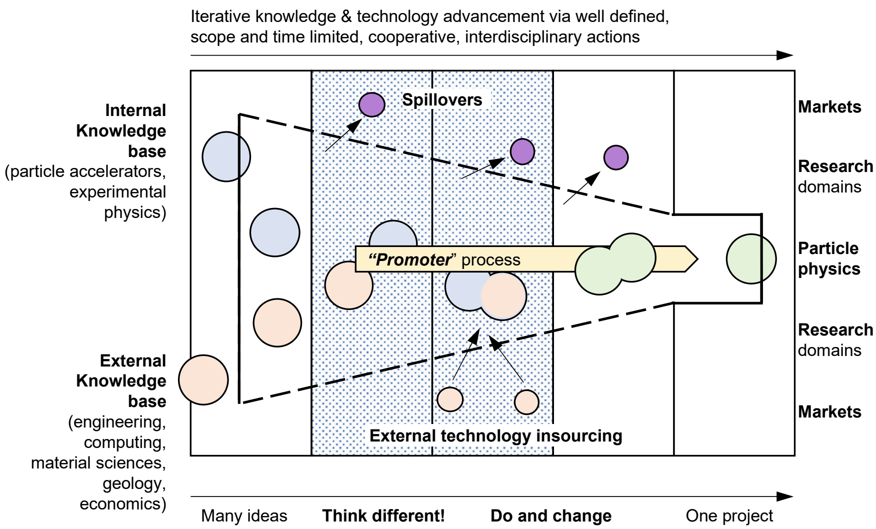


Fig. 2 Open Science and Innovation and Network process that revolves around a core science mission, engaging interdisciplinary actors for scope and time limited actions to iteratively advance knowledge and technologies throughout the entire life cycle of the science mission from the onset

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.

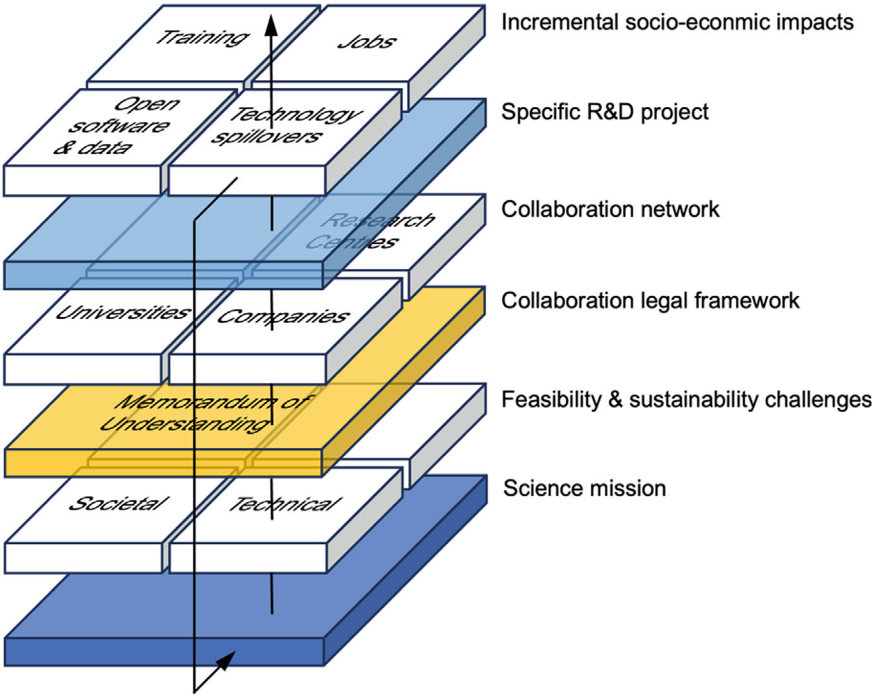


Fig. 3 The integrated Open Science and Innovation and Network architecture

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.

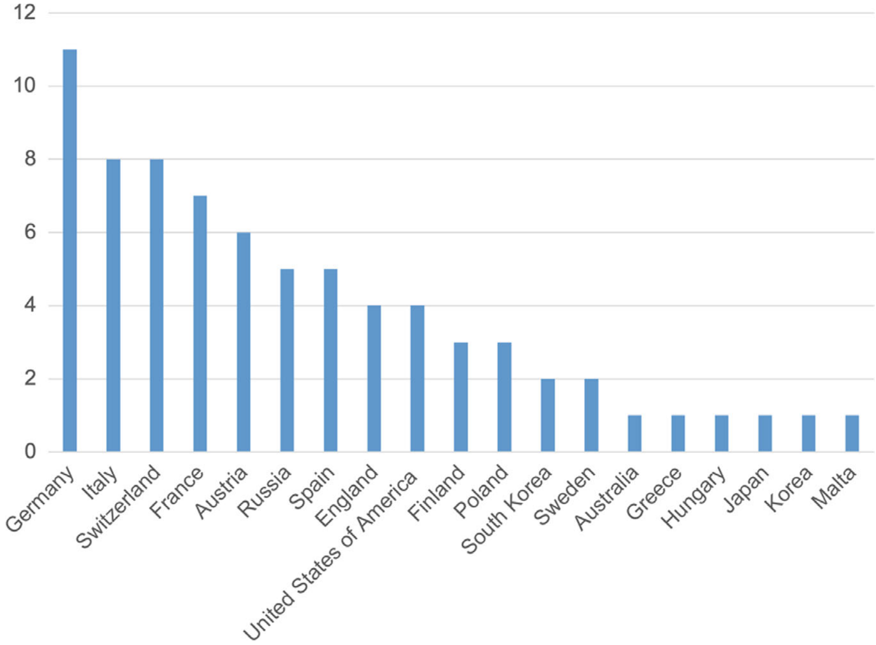


Fig. 4 Number of international collaboration partners by country in the Future Circular Collider conceptual study phase between 2014 and 2019

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

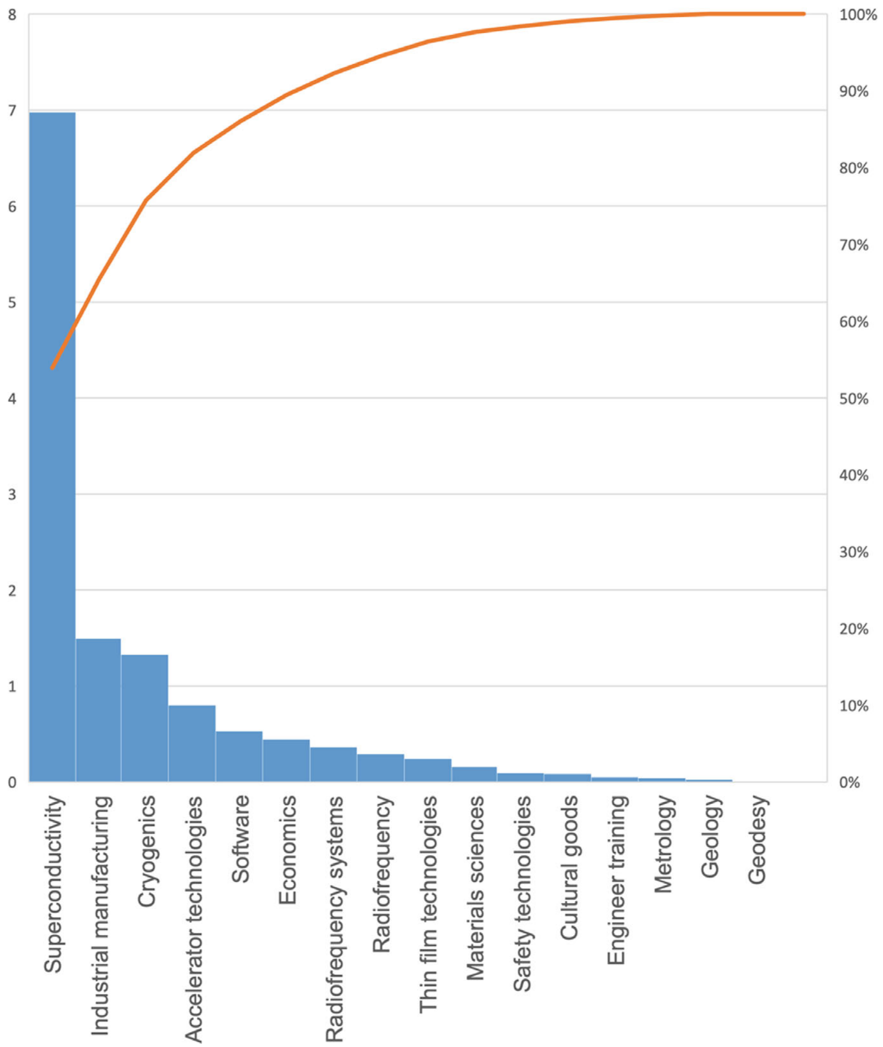


Fig. 5 Intersectoral, collaborative R&D projects carried out during the initial FCC conceptual design phase. The y-axis indicates the cumulative co-funding of the actions in an arbitrary monetary unit. The x-axis indicates the science and engineering domains covered by the R&D projects. Superconductivity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

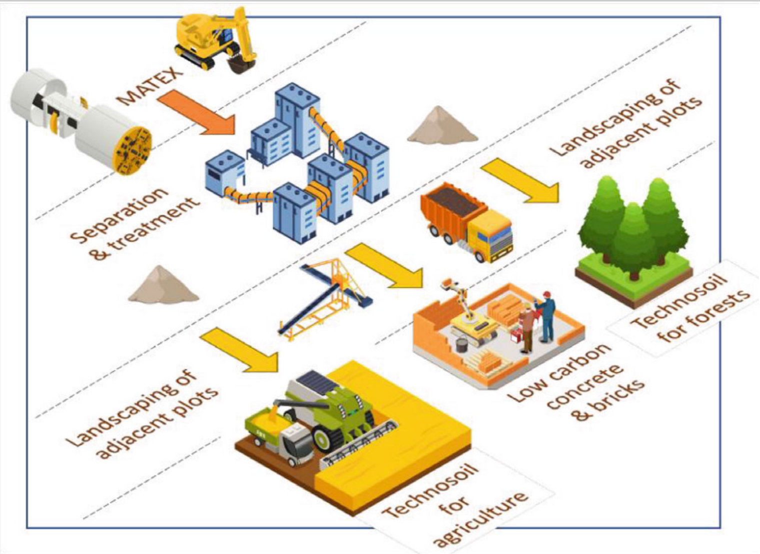
research action due to the need of integrating non-core activities and additional partners that are not related to the objective. This results in a lose-lose situation for the researcher and funding agency, which is a situation to be avoided.

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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Socio-economic Impact Assessment of ESA Programmes

Stephanie Willekens, Charlotte Mathieu, and Jakob Peters

Abstract The European Space Agency (ESA) is an intergovernmental organisation with over 50 years of experience in the space sector. The agency is Europe's gateway to space. Its mission is to shape the development of Europe's space capabilities and ensure that investment in space continuously supports the competitiveness of the European space industry and delivers benefits to the citizens of Europe and the world. For this purpose, ESA has evaluated the socio-economic impact of its activities since the nineties, drawing on experience from its Member States and international bodies like the Organisation for Economic Co-operation and Development (OECD). Since 2012, ESA has been consolidating its methodological approach, promoting best practices from the European Commission and the OECD. This contribution provides an overview of ESA's socio-economic impact assessment, its methodology and several examples of indicators measuring socio-economic impact of its programmes.

Keywords Space programmes · Impact assessment · Innovation · Knowledge · Economic growth · Societal impact

1 The European Space Agency

The European Space Agency (ESA) is an intergovernmental organisation with over 50 years of experience in the space sector. Within Europe, ESA has the mandate *to provide for and promote, for exclusively peaceful purposes, cooperation among European states in space research and technology and their space applications*. As

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presented in Fig. 1, among ESA's 22 Member States, 19 are EU Member States, with the addition of the United Kingdom, Norway, and Switzerland. Furthermore, ESA has four associate members, and four additional Cooperation agreements with EU Member States. Lastly, Canada has a special Cooperation agreement with ESA to participate in its programmes. ESA's staff members are working mainly on its 8 different sites in Europe. ESA's programmes are financed by an annual budget of around € 7 billion (2023).

At the ESA Council at Ministerial level held in Paris in November 2022, the Member States increased their financial contributions to ESA by 17% compared to the previous year. Ministerial meeting in 2019, subscribing to both the continuation of existing activities as well as to new programmes.

About a fifth of ESA's budget contributes to the Scientific programme, thus representing the largest set of activities in the Agency, followed by Launchers (Space Transportation), Human Spaceflight and Exploration and Earth Observation (see Fig. 2). ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity. Space science is a mandatory programme,

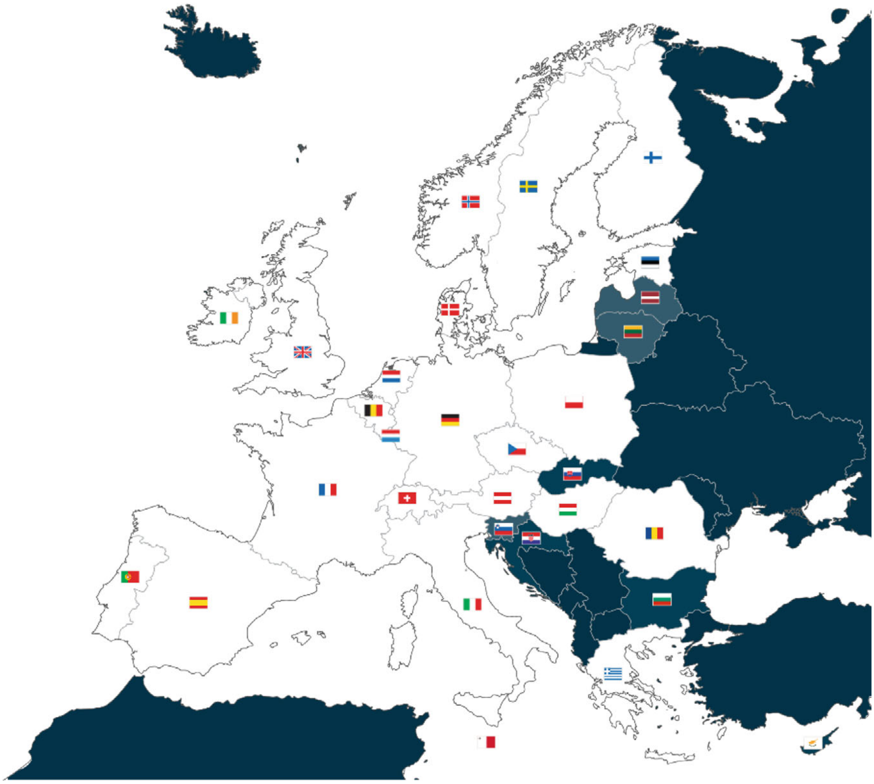

Fig. 1 Mapping of the 22 ESA Member States (in white), associate members and states having Cooperation agreements (in grey). *Credits* © ESA

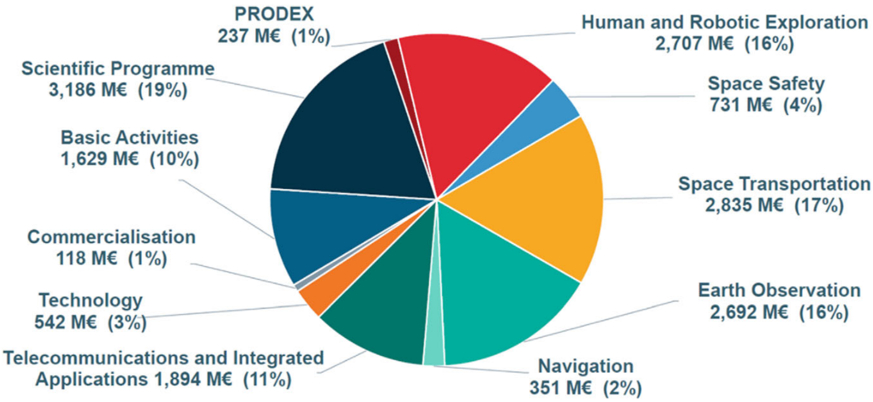

Fig. 2 ESA by domain—total Ministerial Council 22 subscriptions 16.9 B €. *Credits* © ESA

meaning that all Member States contribute to it according to the level of national GDP. All other programmes are optional, funded "a la carte" by Participating States.

About 85% of ESA's budget is spent on contracts with European industry and ensures that Member States get a fair return on their investment. With this, ESA promotes and improves competitiveness of European industry and supports its development, which today, for the manufacturing part, sustains around 57,000 jobs.[1] Europe has been particularly successful on the commercial markets, with a market share of telecom and launch services higher than the fraction of Europe's public spending worldwide. European scientific communities are delivering world-class results and attract international cooperation. European space research and innovation centres are recognised worldwide. European space operators (Arianespace, Eumetsat, Eutelsat, SES Global, etc.) are among the most successful ones in the world.

ESA's governing body is the Council, in which each Member State is represented and has one respective vote on policy decisions. On a three-year basis, the Council meets at the Ministerial level ("Ministerial Council") to agree on key decisions for the continuation of ESA programmes and new proposals, as well as on their respective funding. After the successful Ministerial Council in 2022, the Council will meet again in 2025. For this, ESA is currently preparing proposals for European space activities beyond 2025, which will be supported by assessments of the socio-economic impact of its programmes.

[1] ASD-Eurospace, Facts and Figures annual release, the European space industry in 2022, 27th edition, 2023.

2 Measuring the Impacts of ESA Programmes on Europe's Economy and Society

The benefits of space activities and positive effects of public investment in developing ever more innovative space programmes are becoming increasingly significant in a world characterised by multiple crisis. In a context of economic constraints and social issues, the continuous investment in innovation, science and technological breakthrough is essential to ensure a sustainable recovery and prevent the loss of research and development (R&D) capabilities and critical skills essential to Europe's sovereignty.

At the same time, R&D activities have the potential of growing into new or improved operational services, providing benefits to society and contributing to the creation of both state-of-the-art European technical capabilities and economic growth.

The European Space Agency is Europe's gateway to space. Its mission is to shape the development of Europe's space capabilities and ensure that investment in space continuously supports the competitiveness of the European industry and delivers benefits to the citizens of Europe and the world.

For this purpose, ESA has measured the socio-economic impact of its activities since the nineties, drawing on experience from Member States and international bodies such as the OECD.[2] The Agency is dedicated to continuously improve the robustness and harmonisation of its applied methodologies to offer consistent measures of the impacts of ESA programmes. Purpose is not only to demonstrate the benefits of space activities on the economy and society but to understand what the impacts from space programmes are, how they materialise or are expected to materialise, over the entire value chain.

Through socio-economic impact studies, the European Space Agency has developed indicators to measure the value of its programmes, assessing the benefits of its Member States' investments to the European economy and society. These indicators reflect the technological, scientific, economic, strategic and societal benefits of ESA programmes. In preparation of its last Council at Ministerial level in 2022, ESA conducted 15 studies covering most of ESA's fields of activities. The methodologies of the different studies are harmonised to ensure coherence. The studies are tailored to the unique needs of specific programmes, cover a wide range of indicators, and were conducted not only ex post but also ex ante. Among others, these include large scale socio-economic impact assessments of full ESA programmes, cost benefit analysis of future technologies (such as space-based solar power), benefit case studies (such as impacts from specific technology transfers or core technology developments), market assessments, and strategic impact evaluation (such as European Human Space Flight Autonomy). All studies are freely accessible on ESA space economy website.[3]

[2] Organisation for Economic Co-operation and Development.

[3] https://space-economy.esa.int/.

3 Methodology of Socio-economic Impact Assessment of ESA Programmes

Since 2012 ESA has consolidated its own methodological approach, aligned with international standards. It utilises best practices from the European Commission, OECD and continuous exchange with an ever-growing international Space Economy community. The methodology of all assessments conducted by ESA on its programmes is harmonised to the extent possible but remains tailored to the mandate and strategic objectives of the programmes and respective stakeholders. The specificities of the programmes imply differences in the scope and parameters of the impact assessments, be it the timeframe for the analysis, the availability of underlying data and data sources or an emphasis on certain types of impacts. I.e., indicators for successful Science or Exploration programmes are fundamentally different than the commercial applications from the Earth Observation or Navigation programmes. For that reason, the results of the various assessments are independent for each study and a direct comparison between the results is only possible to a limited extent.

For all studies, a streamlined approach has been implemented. In an initial step, a tailored selection and definition of impact indicators is determined to each unique study framework. Secondly, the most fitting methodological approach is selected, followed by the data collection and a data gap analysis.

The current set of ESA socio-economic studies is based on three types of analyses:

- Socio-economic Impact Assessments
  – Large scope, wide set of impacts, methodology includes economic modelling (not mandatory) and extensive stakeholder consultation.
- Benefit Case Studies
  – Smaller scope, focus on selected types of benefits, methodology uses desk research and limited stakeholder consultation.
- Market Assessments
  – Scope exclusively focused on the economic dimension, and in particular the market potential for the European space industry, methodology uses market forecasts and expert validation.

All socio-economic impact analyses from ESA are based on evaluating the design, development, and implementation of state-of-art European space industrial capabilities that originate from Member States investment into ESA. Common qualitative and quantitative indicators include economic impacts (market assessment, economic modelling, etc.), strategic impacts (independent access to space, supply chain dependencies, etc.), technological impacts (R&D developments, technology transfers, etc.), as well as social and environmental impacts. See below a collection of selected examples of evaluated indicators for the Ministerial Council 2022:

Creating Knowledge

As of September 2021, Europe's participation to the International Space Station (ISS), and all other ESA low gravity platforms, had contributed to more than 6400 publications. Almost 2000 European researchers were involved in conducting ISS experiments.

European Non-dependence

ESA's Science Core Technology Programme, through the development of AQUILA,[4] eliminated European dependence on export restricted critical technology and enables a new addressable market for European space industry (€ 250 million by 2025).

Societal Benefits

ESA's Aeolus mission data helps filling significant existing gaps in the global observation system.[5] Total benefits of the data and information to European stakeholders and society are estimated up to € 3.5 billion over its lifetime.

Economic Growth

ESA's Space transportation activities contribute 3–4 times Member States' investment through ESA to Europe's GDP while ensuring European non-dependence in space through the development of key technologies.

Zero Carbon Emission

ESA's Solaris programme prepares a possible decision in 2025 for a full space-based solar power (SBSP) development programme. By providing a future source of clean energy, benefits could reach up to € 183 billion, including avoided social cost of CO_2 emissions.

Planetary Protection

ESA's Space Safety activities provide services protecting critical infrastructure essential for Europe's safety and security. A near-Earth object colliding with Earth could cause damage estimated from € 3.8 billion for a 50 m NEO to € 3.2 trillion for a 1 km NEO.

Further highlights of ESA's socio-economic impact assessment of its programmes can be found in the 2022 public Space Economy Brochure and Space Economy Factsheet.[6,7]

[4] High-accuracy 3-axis accelerometer, pre-selected to fly on ESA's PLATO and ARIEL missions.

[5] E.g. poles, oceans, and upper troposphere, which lacked wind profile measurements.

[6] CM22_ESA_benefit_Brochure.pdf.

[7] CM22_ESA_benefits_fact_sheet.pdf.

4 Conclusion

The above chapter provides an overview of ESA's socio-economic impact assessment and methodology of its programmes. The next cycle of studies for the Ministerial Council is currently prepared and will be released in 2024 and 2025. All studies will be available on ESA's Space Economy website.[8] ESA's programmes have demonstrated significant and diverse benefits, which will continuously be evaluated through socio-economic impact assessment. For this, the Agency will continue cooperating with other large public science institutions to exchange on methodology, lessons learned, and best practices.

[8] See Footnote 3.

Observation, Analysis and Evaluation of the Industrial Contribution to the Peer-Reviewed Public Access of the ESRF: A Pilot Study

Junhanlu Zhang and Ennio Capria

Abstract Although achieving excellent science remains the primary goal for Research Infrastructures (RIs), RI stakeholders share an increasing interest in understanding the broader contribution of RIs to tackle societal challenges. In such a context, an attempt has been made to identify the direct synergies between the ESRF (European Synchrotron Radiation Facility) and industry, as industrial contribution to publicly funded initiatives provides a key route to understanding the socio-economic impact. While all activities at the ESRF result in effects on the innovation process, direct synergies with industry act as one of the only attributive mode of innovation leading a tangible way to sustain innovation. Therefore, this contribution zooms in on the ESRF's peer-reviewed public access and how industry is directly and indirectly involved in generating not only scientific but also potentially social and economic impact of the facility.

Keywords Industrial engagement · Socio-economic impact · Research infrastructure · Synchrotron facility · Innovation

1 Introduction

As emphasized by the OECD (2019), the impact of RI is not limited to fostering knowledge for the scientific community but also affecting their environment socially and economically. With scientific excellence being the core mission of RIs, RI stakeholders, including researchers, policy-makers and the public, share an increasing interest in understanding the broader contribution of RIs to tackle societal challenges. In this regard, RIs act as focal points for continuous interaction between scientific, technological and socio-economic development [25]. Understanding the link between infrastructure investment and development outcomes has therefore become

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one of the most popular for debate in recent decades [4, 28, 27]. The demand to assess socio-economic impact of RIs has triggered the need to develop a standard methodology for impact assessment in the European context [13, 15, 23]. The existing studies cover a wide range of methods which can be categorized into four general strands: (1) analytical framework reflecting return of investment and net contribution of RIs, such as input–output and cost–benefit analysis (CBA) models [10, 16, 17], (2) mixed-method approach to performance indicators [13, 23], (3) theory-based approach with a focus on context analysis or to impact pathway analysis [3, 25], and (4) case study approach, including both within-case and cross-case studies [2, 8].

While the notion of "impact beyond science" is centered in today's impact evaluation of RIs, defining "what to evaluate" in terms of socio-economic impact and "how to evaluate" the impact remains a challenging task. The definition of "socio-economic impact" often leans towards the idea of economic rather than social impact. On the one hand, justifying the financial return of funding is rather the original and fundamental motivation for the impact assessment of RIs. On the other hand, economic impact, in comparison to social impact, is a rather tangible and quantifiable element throughout the lifecycle of a RI. The existing literature also leave the impression that socio-economic impact assessments are often approached with a focus on quantification of scientific quality and financial productivity as the justification of social contribution. Overall, recognition of the heterogeneity of RIs and their impact has led to the mutual understanding that "one-size-fits-all" approach is no longer an option for establishing a holistic approach to socio-economic impact assessment [13, 19, 31]. The pilot study of the ESRF zooms in on its industrial engagement through the peer-reviewed public access as on one of the main tracks to generating socio-economic impact at large-scale and publicly funded RIs. Among many of the impact generation pathways, engaging with industry does not only contribute directly to innovation but it also provides a tangible way to assess and demonstrate the potential impact.

2 From Industrial Involvement to Socio-economic Impact

Recent research on knowledge ecosystem for large-scale RIs emphasizes on the important role of RIs in developing innovation by being a platform for scientific and technological collaborations between academia and industry [24]. Knowledge cultivated in such an ecosystem, although fundamental, often leads to breakthrough innovation that can impact varying fields and sectors and benefit the economy and society at large [26]. There is broad consensus that interactions between scientific research and industry are significant fuels to the advancement of knowledge innovation [29]. These interactions can take a variety of forms from co-authorship to formation of start-up companies through different channels from informal collaborations to contracted joint research projects. In the past decades, there has been a growing interest among academics and policy makers in the involvement of industrial partners in the process of knowledge and technology transfer. Empirical literature recorded an increasing level of academic commercial activities accompanied by an increase in research joint ventures and joint scientific publications [11]. On the one hand, from the RIs' point of view, academia-industry collaborations contribute to the potential application of fundamental research and expansion of scientific knowledge through technological breakthroughs. The pure scientific quality does not tell a full story about a RI's socio-economic value. By engaging with industry, research organisations are able to sustain scientific and technological progress and eventually bring about societal benefits [21]. It also provides an alternative way to track the socio-economic return of a given investment in a RI as scientific discoveries often have implicit indirect benefits to society. On the other hand, it is also observed that industry is motivated to partner with RIs for a diverse set of reasons, including increased problem-solving competence, product quality discoveries, and scientific learning processes [2]. Although there is still a lack of understanding in RI-industry linkages possibly due to the variety of channels through which knowledge and technology transfer takes place, industrial involvement remains a significant way for innovation to manifest in the context of RI.

3 The ESRF's Pathways to Engaging with Industry

Located in Grenoble, France, the ESRF is one of the most intense synchrotron light source worldwide providing research scientists from both academia and industry a unique tool to investigate materials and living matter. Since its establishment in 1988, ESRF has become an internationally renowned centre for scientific excellence with a strong commitment to applied and industrial research. As an international organisation, the ESRF's capital and operational costs are supported by 21 partner nations. Similar to other RIs, the ESRF considers contribution to innovation through knowledge and technology transfer as one of the core missions as well as one of the major indicators for impact of publicly funded initiatives. As defined by European Commission [14], RI missions focus on the conduct of research and the fostering of innovations in the relevant fields. Similar to other synchrotron facilities, there are two routes to accessing beamtime at the ESRF: the peer-reviewed public access and the proprietary or commercial access. The majority of research activities at the ESRF take place through the peer-reviewed public access; this mode of access is free of charge to all users who are granted experimental beamtime based on a competitive application process and who commit to publish scientific results. In comparison, the proprietary access is popular among industrial users for confidential experiments. In this study, tracking contributions from industry on the research conducted and knowledge produced through the peer-reviewed public access provides evident indicators of the ESRF's broader socio-economic impact on society. While all activities at the ESRF contribute to the innovation process, direct synergies with industry lead directly and in tangible ways to innovation. It is commonly agreed that the impact of RIs can be complex to trace due to the attribution problem. Similar to higher education institutions, research infrastructures also face the challenge in identifying and cataloguing the impacts that are generated from a high volume of research activities from diverse scientific fields [27]. The fundamental nature of research activities facilitated at the ESRF creates another layer of difficulty in tracking the research outcomes, let alone the socio-economic impact of these outcomes. Other than the attribution problem, there are also the problem of causality in which it is not clear which impact can be attributed to which cause as well as the timescale problem which often results in ignoring or under-evaluating the long-term potential impact of research [6]. To effectively assess the ESRF's impact on society through engaging with industry, it is useful to explore how much of the knowledge produced at the ESRF is obtained with a direct contribution or investment of industry. The idea is similar to the concept of Return on Research Capital (RORC), which is a metric that describes the revenue generated by a company as a result of capital spent on R&D. Overall, the ESRF engages with industry through four different modes. The first three modes refer to industry as the ESRF's client or user, while the fourth one refers to industry as a provider. The four modes are specified as follows:

(a) In the first mode, industry can access the ESRF through either the peer-reviewed public access or the proprietary access.
(b) The second mode involves industry interacting with the ESRF is a collaborative effort, for example, as a partner based on publicly funded grant agreements or consultancy contracts.
(c) The third mode highlights the most traditional technology transfer activity, where the ESRF own partial IP (Intellectual Property) derived from an effort in product development and valorise it in the usual ways, such as licensing and commercialisation of products.
(d) Finally, the fourth mode emphasizes the role of industry as a supplier, in some cases with a pre-competitive procurement approach.

All modes can result in the generation of joint IP. In this study, only the generation of societal impact deriving from a context where industry is an ESRF's client or user will be analysed (i.e. the first three modes). Despite the above-mentioned challenges faced in assessing the impact of RIs, there are multiple ways to capture the direct and potential engagements with industry at the ESRF. On the one hand, the study performs analysis on publications and patents using bibliometric techniques. As all research proposals approved through the peer-reviewed public access share the commitment of producing peer-reviewed publications, the ESRF's publication database allows not only the path to observe industrial collaborations in research activities, for example, through co-authorship, but also an understanding of possible applications of the knowledge created through patent citations. On the other hand, we attempted to estimate the ESRF's involvement with industry based on existing data on the industrial contribution towards academic partners as well as to collect first-hand data through surveying ESRF users.

4 Industrial Engagement in Publications and Patent Citations

There are various types of collaborations between academia and industry which can result in variety of outputs from co-authored papers to spin-offs. Bibliometric techniques are used to support the mapping of university-industry collaborations and to provide performance indicators for assessing research quality stemmed from such collaborations [1, 5, 9]. Over the past decades, analysts and scholars have produced bibliometric evidence to record the increase of jointly authored papers reflecting the growing interest of research collaboration from both universities and industry. Although studies have measured research collaboration using bibliometric indicators such as co-authorship and citations, there are inadequacies in using this method [7]. Not only do co-authorship based indicators have the limitation on detecting a substantial amount of collaborations considering that many collaborations do not result in co-published papers, but they also fail to capture sufficient information on the type of collaborations and the relationship between collaborators. At the ESRF, industry can play a role in different collaboration models, including research-industry collaboration, pure academic collaboration and pure industry collaboration. During the pilot study, it is observed that existing bibliometric tools, such as Web of Science and InCites,[1] indeed have a lack of accuracy when it comes to identifying industrial engagement in publications from works done at the ESRF. Hidden industry presence exists in pure academic collaboration and research-industry collaboration when industry acts as a sponsor or sample provider. Whilst in the case of pure industry collaboration, the use of outsourced research services results in the difficulty of recognising outsourcing companies as they may not be affiliated with the co-authored papers. In addition, companies such as SMEs and start-ups are often not recorded in the database of existing bibliometric tools, which causes a lower number of industrial collaborations being identified and reported. Although the above-mentioned barriers significantly limit the acknowledgement of research-industry collaborations through publications, bibliometric data is still a valuable source for estimating industrial engagement in research activities at the ESRF.

To calculate the percentage of ESRF's publications involving industry, the pilot study extracted the number of publications with industrial collaborations based on the publications each year. The publication database was provided by the Joint ILL-ESRF Library. The database consists of two categories of publications, namely publications with authors affiliated to the ESRF and publications replying on access to the ESRF.[2] In the analysis of industrial engagement, both groups are considered the ESRF's publications, or publications from works done at ESRF. Using InCites as the main

[1] Web of Science (https://www.webofscience.com) is a Clarivate *platform consisting literature search databases covering different scientific fields.* InCites (https://incites.clarivate.com/) is a Clarivate citation-based evaluation tool.

[2] In this case, publications are based on experiments done at the ESRF but no author of the publication is affiliated to the ESRF.

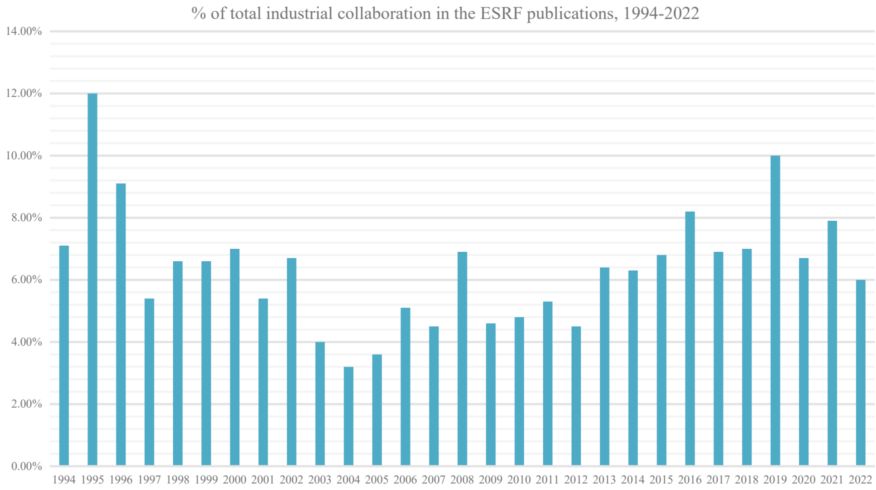

Fig. 1 Percentage of industrial collaboration in the publications from works done at the ESRF between 1994 and 2022. The calculation was done based on data extracted from InCites

bibliometric tool, data extraction of industrial collaborations in the ESRF's publications indicates an average percentage of 6.4.[3] The total number of ESRF publications between 1994 and 2022[4] is 37,299, while the number of ESRF publications involving industrial collaboration is 2038 representing 5% of the total publications.[5] InCites defines an "industry collaborative publication" as "one that lists its organisation type as 'corporate' or 'global corporate' for one or more of the co-author's affiliations" [18]. Figure 1 demonstrates the details of percentage of industrial engagement in the ESRF's publications between 1994 and 2022. The percentage is the number of industrial collaborations at the ESRF divided by the number of publications relying on access to the ESRF on a yearly basis.

To understand the intensity of industrial collaborations at the ESRF, the study compared the number of industry collaborative publications and the number of industrial partners involved in the collaborations. The result suggests that every industrial partner that engages with the ESRF through the peer-reviewed public access, publish an average of 1.2 publications. Figure 2 also indicates a gradual and yet steady increase of the collaboration intensity between 1994 and 2022.

Similar to publications, patents can play a key role in understanding the link between scientific research and its societal application. Although recent debates

[3] The percentage refers to the number of industrial collaborations compared with the total number of ESRF publications (recorded on Web of Science database).

[4] The Joint ILL-ESRF Library provided the publication data in November 2022. Due to the missing data from December 2022 as well as the time lag between a paper's publication date and the time when the publication is recorded in the library database, the analysed publication data in 2022 was incomplete.

[5] The percentage refers to the number of publications involving industrial partners compared with the total number of ESRF publications (recorded on Web of Science database).

Fig. 2 Collaborative productivity of the ESRF's industrial engagement between 1994 and 2022

have questioned the actual value in demonstrating the flow of knowledge due to the multiple functions of and various citation motivations behind patents, many researchers believe that "the embedded knowledge of scientific papers cited in patents indicates the prior usage in the development of these patents" [20, p. 1008]. As scientific linkage, often quantified as the total papers cited in a patent, is a common indicator of scientific application and innovation, it also provides insights into the ESRF's post-publication engagement with industry and its potential impact on society. The present pilot study used patent search tool, Lens PatCite,[6] to identify the patent applications that cited publications from works done at the ESRF (Fig. 3) as well as those citing publications from works done at the ESRF (Fig. 4). The difference between the numbers of granted patents indicated in Figs. 3 and 4 demonstrates a delay of patent applications citing the citations of the ESRF publications. The delay is likely associated with the time lag between publications and citations.

5 Further Estimations on Industrial Contribution

Other than contributing directly to the successful production of research outputs such as publications and patents, industrial support can be hidden behind less tangible contribution including sample provision, training, marketing and engagement support and more. The lack of direct evidence of industrial presence in the above-mentioned areas poses great challenges in accounting the relatively less visible and tangible engagement with industry.

[6] The Lens (https://www.lens.org/lens/patcite) is an online patent and scholarly literature search facility.

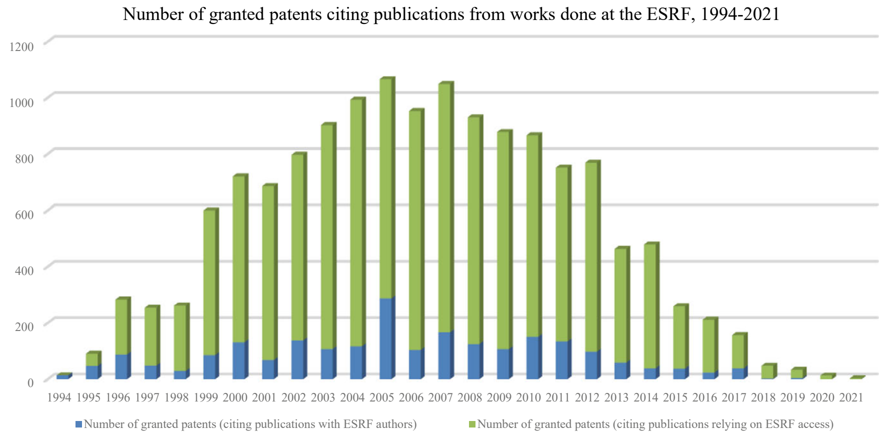

Fig. 3 Analysis of patent citations on publications from works done at the ESRF between 1994 and 2021. Patent data was collected from Lens PatCite in March 2023

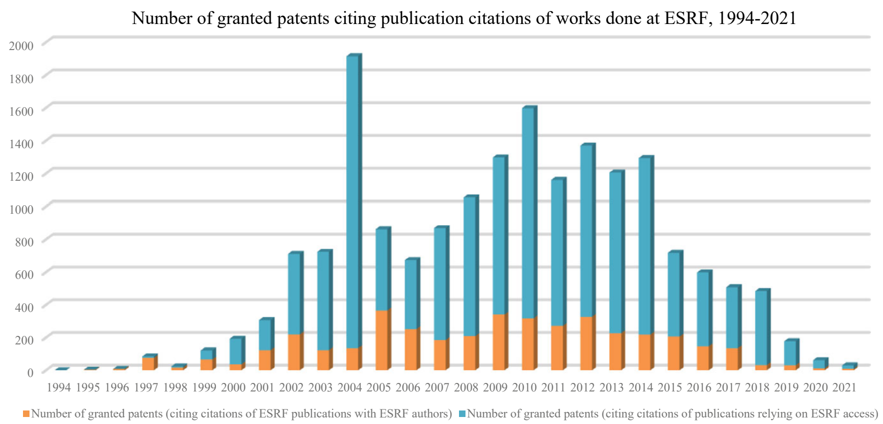

Fig. 4 Analysis of patent citations on citations of publications from works done at the ESRF between 1994 and 2021. Patent data was collected from Lens PatCite in March 2023

In the context of a bigger picture, existing literature has provided indications on industry's contribution to universities and RTOs (Research and Technology Organisations). At the European level, the average industrial involvement in the Horizon 2020 projects increases to 34% when RTOs are involved [12]. According to the Times Higher Education [30], research income from industry is somewhere between 10 and 30% of the total research incomes at universities. The funding share from industry reached approximately 30% in the case of RTOs like Fraunhofer [22]. Taking into consideration that publications produced on ESRF access are roughly equally shared between universities and RTOs, we can estimate that each publication generated at the ESRF, even if do not present any industrial co-author brings, statistically, an embedded industrial contribution equal to roughly 22.5%. After adding the explicit 5% contribution described above, the overall estimation reaches 27.5%. Although more rigorous calculations are necessary, the estimation sheds light on a potential support from industry, taking into account the crucial role of academic intermediaries.

Besides, efforts have been made at the ESRF to collect first-hand data on the peer-reviewed public access through surveying the ESRF users as well as monitoring the research activities in the proposal stage. The ESRF proposal form requires all users who apply for beamtime through the peer-reviewed public access to categorise their proposed research activities as "Fundamental Science", "Applied Science" or "Industrial Science". According to the 4390 proposals recorded in the proposal database between 2017 and 2022,[7] 6% of the proposals are self-identified entirely or partially as "Industrial Science" while 44% of them are claimed to be entirely or partially "Applied Science". The figures show significant relevance with the results from two further surveys collected both in 2012 and 2023. During the survey distributed to the ESRF users in 2012, 40% of responses indicate that the research outcomes have applications for industrial R&D. The results also suggest that almost 50% of ESRF users have direct links with RTOs and 30% of them received financial support from industry. The 2023 user survey targeted main proposers of beamtime application between 2017 and 2022. Among the respondents, 22% indicated that they always or often collaborate with industry, and almost 20% specified that they have done their research at the ESRF in collaboration with industrial partners. As a step further to understand industrial engagement in various forms, the surveys have suggested the industrial relevance at the ESRF to be between 20 and 30%. Specifically, 25% of the ESRF users characterise their research as "applied science" or "relevant for industrial use". About 20% of them have done their research at the ESRF collaborating with "industrial partners", while around 27% of them collaborated with "applied research organisations". The results validate previous estimation based on secondary sources.

6 Conclusion and Direction of Future Work

The pilot study of estimating the industrial engagement of the ESRF, highlighting the industrial contribution to the ESRF's scientific production, presents one of the important pathways to socio-economic impact. Some pathways involve a more hidden presence of certain stakeholders including industry and less attributive ways to sustain innovation. Despite the difficulties posed by both conceptual and methodological challenges, the study demonstrates possible practices and tools for assessment in the context of analytical RIs and light sources in particular. Understanding not only the direct, but also the indirect contribution of industry to research activities requires attention to both quantitative and qualitative assessment methods as well as a continuous monitoring framework that is feasible and beneficial to the whole stakeholder

[7] The proposal database was provided by the ESRF User Office.

ecosystem of an RI. Ideally, the enhancement of assessment and presentation of socio-economic impact is brought forward together with the shared vision of developing the impact itself.

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Tracing Different Types of Local Economic Benefits of RIs: The Case Study of LHC

Leslie Alix and Johannes Gutleber

Abstract CERN is operating the world's largest particle accelerator complex in the world. The interconnection of versatile particle accelerators working with different particle beams at different intensities and energies continue to attract scientists and engineers from all over the world. The socio-economic effects generated by the presence of in the region are manifold. They include, but are not limited to consumer spending, real-estate investments and local business and services activities, investments in education, leisure activities and tourism, urban development and tax contributions. This chapter traces different local socio-economic effects of concentrating a large number of people around a research infrastructure.

Keywords Territorial benefits · Consumer spending · Local services · Research infrastructure · Socio-economic effects

1 Introduction

CERN is operating the world's largest particle accelerator complex in the world. The interconnection of versatile particle accelerators working with different particle beams at different intensities and energies continue to attract scientists and engineers from all over the world. While a large part of the scientific analysis is carried out by the researchers at their home institutes, scientists and engineers involved in the research programmes spend significant time at CERN, both to advance the scientific capabilities of the infrastructures and to learn about the possibilities that this infrastructure can offer to them. The presence of these people in the region

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leads to significant consumer spending over sustained periods of time. The socio-economic effects generated by the presence of staff and project associated scientists, engineers, technicians, and early-stage researchers that "legally reside" in France or Switzerland, where the infrastructure is located, perform professional activities for typically one to three years in the region are manifold. They include, but are not limited to consumer spending, real-estate investments and local business and services activities, investments in education, leisure activities and tourism and tax contributions. However, these effects are not truly socio-economic impacts that the research infrastructure generates as compared to the capital and operation expenditures. Such consumer spending would occur with or without CERN, but without CERN they would occur in other regions and countries, where people reside and work, and would not necessarily be concentrated. Hence, the type of nationally, regionally and locally perceived benefits of the research infrastructure associated consumer spending is rather an economic transfer. This transfer eventually contributes to society's wealth increase. This effect is, however, not the primary concern of this contribution.

In the first part, I will present the contribution of a large research infrastructure, such as the current Large Hadron Collider (LHC), to the local economy through consumer spending. In the second part, I will show examples of what socio-economic effects can be catalysed at local level by the concentration of personnel participating in a large research infrastructure.

2 The Contribution of a Large Research Infrastructure to the Local Economy: The Value of Consumer Spending

2.1 Background Data

First of all, it is important to define what we mean by consumer spending. The method used to estimate local consumption expenditure attributable to CERN's research programmes is based on data from the national institute of statistics and economic studies (INSEE) for France and the federal statistical office for Switzerland (OFS), in particular on the so called "spending per consumption unit" [7] for persons living alone and the "household consumption spending" [5] for persons who do not live alone. We also consider data on the value of annual household expenditure for different income categories. Indeed, depending on income, the structure of consumer spending varies, creating disparities between consumer products [6, 8]. The categories of household expenditure considered here are as follows: food and non-alcoholic beverages, alcoholic beverages and tobacco, housing, water, gas, electricity and other fuels, furniture, household goods and routine maintenance of the home, health, Transport, Communications, Leisure and culture, Education, restaurants and hotels. As some expenditure is tradable goods and services (clothing and shoes, miscellaneous goods and services), we deduct this amount from the household expenditure figures used in our estimates, as this chapter focuses on the national economic effects of consumer spending.

The annual reports on CERN's personnel statistics [3] provide us with the basic data for estimating the effects of the value of consumer spending.

In total, in 2019, out of 14,000 active members at CERN, more than 8000 people live in France and in Switzerland. Due to the higher cost of living in Switzerland, 63% of them live in France and 37% in Switzerland. They usually live in the surroundings of the research infrastructure (most of them within a 40 km radius) leading to a concentration of expenditure at local level. Moreover, 39% of them are employed member of personnel by CERN and 61% are associated members, employed by their home institutes but living in the territory for a better proximity with the research infrastructure. We also have data on household composition (single-person or multi-person household), and income enabling us to estimate the spending according to the standard of living quintiles (Fig. 1).

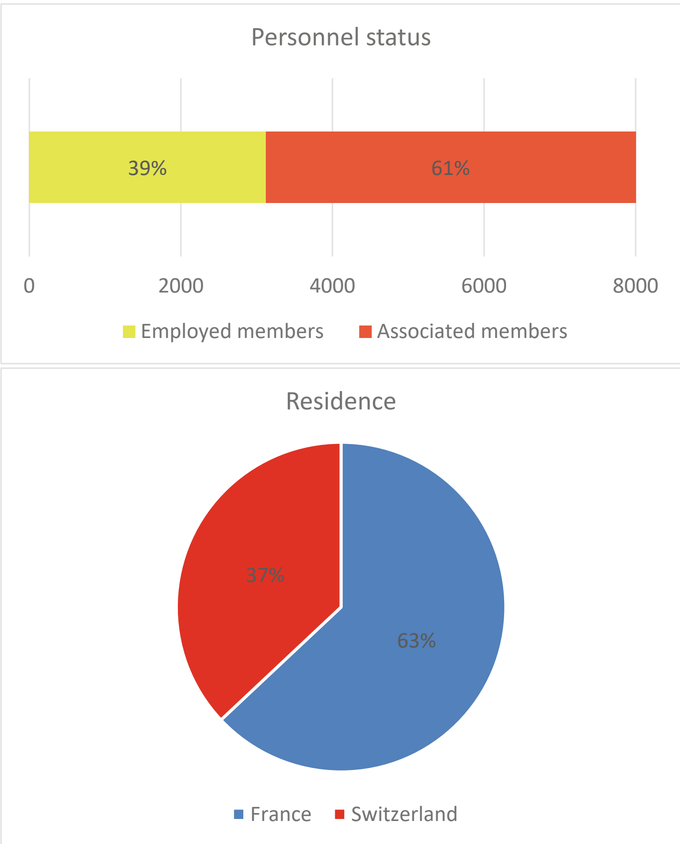

Fig. 1 Personnel status and geographical distribution of residence. *Credits* L. Alix

2.2 *Economic Effect of Consumer Spending Due to CERN and Its Main Research Infrastructure*

The reference period covers the LHC/HL-LHC programme with an operational timescale of about 30 years. This means that the 8000 people live in the territory and spend money during these 30 years. In the report on the contribution of the Future Circular Collider to the local economy [1], we have estimated that 8.9 billion euro (not discounted and price evolution adjusted) are spent in the local territory through the consumption expenditures of residents, which represents almost 300 million euro per year. As there are more residents living in France than in Switzerland, the spending amount is higher in France, but the difference is not too important given the much higher cost of living in Switzerland (see Fig. 2).

CERN has several scientific research programmes. Its flagship research programme with different experiments is based on the Large Hadron Collider (LHC). About 80% of CERN's total personnel are involved in its flagship programmes (the LHC and HL-LHC particle colliders). Indeed, not all members of staff work 100% on the particle colliders and their experiments, but they do ensure the smooth running of a platform for several programmes. Thus, staff working on particle accelerators generally ensure the operation and maintenance of all particle accelerators and technical infrastructures, including the particle collider and the entire chain of injectors needed to operate the collider. As an example, according to CERN's internal data, 20% of the staff work for experiments that are not linked to the main research programme, 24% work in sectors that ensure the smooth running of all the research infrastructures, including the particle collider, and 56% are attached to the particle collider experiments. This gives us 80% of people who are considered to be active in the infrastructures and experiments linked to the particle collider.

These 8000 residents are members of personnel participating in all CERN's research activities. To know the impact of a large research infrastructure such as LHC, one needs to consider the people only working for it, so 80% of them, which is

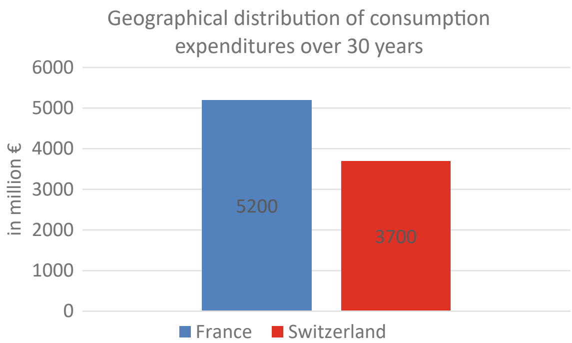

Fig. 2 Personnel status and geographical distribution of consumption expenditures. *Credit* L. Alix

around 6400 persons. Therefore, on the 8.9 billion euro spent consumption expenditures, 7.2 billion euro are directly allocated to the LHC/HL-LHC research programme and the other to CERN in general.

This report only considers the amount of personnel spending, but the local economy is also fueled by the large amount of tourist spending coming to the region to visit CERN. It also does not consider the expenses of people working at CERN on a subcontracting basis.

3 Effects of Concentrating People Around a Large Research Infrastructure

As stated above, the concentration of people linked to a large research infrastructure produces multiple quantitative and qualitative socio-economic effects at local level, whether directly linked to consumer spending or not. I will list a few significant examples, but this list is of course not exhaustive.

3.1 Effects on Cultural Activities

An organisation hosting such a large number of people has a personnel association to represent them and facilitate the link with the territory. One of the most significant examples is the possibility to join organisation-internal or local clubs. Indeed, clubs offer sports, leisure and cultural activities, thus enhancing non-professional relations between CERN staff members and facilitating integration of them and their families into the local area. These clubs are also frequently used by non-CERN members which is a real benefit for the territory to offer cultural activities. The Staff Association is also in contact with local artists and offers both artists from CERN and from the local area the possibility to showcase their works at CERN. The concentration of people within a research infrastructure from different backgrounds makes it possible to organise conferences in a wide range of fields, benefiting both CERN staff and the local public.

3.2 Effects on Local Stores and Services

For the daily life of the people onsite, local services such as cafeteria and restaurant, accommodation, shop, bank, mobility offer, etc. are required. These services can be proposed directly in the campus or in the local area through subcontracting or partnerships.

As an example, there are three restaurants within the two CERN sites. Interviews with the restaurant staff allow to estimate an average of 2700 meals a day during the week and an average of 14 euro spent per meal. Then, around 650,000 meals are for sure provided a year with a turnover of 9 million euro per year for the local economy, just to meet the day-to-day needs of the personnel.

Another example is the accommodation offer. There are 3 hotels within CERN site, with a total of 423 rooms, an occupancy rate of 71% and an average price of 49 euro per room, open all year, it is assured a turnover of 5.4 million euro per year thanks to the concentration of the people within an area. These hotels are operated by sub contractors, but there exists also a residence located in Saint-Genis-Pouilly, a neighbouring commune in France, which has a partnership with CERN to reserve 151 on 260 rooms for CERN associated visitors. With an occupancy rate of 80%, this assures a minimum of turnover for the residence per year.

We can also mention the 12 fully furnished and equipped apartments, subleased by CERN, located in Meyrin and Grand-Saconnex in Switzerland. Moreover, a CERN website has been created where local landlords can post their accommodation offer. The concentration of the population and its housing needs have the effect of sustaining the local housing market including seasonal rental.

3.3 Effects on Local Public Transportation

The daily needs of people working at CERN are diverse.One is related to mobility, mainly commuting which requires an adapted local transport offer. Today, it is possible to go to CERN by bus and tramway which are linked to neighbouring French and Swiss communes. A survey launched in 2018 [2] has shown that 10% of the 4300 respondents use the public transport to commute every day, which represents at least 430 persons. 13% of them come by bicycle, i.e., 560 persons. These numbers are low estimates as many people working at CERN did not respond to the survey. The improvement of the local mobility offer, passing through CERN, is indeed a local actors' objective and the important number of people using the public transportation or environmentally friendly transport for commuting contribute to justify the improvement of the public transportation offer.

3.4 Effects on Public Services

Another socio-economic effect that we do not think of immediately is the improvement of local emergency services through CERN. Such a huge infrastructure concentrating a large number of people requires public services for the people onsite. A tripartite agreement between CERN, France and Switzerland on mutual assistance was officially signed in 2016 [4].

In the event of an incident in the area surrounding CERN or on CERN property, and if a request for back-up is required, CERN or the French or Swiss services can intervene mutually to help the services that need it. This is mutually beneficial, firstly in the event of an emergency, but also because on one hand, CERN and its fire brigades have very specific skills and equipment that local services do not necessarily have, and on another hand, because local services have more staff than CERN. For example, if there is a need for intervention related to radiation protection at Geneva airport, it is common for CERN to intervene at the airport, as it has all the necessary equipment.

In addition to interventions, this collaboration enables each party to benefit from the other's specific expertise through training. CERN, which specialises in chemical and radiological risks, has been able to train firefighters from Geneva and the Ain department in France, and the latter have shared their own skills with further fire fighting services. Other examples show that, thanks to the size of the CERN campus, large-scale training courses have been carried out on its premises, whereas it is usually difficult to find a suitable location for such courses.

CERN's emergency services employ 60 people, including 48 contract firefighters. As well as acquiring very specific technical skills, the international context of CERN also enables them to improve their mastery of foreign languages. Today, in the Pays de Gex in France, close to CERN, professional firefighters who have already worked at CERN stand out for their skills.

The tripartite agreement (one of the few in existence), has benefited both CERN and the region in terms of operations, training and career opportunities. This was made possible and relevant by the sheer size of the research infrastructure and the large number of people grouped together on the same area.

The list of local socio-economic benefits mentioned in this article is not exhaustive. CERN has also partnerships with local companies, local sport facilities and local cultural centres. We can also think about the needs for doctors, personal services, financial and legal services, or the local companies that have been created related to CERN's presence in the area. The presence of an important number of persons in a research facility contribute to increase and develop the residential economy, in terms of added value and employment added to an overall positive social effect.

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The Value of Open Science at CERN: An Analysis Based on a Travel Cost Model

Irene del Rosario Crespo Garrido, María Loureiro García, and Johannes Gutleber

Abstract Open science is a fundamental root of the European Organization for Nuclear Research, known by its acronym CERN. This international organization, located between Switzerland and France, has distinguished itself since its inception by sharing its discoveries, innovative technologies, and the information generated by its most ambitious project, the Large Hadron Collider (LHC) so that researchers around the world and society can benefit from the data gathered and the knowledge created. One of the main characteristics of the organization is the possibility to freely visit the particle accelerators and the experiments at these machines. On these occasions, visitors can meet the scientists and learn directly from them about the organization, its discoveries, and its daily activities. This study is one of the few assessing the economic value of these initiatives. It is based on a survey using a sample size of 900 visitors to CERN during one calendar year. Results from a travel cost application show that visitor would be willing to pay a total on average at least 0.72 € over the cost of the trip per person, owing to the experience and knowledge gained during their visit to the infrastructure.

Keywords CERN · LHC · Travel cost method · Willingness to pay · Consumer surplus · Open science · Economic impact · Social impact

1 Introduction

CERN, the European Organization for Nuclear Research, is one of the world's most prestigious research institutions in particle physics. Founded in 1954, CERN is situated at the convergence of Switzerland and France, with a mission to decipher the fundamental laws that govern the universe. Employing advanced particle accelerators

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and colliders, notably the powerful Large Hadron Collider (LHC), CERN delves into the conditions of the early universe, providing insights into its inception. The LHC, described by Professor Brian Edward Cox in a TEDx talk (2008) as "the biggest scientific experiment ever attempted", spans 27 km and hosts four main experiments: Atlas, CMS, Alice, and LHCb. These experiments focus on general-purpose detection, heavy-ion physics, and the investigation of matter–antimatter differences. CERN's impactful contributions include the development of the theory underlying the Higgs boson [1], confirmed in 2012; the translation of particle physics technologies into cancer treatment (hadron therapy) [2]; and Medipix detector chips [3], enabling high-definition imaging of human tissues.

Educational trips to CERN are a valuable opportunity for students and educators to learn about cutting-edge physics research, explore the world of particle physics, and gain insights into the workings of one of the most advanced scientific facilities on the planet. CERN is where Tim Berners-Lee and Robert Cailliau developed the World Wide Web in 1989. The Web [4] was originally developed as a system that allowed physicists worldwide to exchange information freely in a decentralized, open, and scale-free manner. The underlying communication protocols and software were made freely available to the public in 1993 so that anyone with a server and a browser could use it and continue to develop the infrastructure. This discovery made CERN and its most audacious project, the Large Hadron Collider (LHC), one of the well-known names in the "open science" movement.

The open science policy is not only conducted by sharing information over the Internet. There are numerous ways in which information can be disseminated, both to the scientific community and society at large. In the case of CERN, programs for students and professors, subcontracting of research infrastructure work to companies in member countries, or work contracts promote research and learning to all who wish to benefit. Another means of disseminating knowledge is CERN's visit program. CERN has been open to the public since 1958, i.e., only four years after its creation. Since its beginnings, it has evolved its way of engaging laypeople and has become increasingly accessible. Numerous studies and organizations such as UNESCO [5] and the OECD [6] have endeavored to show that the "open science" movement promotes free access to scientific research to enrich society.

The study presented in this article aimed to capture a part of the total social impact of CERN a global reference for "Open Science", in monetary terms by measuring the economic value of the socio-economic impact potentials of on-site visitors. It sheds light on this question by examining a subset of the economic values created that are directly related to CERN's research program. The impact potential has been estimated based on an anonymous survey administered to different class visitors during one calendar year. The data have been examined methodically and in detail, distinguishing between registered and unregistered visitors. The goal is to obtain an estimate of the potential value of all on-site visitors based on the generalized estimated willingness to pay (WTP) by visitors to CERN between June 2018 and May 2019. The survey was administered before the closure of visits suffered by the organization due to the COVID-19 pandemic. This article proceeds as follows: Initially, we will present a comprehensive examination of the diverse impacts generated by

CERN, encompassing both scientific and social aspects. This exploration is underlined by a robust correlation, stemming from the organization's commitment to the Open Science movement. To conclude, we will describe the most relevant policy implications of our findings.

2 Impacts of CERN

The 1953 CERN convention established the principle that "all scientific findings should be easily accessible to the general public." Although the term "open" lacks a specific definition, CERN has consistently honored this commitment by generously sharing its scientific discoveries and technological advancements with the scientific community, private industry, and society at large. This dedication has led to significant advancements in scientific knowledge, firmly solidifying CERN as a stronghold of open science.

The impact of CERN's foundational principle extends across various domains aligned with its mission and discoveries. Consequently, studies examining the organization's influence have categorized their results into four primary areas: Scientific knowledge, Innovation and knowledge transfer, Training and education, and engagement of individuals not directly affiliated with the organization's core activities, considered the public audience. This broad-reaching influence underscores CERN's role as a pioneer in promoting transparency and accessibility in the realm of scientific research.

2.1 Scientific Knowledge

LHC is not the only research infrastructure that CERN operates. There are other unique facilities available to the scientific community. Some examples are:

- **The Antiproton Decelerator (AD)** [7], a machine that produces low-energy antiprotons for antimatter research.
- **The Isotope Mass Separator On-Line facility (ISOLDE)** [8], a source of low-energy beams of radioactive nuclides.
- **The Cosmic Leaving Outdoor Droplets (CLOUD)** [9], an experiment that uses a special cloud chamber to study the possible link between galactic cosmic rays and cloud formation.
- **OpenLab** [10], a platform to jointly develop and test ICT technologies with industrial partners.
- **IdeaSquare** [11], an open environment to engage creative minds in technology projects from a diverse set of academic and business backgrounds.
- **S'Cool Lab** [12], a hands-on particle physics learning laboratory for high-school students and their teachers from around the world.

- **HiRadMat** [13], a facility to study the effects of ionizing radiation for the benefit of academic and business users such as the space industry and several more.

Roughly 70% of the worldwide community of high-energy and particle physicists actively participate in institutions dedicated to exploring the fundamental principles of the natural world. According to [14], this collaborative endeavor has produced around 27,000 publications linked to Large Hadron Collider (LHC) experiments, with a significant presence in approximately 24,000 other research works. Consequently, these 24,000 publications have been cited in an impressive 862,000 additional research papers, illustrating the extensive impact and influence of collective efforts in the field.

2.2 Innovation and Knowledge Transfer

Knowledge transfer involves sharing or disseminating knowledge and contributing to problem-solving [6]. In 1988, CERN established the Industry and Technology Liaison Office to manage knowledge and innovation transfer. A year later, Timothy Berners-Lee and Robert Cailliau developed what is now commonly known as the Web. Four years after that, CERN made the underlying communications protocols and software freely available to the public. Despite the initial perception that providing such a crucial service to humanity would have minimal impact, a study by [15] estimated the global impact of the Internet to be 2.9% of world GDP, equivalent to $1,672 billion.

The extensive data flow produced by the LHC project prompted the establishment of the Worldwide LHC Computing GRID. This network facilitates the distribution of data from CERN to 11 major computing centers across Europe, North America, and Asia, which then disseminate it to 170 centers in 42 countries. Initially, raw, preprocessed, and annotated data is shared with members of the LHC experiment scientific collaborations. However, a subset of annotated data and simplified data suitable for home-programmed analysis software is later made available, with a time delay, to researchers outside of the collaborations, as well as to schools and the interested public through open-access data infrastructures. This global integration of data storage and processing centers has empowered thousands of scientists worldwide to engage with this data. The infrastructure processes an impressive 50–70 petabytes of data per year during the operation of the Large Hadron Collider (LHC) at CERN. The Worldwide LHC Computing GRID actively collaborates with entities such as the European Grid Infrastructure, the Open Science Grid, and the Nordic e-Infrastructure Collaboration.

Open science at CERN extends beyond the dissemination of information about projects conducted on the infrastructure. It encompasses more than the sharing of scientific research, as the organization has developed various tools and software to enhance day-to-day operations. These include the Zenodo virtual repository [16], the Indico meeting, workshop, and conference management tool [17], the Root data processing framework, and the Protonmail encrypted email service [18]. All these tools are freely available and compatible with any computer. Protonmail, the encrypted email service, is offered to users in different models, either for free or on a subscription basis, depending on the user's requirements.

CERN delegates a substantial portion of its work conducted at its facilities to companies located in its member countries, constituting approximately 50% of CERN's annual budget. This practice has a direct impact on the contracted companies. As illustrated by Bianchi-Streit et al. [19], CERN's economic influence can be measured by the combined increase in revenue and reduction in costs. Through a comprehensive survey involving 160 high-technology companies, the researchers found that during the period from 1973 to 1982, the adjusted utility/sales ratio was 3. This result indicates that for every Swiss franc invested by CERN in high technology, it yields three Swiss francs in economic benefits.

CERN also brings additional advantages, including knowledge transfer to scientists, engineers, and all those working in its infrastructures. This knowledge transfer extends to assisting workers and entrepreneurs in creating spin-off companies. An example of this is the establishment of nine Business Incubation Centers (BICs) in 2016 to transform CERN innovations into marketable products.

Another notable example of a spin-off is Advanced Accelerator Applications (AAA). Established in 2002, AAA emerged as a spin-off from CERN under the guidance of physicist Stefano Buono, intending to commercialize a patent developed during his tenure at CERN, alongside Nobel laureate Carlo Rubbia. Specializing within the scope of nuclear medicine, the company's product line encompasses molecular imaging diagnostics and therapeutics designed to facilitate disease assessment, monitoring, and the selection of appropriate treatments. Central to their offerings are radiopharmaceuticals, which consist of radioactive particles known as radioisotopes and are utilized in positron emission tomography (PET) and single photon emission tomography (SPECT) [20].

Advanced Accelerator Applications has effectively positioned itself as a trailblazer in the global nuclear medicine market. The company has consistently expanded its sales and international footprint by acquiring companies and laboratories, as well as fostering collaborations with institutions like Warsaw University. Currently, Advanced Accelerator Applications operates in 12 countries and maintains 29 centers across Europe and the United States. In 2018, the multinational corporation Novartis acquired Advanced Accelerator Applications for € 3.4 billion [21]. The establishment and growth of Advanced Accelerator Applications have not only had a significant economic impact on CERN but have also contributed to social progress through the company's innovative advancements in the field of nuclear medicine.

2.3 Training and Education

Training and education form integral pillars of CERN's mission. As per a 2016 study conducted by the organization, there are consistently over 2400 doctoral students enrolled at CERN at any given time, leading to the completion of approximately 600 theses annually. In the summer season, around 300 undergraduate students, representing both CERN member and non-member countries, partake in an internship program spanning between 8 and 13 weeks. Additionally, several hundred engineering, physics, and technical students engage in dedicated, long-term assignments at CERN, typically lasting about a year, allowing them to accrue valuable knowledge and innovative experience.

Since 1966, approximately 350 students have been or are currently involved in CERN's apprenticeship program. Each year, about 10 students aged between 15 and 19 embark on this comprehensive training, which includes both theoretical and practical components over about four years. The program equips them to obtain a technician diploma in their chosen field upon completion.

Reference [22] assessed the impact of CERN on the development of human capital. Their research revealed that individuals engaged in scientific high-tech projects at CERN for one to three years experience a 5–11% increase in their lifetime earnings upon entering the job market following their CERN experience. This study involved comparing the salary outcomes for students who participated in programs at CERN with those who received similar training at the university alone but did not engage in high-tech scientific projects at CERN.

Students are not the only ones who have access to programs to improve their learning skills. Teachers and faculty members, too, can improve their teaching skills by using examples from CERN's research to make their lessons more engaging. Since 2006, each year about one thousand teachers have participated in CERN's programs.[1] The impact of these teachers' programs affects not only them but also all the students who attend their classes daily.

2.4 General Audience

The development of the World Wide Web revolutionized information access for the global population, creating more efficient horizontal and vertical linkages in society. As of 2021, a study by Global Digital revealed that 59.6% of the world's population were active internet users, with 53.6% actively engaged in social media. Many individuals utilize these platforms for news consumption, exploring topics of interest, and interacting within their social circles. However, it's important to note that the substantial influence of this digital landscape is primarily dominated by a select few corporations, often referred to as the "big five FAAMG": Facebook, Amazon, Apple, Microsoft, and Google. Notably, these giants are not directly associated with CERN. It's essential to recall that the technology underpinning the internet was initially developed to meet the demands of fundamental physics research and was entirely funded by taxpayer money, thus rightfully accessible to all of humanity for free.

[1] CERN Teacher programmes. https://teacher-programmes.web.cern.ch/.

The initial assessments of the socio-economic benefits arising from CERN's diverse impact pathways linked to the Large Hadron Collider were conducted by [14]. The data on the World Wide Web (WWW) and social media usage were collected at an early stage of these technologies before they were fully integrated into society. Subsequent studies [23], have successfully assigned a monetary value to the time people spend on these various channels to learn about CERN and its research activities. The calculated monetary value for the time spent by internet users on CERN's websites and social media platforms, including YouTube, Facebook, Twitter, and Instagram, from 2007 to 2025, amounts to 2.9 billion euros (base year 2007). The impact derived from social media appears relatively modest compared to the global reach of mainstream media. This may be related to the fact that the analysis has not fully captured the additional impact generated through responses, comments on other platforms such as blogs or websites, and the dissemination of information. Therefore, the results should be interpreted as rather conservative.

CERN is committed to open public access, offering free entry year-round. The organization has established two permanent exhibitions and guided tours designed to help visitors understand its research activities, enabling them to delve into the world of particle physics and trace the origins of the universe. Additionally, certain times of the year provide the public with the opportunity to visit the underground sites of the LHC experiments, with guided tours available. CERN's records indicate that approximately 120,000 individuals visit the facility annually, including around 70,000 high school students. The study presented in this article evaluates the economic impact potential associated with visitors to CERN.

3 Assessing the Economic Impact of On-Site Visitors at CERN

CERN offers visitors two permanent exhibitions and a year-round free guided tour for those who wish to discover the cathedrals of technology housed in the organization. In the Microcosmos exhibition, visitors can take a behind-the-scenes look at the organization to discover CERN's experiments and find out what goes on inside its flagship Large Hadron Collider. In this exhibition, visitors discover the history of CERN, told by the organization's staff in interactive videos.

In 2004, the Swiss government donated the Universe of Science and Innovation building to CERN, also called the Globe because of its shape, in celebration of the organization's 50th anniversary. Since then, the building has been used as a tool for outreach and events by CERN. In this exhibition, visitors can immerse in the world of particles and discover the traces of cosmic rays, the first web server, and the main questions of today's physics. The visitor can also enjoy a show about the origins of the Universe.

A guided tour is offered for all visitors to experience first-hand what the first accelerator built by CERN looks like (Figs. 1 and 2).

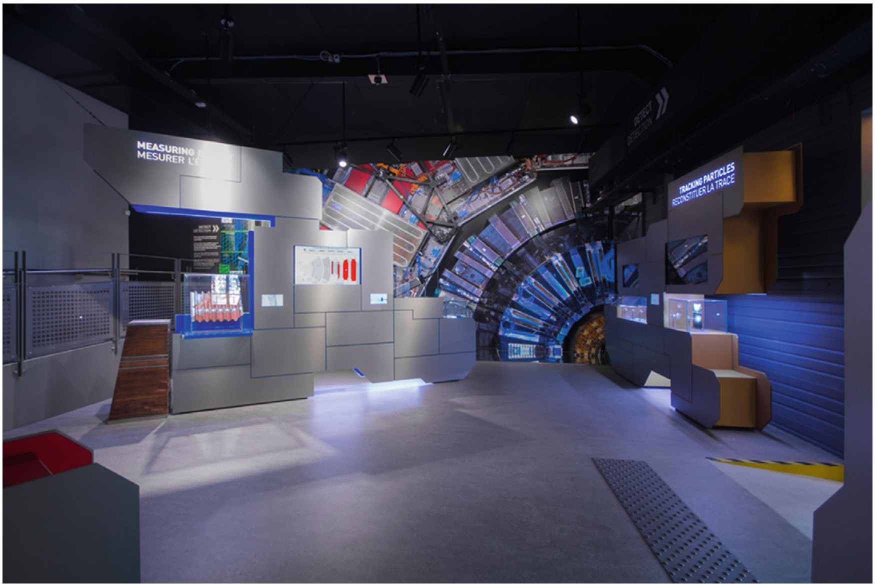

Fig. 1 Inside the Microcosm exhibition. *Credits* CERN

Fig. 2 Inside and outside of the Universe of Particles exhibition. *Credits* CERN

Although 120,000 visits are typically recorded per year, about twice as many requests (300,000) reach the CERN visit service every year. Therefore, it is safe to assume that the number of visitors each year may increase as soon as visit capacities increase, for instance with the newly constructed visitor center. CERN's records only have data on visitors who sign up for a guided tour. However, many visitors also profit from the freely accessible visit facilities without guided tours or are part of dedicated tours to one of the LHC experiments, which are managed by the experiment collaborations and not by CERN's central visit service.

This study aims to answer the question "How much are visitors valuing the knowledge achieved during this visit, and how much they would be willing to pay for it?"

3.1 Prior Efforts

Reference [14] conducted an economic impact assessment of visitors to the CERN site, attributing a conservative discounted value of approximately € 1.1 million to their economic contribution. The study, using data from 2013 as the reference year, covered the observation period from 2004 to 2025. The benefits estimation employed the revealed preference method, anchored in the Marginal Social Value (MSV) of the time spent during visits to the Large Hadron Collider (LHC).

Historical data on visitor numbers from 2004 to 2013 were obtained from the CERN Education, Communication, and Outreach Group, as well as from each of the LHC experiment collaborations (Alice, Atlas, CMS, and LHCb). Projections extending to 2025 were determined by extrapolating the figures with a consistent annual increment, based on trends observed in prior years. It was assumed that there was an 80% overlap between visitors to the LHC experimental facilities and the permanent exhibitions at CERN, namely Microcosm and Universe of Particles located within the Globe of Science and Innovation. Consequently, only 80% of the total visitor count to CERN was attributed to the LHC/LHC program.

To estimate the benefits, the study employed the travel cost method. Visitors were categorized into three source zones, each representing increasing distances from CERN. Average travel costs for each zone were computed using cost benchmarks derived from seven source cities, considering a combination of transportation modes and length of stay. The economic value of the time spent by travelers was drawn from HEATCO guidelines for each CERN member country, as well as some non-member countries.

Our research distinguishes itself from prior studies by relying on empirical data related to visitor expenditures on travel, on-site visits, accommodations, and local spending. The travel cost method was used to provide a more practical estimate of visitor spending within the region, offering deeper insights into the additional amount visitors would be willing to invest during their visit.

3.2 Methodology

The travel cost method of economic evaluation was formulated by [24] and is a demand theory-based preference disclosure method. The purpose of this method is to relate the characteristics of the cultural resource to the concept of "Willingness to Pay" (WTP) for recreational activities. In this way, it postulates that the existing demand for a place and the WTP for traveling to that place are related. Previous economic evaluations of heritage sites by [25–28] have demonstrated the reliability of this method in assessing the economic impact of visitors and their impact on the region in which the heritage site is located.

In the study, the travel cost (TC) was determined by the survey. In this way, it was possible to determine the total expenditure of the visitors and, based on the theory of marginal utility, to measure economically the benefit of the visitors through the "Consumer Surplus" (CS) using the "Individual Travel Cost Method" (ITCM). CS [27] is the result of the difference between what a consumer pays for a good or service and what the consumer would be willing to pay for it and provides a value that can be considered the visitor's net benefit. This value increases the visitor's initial TC, which is considered the net benefit of the visitor's travel experience. In the case of CERN, consumer surplus shows the additional benefit of visitors reaching the organization's facilities.

The first part of the study analyzes the expenses accrued by visitors throughout their journey, including both; during the trip and in the pre-trip phase, referred to as the methodology for calculating travel expenses (TC). Responses were obtained from a questionnaire administered to visitors between June 2018 and May 2019, comparing seasonal dependencies of spending. Results were acquired by analyzing responses from 900 valid form-based inquiry responses. The visitors reported their actual spending on visiting CERN before and during their trip. The questionnaire asked clearly if the motivation for the trip CERN was or if CERN was a visit carried out during the trip without being the primary motivation for the travel. The questionnaire was anonymous and asked only about age group and country of origin. The averages per person in that group were recorded for a questionnaire handed to an entire group.

Then, two types of scenarios were distinguished. The first scenario includes visitors who come to CERN because it is the purpose of the trip and who have registered for a free visit and are included in the category of registered visitors. The second scenario concerns visitors to the region without having CERN as the primary goal and who have not registered for a particular topical type of visit. These latter visitors were included in the category of unregistered visitors.

The total annual visitor counts in scenario 1 is documented and was supplied by the CERN visitor service. In our survey, we acquired a subset of the overall expenditures made by visitors from specific countries. Regrettably, it was not feasible to gather data on all visitors, let alone obtain a sample representing the entire expenditure by country. Consequently, we had to extrapolate the survey results to encompass countries for which information was unavailable. For these countries, the total trip expenditure was assigned based on the nearest country with available survey records. For scenario 2, the total annual number of unregistered visitors is not known. Each survey was analyzed but no extrapolation to other countries was made. Therefore, this study presents a largely underestimated result for this scenario based on the available survey form responses. The averages of the various individual visitor expenditures (e.g., entrance fees, hotels, souvenirs) were calculated from the factual information provided by the visitors.

The final TC computation has been estimated as follows.

First, the average values of each expenditure reported in the survey responses were calculated. For daily food and transportation, the actual prices for the meals and the public transport tickets were considered. Daily transportation costs were reported as zero in many responses because hotels provide free transportation to visitors. Then, the following formula was applied to obtain the travel cost for the visit per survey response, based on the average values for each category:

$$E_{euro} = \left(Days * Food_{daily}\right) + \left(Days * Transport_{daily}\right) + Accommodation + Tickets + Visit_{museum,exhibition,etc.} + Souvenirs \quad (1)$$

where:

- E_{euro} = Estimated total travel cost in euros.
- Days = Total number of days visitors use on their trip.
- $Food_{daily}$ = Daily food and drinks expenditure.
- $Transport_{daily}$ = Daily transportation spending in the region.
- Accommodation = Total accommodation expenditure during the trip.
- Tickets = Total travel expenses; e.g., tickets, gasoline, toll, etc.
- $Visit_{museum, exhibition, etc.}$ = Total expenditure on visiting other cultural or leisure activities.
- Souvenirs = Total spending on souvenirs during the trip.

Visitors declared that they honestly indicate their spending since the analysis will be included in CERN's future planning for visit services and will therefore have an influence on the evolution of the organization. The expenses declared by the visitors in Swiss francs (CHF) were converted to Euros (EUR) using an exchange rate of 1 CHF = 0.87 EUR.

Then, statistical analysis was performed to estimate consumer surplus (CS) by applying the methodology by Torres-Ortega et al. [27]. The individual travel cost method states that the number of times a person visits a place is inversely related to the total expenditure of that visit. Thus, a demand function can be estimated for the place or location visited. In this case, the demand would be the visitors (Vi) and the price of the product would be the cost of the trip (TCi), giving rise to the following expression:

$$V_i = f(TC_i) + \varepsilon_i \quad (2)$$

where:

V_i = Number of visitors.

TC_i = Total cost of the travel to the site per visitor including travel expenses, meals, accommodation, transport in the region, and entrance fees to exhibitions and souvenirs.

ε_i = Error term.

To estimate the parameters of the function, the above equation is transformed into:

$$Log\ V_i = \beta_0 + \beta_{TC}\, TC_i \quad (3)$$

Having estimated the relevant parameters, and assuming that the coefficient of the variable TC is statistically significant, the CS can be determined as follows:

$$CS = -1/\beta_{TC} \quad (4)$$

The 95% confidence interval can be calculated as follows:

$$CS_{L,U} = -1/(\beta_{TC} \pm 1.96 * (\mathrm{SE}\, \beta_{TC})) \quad (5)$$

4 Study Findings

The results of the study by scenario are reported below.

4.1 Travel Cost of the Registered Visitor Scenario

In this scenario, we assume that individuals who enroll for guided tours at CERN primarily travel to the area for this specific purpose. Consequently, the TC is fully considered. The methodology for determining the economic benefit in the region is applied individually to each visitor's country of origin, using data from the CERN visit service database, which records visitor numbers and their respective countries of origin.

It's important to note that the average TC of visitors is only available for a subset of countries, as the survey covered visitors from only a fraction of nations. To estimate the TC for visitors from the missing countries, we extrapolated the average TC from adjacent countries with available data and multiplied it by the known number of visitors from the respective country. This extrapolation adhered to the parameters employed in the prior study conducted by [14].

We calculated the country-specific TC averages based on the collected responses, considering the variations across different countries. Subsequently, these values were extrapolated to countries where data was unavailable (Table 1).

Table 1 TC by onsite CERN visitors, registered visitor scenario

TC by onsite CERN visitors, registered visitor scenario	
June 1–September 31, 2018	12,657,632.83 €
October 1, 2018–May 31, 2019	33,155,289.94 €
Total	45,812,922.77 €

Table 2 TC by onsite CERN visitors, unregistered visitor scenario

TC by onsite CERN visitors, unregistered visitor scenario	
June 1–September 31, 2018	209,006.97 €
October 1, 2018–May 31, 2019	204,324.81 €
Total	413,331.78 €

These results suggest that, on average, spending is higher in the autumn to spring season owing to the number of visitors being greater in this period, as a large portion of the visitor groups come from high schools and the visits take place during the school year.

4.2 Travel Cost for the Unregistered Visitor Scenario

In this case, the computation of potential benefits closely followed the methodology used in scenario 1. However, a key difference is that the expenditures were underestimated. This underestimation is attributed to the absence of a comprehensive visitor registry, which necessitated reliance on the sample obtained from the survey (Table 2).

The overall estimated Travel Cost (TC) incurred by visitors to CERN for an entire year, amounts to approximately 46.5 million euros. It's essential to note that these findings are exceedingly conservative. This is mainly because the responses gathered in scenario 2 (the unregistered visitor scenario) did not enable us to extrapolate the data to encompass the entire population of visitors within this group. Additionally, the extrapolations executed in scenario 1 (the registered visitor scenario) are also notably underestimated.

4.3 Consumer Surplus Analysis

To acquire useful values for the parameters of the impact estimation function, many possible combinations of the same function were tested. Visitor values were first differentiated by country. This made it very difficult to obtain an optimal static model, so it was decided to group visitors by periods of the year, in the case of the registered visitor's scenario.

The estimated statistical model is:

$$Log\ V_i = \beta_0 + \beta_{TC}\, TC_i \tag{6}$$

The estimation of CS distinguished visitors in the two scenarios described above.

4.3.1 Consumer Surplus for the Registered Visitor Scenario

The survey revealed the TC per visitor for a sample of countries. In this case, the number of visitors per country is known, and by determining the average TC sample of representative countries, it was possible to extrapolate this travel expenditure to all registered visitors per country. Since the sample of registered visitors is sufficiently large, it has been decided to separate it into the two seasons of the year: summer and winter. The results obtained in this scenario are shown in Tables 3 and 4.

The following result has been obtained by applying the equation to determine the Consumer Surplus.

$$\text{Consumer Surplus (CS)} = -1/\beta_{TC} = 0.80\,€$$

The 95% confidence interval can be calculated as follows and has the following results.

$$CS_{L,U} = -1/(\beta_{TC} \pm 1.96 * (\text{SE}\,\beta_{TC})) \tag{7}$$

The confidence interval obtained shows that CS can range from 0.40 to 30 €. The total annual CS for the 21,154 observations, is 16,802.2 €, with a 95% confidence interval from 8514.1 to 633,126 €.

As with the TC of the visit, in this case, a very conservative value was obtained, since only a rough estimate of visitor spending could be made.

The following result has been obtained by applying the equation to determine the Consumer Surplus.

$$\text{Consumer Surplus (CS)} = -1/\beta_{TC} = 0.62\,€$$

Table 3 Consumer surplus coefficients onsite CERN visitors, registered visitor summer scenario

Variable	Coefficient	Standard error
Constant	12.5171**	4.1195
Travel cost (TC)	− 1.2590*	0.6253
Number of observations	21,154	

Significative codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 4 Consumer surplus coefficients onsite CERN visitors, registered visitor winter scenario

Variable	Coefficient	Standard error
Constant	14.7034**	4.7093
Travel cost (TC)	− 1.6100*	0.7213
Number of observations	61,652	

Significative codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 5 Consumer surplus coefficients onsite CERN visitors, unregistered visitor scenario

Variable	Coefficient	Standard error
Constant	5.87873***	0.38062
Travel cost (TC)	− 0.10278	0.05817
Number of observations	494	

Significative codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

The 95% confidence interval can be calculated as follows and has the following results.

$$CS_{L,U} = -1/(\beta_{TC} \pm 1.96 * (\mathrm{SE}\,\beta_{TC})) \tag{8}$$

The confidence interval obtained shows that CS ranges between 0.33 and 5.1 €. The total annual CS for the 61,652 visitors, is 38,293.2 €, with a 95% confidence interval from 20,389.3 to 314,147.1 €.

4.3.2 Consumer Surplus for the Unregistered Visitor Scenario

The model analyzed, in this case, yields the results shown in Table 5.

As expected, the impact of the Travel Cost estimate is negative and significant ($p < 0.05$). It can be confirmed that as the cost of travel increases, the number of visitors decreases. Applying the equation to determine the Consumer Surplus, the following result was obtained.

$$\text{Consumer Surplus (CS)} = -1/\beta_{\mathrm{TC}} = 9.73\,€$$

The 95% confidence interval can be calculated as follows and has the following results.

$$CS_{L,U} = -1/(\beta_{TC} \pm 1.96 * (\mathrm{SE}\,\beta_{TC})) \tag{9}$$

The confidence interval obtained indicates that the consumer surplus can range from 4.61 to 9.84 €. The total annual consumer surplus for 494 observations is 4806.4 € with a 95% confidence interval of 2278.7–4862.71 €.

The result of the TC is € 46 million, increased by 59,901.8 € owing to the ex-post analysis of the consumer surplus, which measures the increase in the original visitors' TC because of the experiences they have and the knowledge they acquire during their visit to CERN.

5 Conclusions

Many researchers and institutions have demonstrated the great economic and societal impact of CERN, but it is worthwhile to examine and document the return on taxpayers' contributions to this research infrastructure. The survey conducted in this study has made it possible to estimate the TC and determine the benefit to these visitors of the knowledge acquisition they experience during their visit.

The quantification of the TC of onsite visits was determined using a questionnaire-based approach to reveal the average expenditures that visitors make during their visit. The resulting TC value was about 46 million € for the period from the beginning of June 2018 to the end of May 2019, which is equivalent to 552 € per visitor. From this data, a regression analysis was performed to determine the consumer surplus of these visitors, estimating a monetary value equivalent for the knowledge experience all visitors gain from their visit at a total of 59,901.8 €, on average at least 0.72 € over the cost of the trip.

The value of the consumer surplus has been used to conservatively measure the willingness of visitors to pay for the experience of visiting CERN and learning from the daily research of the staff.

This study has shown to our best knowledge for the first time, a robust estimate of the benefit to visitors of traveling to and experiencing CERN. Although a single in-depth study has been conducted, in the future the small deficiencies in developing the estimate should be corrected concerning the quality of the available visitor data by planning and carrying out long-term systematic monitoring with a continuous visitor survey. The organization has a record of visitors who are registered to visit CERN, whether it is for experiments or the official visit, but not of individual visitors who have not registered and simply come to the organization to enjoy it like a museum. A long-term data set of the spending is also missing. This makes it difficult to draw general and robust conclusions. This situation could be mitigated by introducing a registration and questionnaire system for each visitor to CERN so that a full accounting of all visitors to CERN can be made for statistical analysis purposes.

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The Regional Impact of Single-Site and Distributed Research Infrastructures Using the Example of DORIS and CTAO

Stephan Haid

Abstract Large-scale research facilities can take a number of forms including distributed research infrastructures, a network of distributed instruments that are geographically scattered, and single-sited research infrastructures but also virtual research infrastructures.

1 Introduction

Large-scale research facilities can take a number of forms including distributed research infrastructures, a network of distributed instruments that are geographically scattered, and single-sited research infrastructures but also virtual research infrastructures.

This article addresses two very different research infrastructures. The first and major part of the article is an ex-post evaluation of the single-sited DORIS storage ring located at DESY in Hamburg. This case very impressively demonstrated how a major research infrastructure could be successfully adapted to meet the developing requirements in science, thus providing research opportunities and long-term sustainability to scientific communities over many decades. The described ex-post evaluation of this unique research infrastructure (see Sect. 2 "Ex-post Evaluation of the Socio-economic Impact of DORIS") is a condensed reproduction of the article "The socio-economic impact of DORIS" by Lehner and Haid [1].

The third section (see Sect. 3 "Ex-ante Consideration of the Socio-Economic Impact of CTAO") of the article discusses the societal impact of the Cherenkov Telescope Array Observatory (CTAO), the first ground-based gamma-ray observatory with two telescope arrays on two different remote sites located in the Northern hemisphere on La Palma and in the southern hemisphere in the Atacama Desert in Chile.

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Moreover, the headquarters of the CTAO are located in Italy in Bologna, and the Science Data Management Centre (SDMC) in Zeuthen, Germany.

2 Ex-post Evaluation of the Socio-economic Impact of DORIS

The 'Doppel-Ring Speicheranlage' DORIS at DESY in Hamburg [2] was built as a multi-GeV storage ring more than 50 years ago as the first of its kind. During its entire lifetime between 1974 and 2013 it has generated a tremendous variety of scientific findings and applications in the fields of particle physics, accelerator science and technology, photon science and in the life sciences. Generations of researchers have used DORIS to generate new knowledge and to pioneer, develop and test innovative experimental methods, instrumentation and related technologies that have subsequently been applied at other research laboratories all over the world and in industry. Hundreds of doctoral students and postdoctoral researchers earned their first merits at DORIS. Countless scientific cooperation was forged between national, international, and often interdisciplinary, teams to carry out joint experiments in Hamburg and many of these connections still exist today and have since then been firmly strengthened on institutional grounds building the core of the multidisciplinary science and innovation campus around DESY in Hamburg-Bahrenfeld.

The nearly 40 years of operation of DORIS represent a unique opportunity for a lifetime analysis of a multidisciplinary facility impacting various scientific and technological fields, promoting the building new scientific communities and creating strong networks that still exist today. In the following, an attempt will be made to highlight some of DORIS relevant impacts and illustrate its effects on the development of the science campus in Hamburg-Bahrenfeld.

a. The storage DORIS at DESY

During the entire lifetime of DORIS between 1974 and 2013 it went through three distinct phases [3]. During its first phase as a new type of accelerator known as a storage ring with colliding electron and positron beams designed, the experiments at DORIS produced most important findings to establish Standard Model of particle physics which was still new at that time.

The use of synchrotron radiation (SR), which was originally seen as a byproduct of the accelerator's operation opened up a plethora of new scientific opportunities at DORIS with truly impressive applications in physics, materials/nano sciences, geoscience, chemistry and with profound impact in biology/life sciences.

In a second phase of DORIS (DORIS II) a new lab, the so-called Hamburg Synchrotron Radiation Laboratory HASYLAB was opened in 1981 with the goal to meet the increasing demand and to better organize SR-related research at DORIS. Soon, it became an internationally renowned facility and one of the incubators of modern and successful research with SR worldwide. In this period, particle physicists and HASYLAB researchers shared the same storage ring in the 1980s.

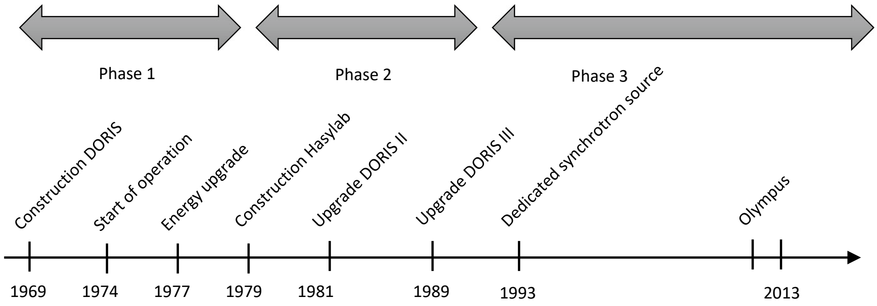

Fig. 1 The scientific life of DORIS in three distinct phases. *Credits* S. Haid

By the end of 1980s a further upgrade to the facility was proposed in order to accommodate the increasing demand for SR users and to stay competitive with other international facilities. In this third phase of DORIS one of the two straight sections was replaced with a curved section that would be fitted with integrated special magnets known as wigglers and undulators. This enabled the number of measuring stations to be increased and also improved the quality and intensity of the X-ray beams considerably. In 1993, almost 20 years after the first beams in DORIS, particle physics stopped and the ring became a dedicated SR facility (Fig. 1).

Research infrastructures such as DORIS were built and operated with a primary scientific mission and with the goal to contribute to the national and international stock of knowledge and to its dissemination and diffusion into other areas. It is well beyond the scope of this paper to record the scientific impact that materialized over the 40 years of the lifetime of DORIS. Instead, the other dimensions of socio-economic benefits of research infrastructures in context of people, economy and region will be addressed in the following.

b. Impact on people

Research facilities in basic science such as DORIS are not only promoting scientific knowledge and stimulating economic growth, but also strongly influencing the people working there and enhancing their capacities. During the service of DORIS (1974–2013), several thousands of people developed, maintained and scientifically exploited the facility. Next to administrative, technical and scientific staff of DESY, these included external users from a wide range of disciplines.

To visualise the career paths of doctoral degree recipients who worked at DORIS and to analyse the acquirement and transfer of skills into other sectors of employment, a survey among all known former DORIS graduate students was conducted by DESY. These included Ph.D. students employed by DESY, EMBL and several universities in Germany and abroad. The idea of the study (carried out in 2015) was to serve as an explicit proxy to track the transfer and utilisation of skills and knowledge created at DORIS in all fields of employment and all sectors of the economy.

In the following, some of the main findings of the survey are summarized:

- The training at large research infrastructures like DORIS enables students to follow careers also outside of public science and research. Even in their first job after the Ph.D., 22% started a career in the private sector. 10% of the students became entrepreneurs, of which 67% had employees.
- Regarding the Ph.D. students in the private sector, the data show major accumulations in the sectors information technology (IT) and healthcare, which will both gain increasing importance in the future due to the megatrends related to the technological and demographic change of society.
- To all appearances, the Ph.D. students did not only gain specific scientific skills and knowledge related to their research area, but also non-specific knowledge and soft skills that are even more valuable for the private sector. Among the five most important skills that the former students acquired during their Ph.D. work, only one refers to science (research methodologies/techniques). Instead, problem solving, team working, creative thinking and independent working were considered the most useful for their subsequent careers.
- Working at the research facility laid the foundations for successful professional careers of the students within or outside the commercial world. Only five years after graduation, more than half of the former DORIS Ph.D. students were responsible for their own budget (55%) and 45% led their own staff. In the long run (current position), 71% managed a budget and 69% had personal staff, clearly indicating an executive position.

Although fundamental science sometimes seems to be vague and hardly application-oriented, the skills that people gain are all the more applied—they solve concrete problems. Besides being trained in scientific methods and techniques, the Ph.D. students at DORIS (and the same most certainly applies to other large-scale research facilities) learn how to manage projects and find creative and innovative solutions in international and interdisciplinary teams (Fig. 2).

c. Impact on the economy

The economic effects of research facilities are manifold. Here we distinguish between direct and indirect economic added value and the effect of research infrastructures on economic innovation.

The construction and development of DORIS demanded major financial investments which generated economic impacts mainly to the metropolitan area of Hamburg and northern Germany, but also beyond. A reasonable method to elaborate these effects is a multi-stage, regionalized input–output-analysis [4], in which financial effects are decomposed into regional and sectoral effects. Essentially one would like to understand the economic "chain reaction" of investments considering that money is re-spent again and again in the economy, creating jobs and income for businesses and other workers.

There are three different aspects of the financial impact to be considered: at first the primary input triggers the so-called direct effects. They include on the one hand revenues of the direct suppliers (direct sales effects) and on the other hand the jobs that were directly generated at the facility (direct employment effects). Secondly,

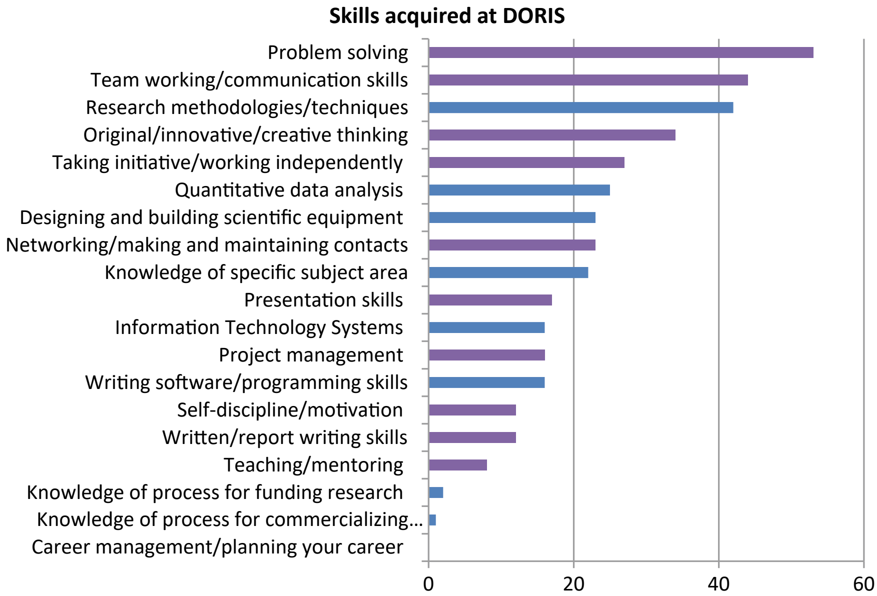

Fig. 2 Result of a survey of former Ph.D. students at DORIS on the rank of the skills acquired during their Ph.D. work that are seen useful for their current job. The horizontal axis is given in % of the respondents. Purple coloured bars indicate soft skills, blue coloured bars indicate knowledge-based skills. *Credits* S. Haid

indirect effects are generated: Since every supplier and subcontractor obtains certain inputs from other companies, there is an economic effect in the supply chain of every direct supplier. Furthermore, the induced effects capture the money flows, which are created by salaries, both directly at the facility and at other companies involved in the value chain. The induced effects can be put on a level with consumer spending of all employees, which are affected directly or indirectly by the facility's spending.

Even though the results of such analysis have to be taken with care—given a scarce data basis of 40 years of investments—it gives an impression of the benefits of the investment in DORIS for the region and which economic sectors profited most.

It is estimated that the overall DORIS investments throughout its 40 years of lifetime summed up to approximately 1.4 billion Euro (inflation-adjusted) including costs for (re)construction and operations. This number was derived by taking as an educated guess an appropriate fraction of the overall budget of DESY during the different phases of the lifetime of DORIS. However, third-party funding, especially from Universities invested in DORIS could be only partially tracked. The spending of the guest scientists is subject to assumptions as well: an approximation was done based on the number of scientists per year and a fixed amount of spending.

From the input–output-analysis we receive an indirect multiplier of 1.83 and an induced multiplier of 1.90. This means that one Euro spent on DORIS produces 0.83

€ sales volume through indirect effects and additionally 0.90 € through induced effects. The following box summarizes the short-term economic impact of DORIS:

Box 1
Short Term Economic Impact of DORIS

- Total budget spent (over DORIS life time): 1.4 bn €
- Direct Sales Effects: 700 M €
- Indirect Sales Effects: 590 M €
- Induced Sales Effects: 1.2 bn €
- Indirect (induced) Multiplier: 1.83 (1.9)
- Additional Jobs created in Germany: 12,500 FTE; which equals 300 FTE per year
- Effects in Hamburg: 200 direct jobs per year at DESY plus 450 Million Euro triggering about 1000 FTEs (= 25 FTE per year).

Even though the knowledge of these demand effects can help to gain political support, basic research is not and should not be regarded as a "business cycle" program to boost employment. The demand effects are socio-economic "side effects". The following effects on economic innovation reflect more the nature of research infrastructures like DORIS.

A large impact has been undoubtedly achieved through all those advancements in computer and network technology, and in electrical engineering, vacuum technology, radiology, and several other fields that have followed in the wake of the pushing of technical and scientific limits in accelerator and detector construction at DESY and other particle physics labs globally. Similarly, the collected global effort in advancing technologies and research in the area of synchrotron radiation has also led to advances that have had direct benefits in the development of more efficient batteries, LCD displays, and data storage devices in consumer electronics, enhanced and completely novel drug treatments, as well as software development, to name just a few.

d. Impact on the region

The regional impact of a research infrastructure is manifold. As described in the previous chapters, large scientific facilities and research labs have characteristic imprints on the regions which are hosting these facilities in terms of scientific output, higher education services, economic innovation, but also in terms of regional collaboration and networks. Moreover, research infrastructures often represent path-shaping investments and carry an institutional resilience that means continued and repeated investments in similar projects locally.

DORIS is a prime example for such structural socio-economic effects in the Hamburg metropolitan region. Already during or after the times of DORIS many other, and even larger science investments accompanied by the co-locations and aggregation of cooperating partner institutions and by auxiliary infrastructures followed—and all of them have made their own specific contributions to the local, regional, national and international economy.

- Research Infrastructures: Many experimental methods and technologies that were pioneered at DORIS have now become standards and led the way to further infrastructure investments. The continued improvements and the innovative atmosphere together with a remarkable collaborative spirit led later to the construction and operation of unique photon science infrastructures on the campus such as PETRA III, one of the most brilliant X-ray source in the world, and FLASH, the world's first free-electron laser in the X-ray range, and lastly the European XFEL as an international flagship facility for FEL science in the hard X-ray regime.
- Aggregation of Research Institutions: Already in 1975, EMBL established an outstation on the DESY campus to use the intense light for the investigation of biomolecules. In 1986, the MPG added another outstation at DORIS for three research group units followed by other external research organisations. The University of Hamburg has strongly increased the presence of its research institutions and interdisciplinary research centers on site and decided recently to also move the complete chemistry institutions to the campus.
- Interdisciplinary Centers: The concentration of world-leading research infrastructures and competences to decode the structure and dynamics of matter led to the establishment of further scientific and multidisciplinary institutions as collaborating platforms such as the Center for Free-Electron Laser Science (CFEL), the Centre for Structural Systems Biology (CSSB) and the Center for X-ray and Nano Science (CXNS).
- Innovation: Even if DORIS was not a major driver of innovation and transfer it is seen as a starting point for a further dynamic development with the recently opened start-up lab Bahrenfeld as a new place for hi-tech and science entrepreneurship and start-ups from the physical and bio sciences.

DORIS as a pioneering facility opened the way to the formation of new competence clusters on the campus, mainly in nano, bio, laser and engineering materials. This marked also the transition of the campus from a previously monodisciplinary site, into a science and innovation ecosystem with a rich and versatile multi-disciplinary landscape characterized by world leading research infrastructures, co-location of renowned research institutes and a stimulating innovation environment from which the Hamburg Metropolitan area greatly benefits today.

The development continues by the establishment of the so-called Science City Hamburg-Bahrenfeld, presently the largest and most ambitious future urban planning project of the City of Hamburg for the coming decades.

3 Ex-ante Consideration of the Socio-economic Impact of CTAO

While the societal benefits of DORIS—a single sited research facility in operation over a lifetime of more than 40 years—were discussed in the previous chapter, CTAO a facility in preparation and construction at four different sites will now be considered.

The Cherenkov Telescope Array Observatory (CTAO) will be the first ground-based gamma-ray observatory and the world's largest and most sensitive instrument for the detection of high-energy radiation. It will seek to address questions in and beyond astrophysics falling under three major themes: understanding the origin and role of relativistic cosmic particles; probing extreme environments; and exploring frontiers in physics. To achieve these goals, the CTAO is building two telescope arrays on two different sites: CTAO-North is located in the northern hemisphere at the Instituto de Astrofísica de Canarias' (IAC's) Roque de los Muchachos Observatory on La Palma (Spain), and CTAO-South is in the southern hemisphere near the European Southern Observatory's Paranal Observatory in the Atacama Desert (Chile). Moreover, the headquarters of the CTAO is hosted by Italy at the Instituto Nazionale di Astrofisica (INAF) in Bologna, and the Science Data Management Centre (SDMC).

Building on the concept of the broad societal benefits of research infrastructures, as demonstrated by the example of DORIS, the expected socio-economic impact of CTAO is outlined below along four dimensions: Science, Business, Region and Public (Fig. 3).

Science

CTAO addresses science questions across disciplines: not only in astrophysics but also in cosmology and particle physics, and in connection to environmental sciences—relevant, since the Earth's atmosphere is an integral part of the 'detector' and light pollution, and atmospheric conditions impact the quality of detection. CTAO is expected to revolutionize astronomy at the highest energies of the spectrum, regarding

- the understanding of cosmic particle accelerators and the impact of the high-energy particles on their environment and on cosmic evolution;
- the understanding of extreme environments in the Cosmos, such as the vicinity of neutron stars and black holes, but also of the radiation fields and magnetic fields permeating the giant cosmic voids;
- and the understanding of how the Universe behaves at the most basic level (fundamental physics), such as the nature of dark matter, the existence of axion-like particle and deviations from Einstein's theory of special relativity.

The CTAO will be constructed and operated to serve the needs of a broad scientific community where individual parties share their knowledge and capacities to enable scientific research that is impossible without such a research consortium. Currently

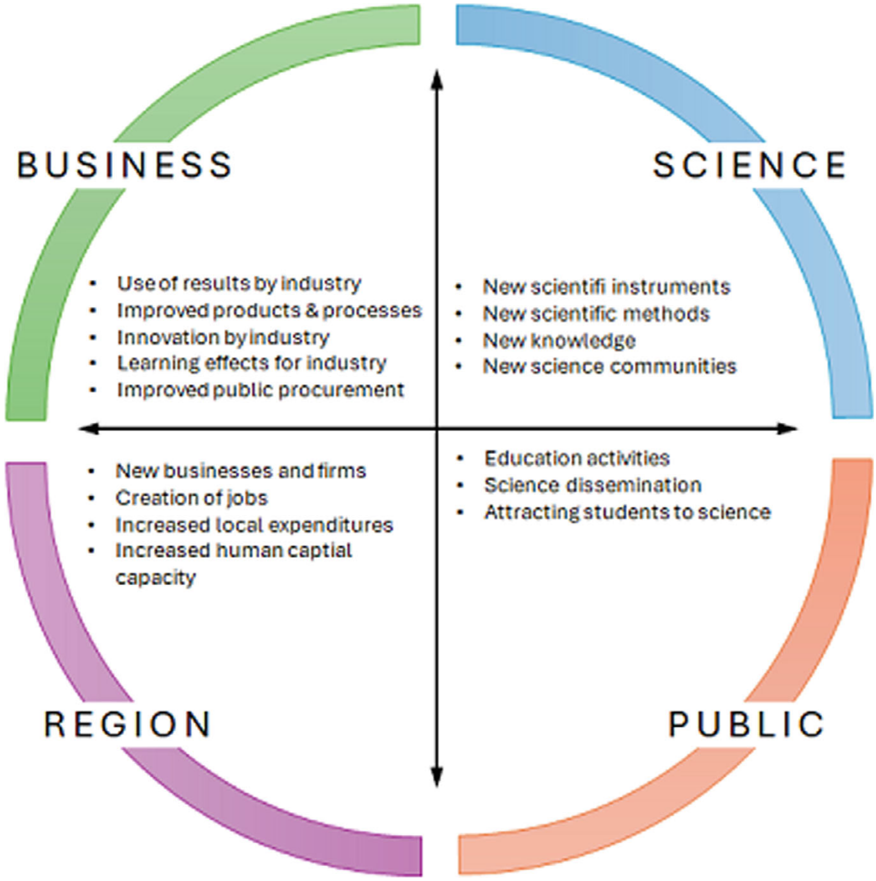

Fig. 3 Illustration of the socio-economic impact dimensions of CTAO. *Credits* S. Haid

about 1500 members from more than 150 institutes in 25 countries are organized within the CTA consortium (CTAC).

Business

The CTAO Construction Project contributes to raising the technological level of European industry and Small and Medium Enterprises, thus improving the competitive position through their involvement in RI development and service provision.

It includes in its design a range of technical innovations, many of which are being developed in cooperation with SMEs as part of the Preparatory Phase, and relying on the SMEs for production of instrument components.

Region

Large-scale scientific installations intrinsically shape the region where they are located and as such, they are important not only as contributors to competitiveness, but also promote the engagement between science and society.

The most important asset for a RI is, arguably, its human capital. This includes its own staff that builds and operates the facility together with the In-kind contribution (IKC) teams from partner institutions as well as the user community who exploits it for research. CTAO will play an important role in capacity building. Young researchers and technical personnel will be trained at this research instrument and gain knowledge that goes beyond scientific methods and techniques. Above all, they will learn how to work in international and interdisciplinary teams on innovative solutions for complex questions. Most likely, the development of this enormous work force of skilled people for the industry will be the largest economic impact that CTAO will on its four different sites.

Public

Research Infrastructures also have a tremendous impact on skills and education agendas irrespective of their size. Through their outreach to students, the general public and other key stakeholders, they steadily improve the perception and understanding of science and technology in society at large. It is the goal of the CTAO to enhance the attractiveness of the research profession at earlier education stages (high school) and to guarantee high-impact quality education in undergraduate students, with the aim of helping prepare potential future workers and science users of the Observatory.

It will also reinforce the partnership between the European Commission, member states and associate countries in establishing a pan-European Research Infrastructure. It includes a wide range of stakeholders from the Americas, Africa, Asia and Australia, promoting world-wide cooperation, linking the worldwide science community and representing a global research infrastructure.

4 Conclusion

The case study of DORIS very impressively demonstrates that a major scientific facility can be continuously adjusted and upgraded to meet the changing requirements in science. DORIS went through various phases and different scientific missions, showing that the facility and its related services was sustainably utilized over many decades. The facility has been a pioneer in several ways: in accelerator science and technology, in particle physics and, most prominently, in photon and life sciences. It paved the way towards modern colliders and 3rd generation SR machines and developed numerous methods and instrumentation that are now being used worldwide.

This transformation of the campus triggered by research at DORIS had and still has a significant impact on the regional development of the larger Hamburg metropolitan area. Not only that the demand effects of the major financial investments in the construction and operation of research infrastructures that followed DORIS such as PETRA III, FLASH and European XFEL generated a large economic impact, but also the multi-disciplinary research at DORIS was the origin of the formation of new competence clusters, the begin of an aggregation of research institutes and the start of the growth of an innovation ecosystem on campus.

Finally, DORIS played and CTAO already plays an important role in capacity building. Young researchers and technical personnel are trained at research instruments and gain knowledge that goes beyond scientific methods and techniques. Above all, they learn how to work in international and interdisciplinary teams on innovative solutions for complex questions.

During the analysis of the case of DORIS it has quickly become clear that the separation of one research infrastructure from the rest of the research center DESY and often from the whole environment of research organizations, universities and other research infrastructures is hardly possible. The impacts are often not only linked to one but to a variety of research infrastructures and instruments. It is the collaboration between these multiple actors around research infrastructures and the open access to these tools that generates their enormous added value for society.

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Social License to Operate—A Critical Success Factor in Realising Impact from Research Infrastructure

Adrian J. Tiplady

Abstract Since publication of Adam Smith's *Wealth of Nations* (1776), modern business has been structured on one objective alone: to increase profit for its shareholders. This shareholder model is recognised in the development of a range of strategic management practices and models, such as Norton and Kaplan's strategy maps. Equivalent models can be adopted for non-profit organisations and research infrastructures, where profit for shareholders is measured rather in terms of a value proposition being delivered to its shareholders.

1 Introduction

Since publication of Adam Smith's *Wealth of Nations* (1776), modern business has been structured on one objective alone: to increase profit for its shareholders. This shareholder model is recognised in the development of a range of strategic management practices and models, such as Norton and Kaplan's strategy maps.[1] Equivalent models can be adopted for non-profit organisations and research infrastructures, where profit for shareholders is measured rather in terms of a value proposition being delivered to its shareholders.

In its simplest version, the value proposition for research infrastructure may be 'scientific enablement'—provided through research infrastructure—that is delivered to the scientific community ('the shareholder'), which evaluates the value proposition from its own value system. This is, however, perhaps too simple and highlights a disconnect between the scientific community and the ultimate shareholder—the funding agency. In reality, the group of shareholders is diverse and complex, all expecting a different flavour of value proposition to be delivered through investment in research infrastructure. In particular, many funding groups—particularly those

[1] Kaplan and Norton [1].

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in the Global South—will see investment in research infrastructure as a vehicle for socio-economic impact. This, of course, is not limited to those in the Global South, although one could potentially argue that the need for tangible socio-economic impact on shorter timescales is a key consideration. The need for short-term tangible impact is more focused at a local level when research infrastructures are deployed in remote, socio-economically depressed rural environments. This is often the case of astronomical facilities, which seek out locations far from major economic activity and urban centres—a proxy for optical and radio interference.

The diversity in value proposition is being mimicked in the corporate sector. Increased global connectivity and access to information has empowered society to become an active citizenry. Recognition of the need to address broader societal issues, summarised in various national and international developmental objectives such as the Sustainable Developmental Goals,[2] has placed greater demand on companies to become corporate citizens—being economic actors whilst also contributing towards achievement of (inter)national developmental goals. The traditional shareholder model has evolved into a stakeholder model, and is already recognised in various modern reports on corporate governance.[3]

The 'stakeholder inclusive' approach has informed the implementation of South Africa's strategic investments in radio astronomy, implemented through the South African Radio Astronomy Observatory[4] (SARAO). These investments have not only been realised in the development of the next-generation MeerKAT radio telescope (see Fig. 1), a pre-cursor to the multi-national Square Kilometre Array (SKA) telescope, but also through the socio-economic impact that has been delivered across various sectors of society—both at local, and national, level. The approach is conceptualised as ensuring a 'social license to operate'.

2 Social License to Operate

Various texts describe the 'Social license to operate' as the level of acceptance by a local community and/or stakeholder of an organisation and its respective activities. In short—is an organisation seen as legitimate from the perspective of its stakeholders. The model for evaluation requires defining a clear value proposition for the investments, as well as defining the set of influential stakeholders and their respective value systems (i.e. how they value what is being delivered through the investments).

Maintaining and ensuring a social license to operate is seen as a critical success factor by SARAO for ensuring successful implementation and operation of radio astronomy research infrastructure platforms in South Africa. Failure to do so could

[2] https://sdgs.un.org/goals.

[3] King IV Report—Report on Corporate Governance for South Africa 2016, Institute of Directors in Southern Africa, ISBN 978-0-409-00436-6.

[4] The South African Radio Astronomy Observatory is a National Facility of the National Research Foundation.

Fig. 1 View of SARAO's MeerKAT radio telescope, a 64 antenna array located in the Karoo region of South Africa. *Credit* Sarel van der Merwe and Maryna Cotton

easily have resulted in the shutdown of any new facility, as was seen in the case of the Thirty Metre Telescope in Hawaii.[5]

A majority of the platforms implemented by SARAO, including the premier MeerKAT radio telescope, are located in the semi-arid Karoo region of South Africa. An area known for its agricultural economy (sheep farming), in more recent times the impact of climate change, and other factors, in the Karoo have led to many of the small rural towns in the area becoming economically depressed. The value system of this stakeholder is clear and immediate—requiring an acceleration of the efficiency and efficacy of the 'research infrastructure impact pathways'.

3 Impact Framework

An impact framework, shown in Fig. 1, has been adopted by SARAO to inform, and enable optimisation of socio-economic impact arising from South Africa's investments in radio astronomy. The first two pillars, 'Research Enterprise & Science Products' and 'Innovation & Industrial Spillover', are typically derived through the pursuit of SARAO's core mandate—the establishment of world-class research infrastructure to enable transformational science. The outcomes of this mission driven innovation are significant, in both quantitative and qualitative terms, from the national context. The rise in prominence of SARAO, and South Africa, as a global partner to radio astronomy over the last two decades is well known within the radio astronomy community. South Africa has seen significant improvement (in some cases, by orders of magnitude) in various scientometric parameters in the field of astronomy, including Relative Field Strength (RFS) and Mean Normalised Citation Score (MNCS). Similarly, the design and development of research infrastructure

[5] Witze [2].

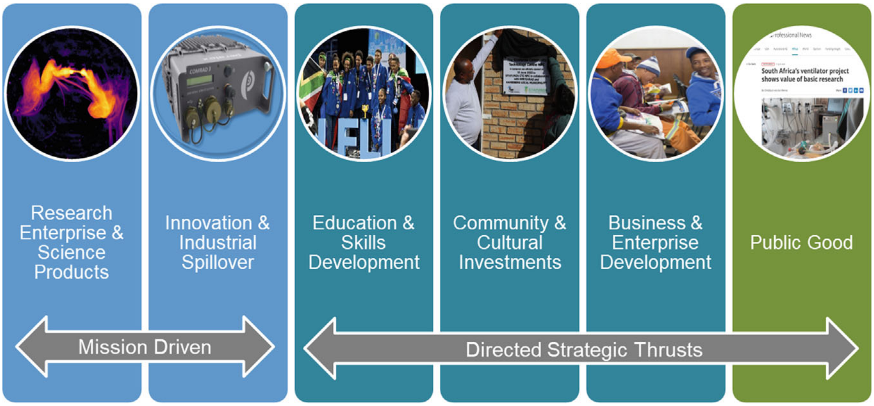

Fig. 2 Impact framework adopted by SARAO to inform and optimise impact from radio astronomy investments. *Credits* Adrian J. Tiplady

platforms such as MeerKAT has resulted in the development of unique methods and intellectual property that, once subjected to the internally managed innovation lifecycle, results in commercialisable products and services. A good example is development of the 'COMRAD Passive Radar System', a passive radar system with no active radar transmitting equipment. This equipment is currently deployed at the radio protected astronomy reserve in the Karoo, which hosts the MeerKAT and future SKA telescopes (Fig. 2).

The scope of impact is, of course, broader than the first two pillars—although, its perhaps the most noticeable from the perspective of the science community and funding agencies. Definition of the remaining pillars—'Education & Skills Development', 'Community & Cultural Investments', 'Business & Enterprise Development' and 'Public Good'—are informed by ongoing and periodic socio-economic and sentiment analysis to understand community needs and expectations. However, these pillars should be seen as opportunities for impact—delivery against these pillars do not automatically arise as a natural consequence of SARAO undertaking its core mandate. Instead, specific and directed strategic thrusts must be implemented in order to optimise realisation of these benefits. For example, implementation of targeted skills development programs for the local community to maximise scientific and technical participation in the research infrastructure by members of the local community. This is in turn results in increased community ownership and support, and ultimately contributes towards ensuring a social license to operate.

Whilst delivery against all pillars of the impact framework contribute towards ensuring a social license to operate, there is some regional discrimination with the first two likely being experienced at a national scale, whilst the latter three typically realised within the local communities—a key set of stakeholders for which securing a social license to operate is seen as a critical success factor for new research infrastructures. The final pillar, 'Public Good', has no specific regional discrimination. In the case of SARAO, a relevant example would be its coordination and implementation of the National Ventilator Project, South Africa's strategic response to the COVID-19 pandemic. This resulted in the design, development, production, certification and distribution of 20,000 ventilators for use on COVID patients in approximately eight months.

4 Realised Impact: SARAO Case Study

It is beyond the scope of this article to address the broader national socio-economic impact that has arisen from South Africa's radio astronomy investments. However, in a recent year long study undertaken specifically to evaluate the socio-economic impact arising from South Africa's investments in radio astronomy, the report makes the following two conclusions:

- "… *expenditure has had a significant positive impact on the South African economy, and is expected to continue once all construction is complete. These positive impacts have been critical in contributing to the developmental objectives of both the Northern Cape and South Africa.*"
- "… *the project has had a largely positive and significant impact on the national socio-economic conditions and scientific activity. Substantial contribution has been made towards education, skills development and employment opportunities in the country, as well as towards innovation, society and scientific activity.*"

Impact that has arisen from the three, community focused pillars, is summarised in the subsections that follows.

4.1 Education and Skills Development

Driven by two key objectives—to establish a sustainable and diverse research community, and to maximise participation of local communities in the science and engineering of the MeerKAT and SKA telescopes—a range of human capital development initiatives were implemented, some of which have been running for close to 15 years (SARAO Bursary Program) and been successful in awarding well over 1500 grants and bursaries for studies in astronomy and related engineering and technical disciplines. Support for the development of a sustainable research community even extends across Africa, whilst international partnerships have enabled the rollout of high impact skills development programs such as the Development of Africa through Radio Astronomy (DARA) and DARA BigData—a unique program focussing on the development of data intensive research skills.[6] The 2022 edition of the Data Science Intensive program attracted 2,268 applications from across Africa.

[6] DARA and DARA BigData is run in partnership with institutions in the United Kingdom.

At a community level, investment in schools and educational resources has resulted in the first intake of learners from local community schools to attend university to study for careers in maths and science. Investment in artisan training, with over 110 already trained, has enabled locals to access employment opportunities with SARAO to operate and maintain radio astronomy installations—well over 95% of SARAO employees in the Karoo are from the local community. Introduction of a robotics program by SARAO has made a significant impact, with teams from the local high school twice representing South Africa at international robotics Olympiads.

4.2 Community and Cultural Investments

Active participation and investment in community programs and social events legitimise the role of SARAO as a 'corporate' citizen. This has been realised through a range of interventions, which include: annual development granting program to fund community identified social development programs; science engagement and implementation of Astro-tourism programs; and investment in cultural preservation areas such as medicinal plant studies and support the 'Annual Riel Dance'.[7]

4.3 Business and Enterprise Development

Perhaps the most visible of areas within a socio-economically depressed environment, key strategic interventions are designed to implement a principle of 'lowering the barriers to economic opportunity' in the Karoo communities. A two-pronged strategy is adopted: development of local technical, business and entrepreneurial skills, and the appropriate structuring of procurement opportunities that enable local small, medium and micro- business enterprises to access, and be successful, in procurement opportunities during construction and long-term operations of radio astronomy facilities.

This strategy has realised significant increase in economic activity within the local communities, with major companies actively seeking to sub-contract to local business enterprise for delivery of a range of services. Specific support mechanisms have been put in place by SARAO to equip local business, whilst spinoff programs continue to drive entrepreneurship across the broader hospitality and tourism sector. This includes the implementation of an Astro-tourism strategy through the training of Astro-guides, and the MeerKAT Creative Crafts Initiative—meant to catalyse and support the local arts and crafts industry.

[7] The Riel dance, or *Rieldans*, is an indigenous celebratory dance of Khoisan origin.

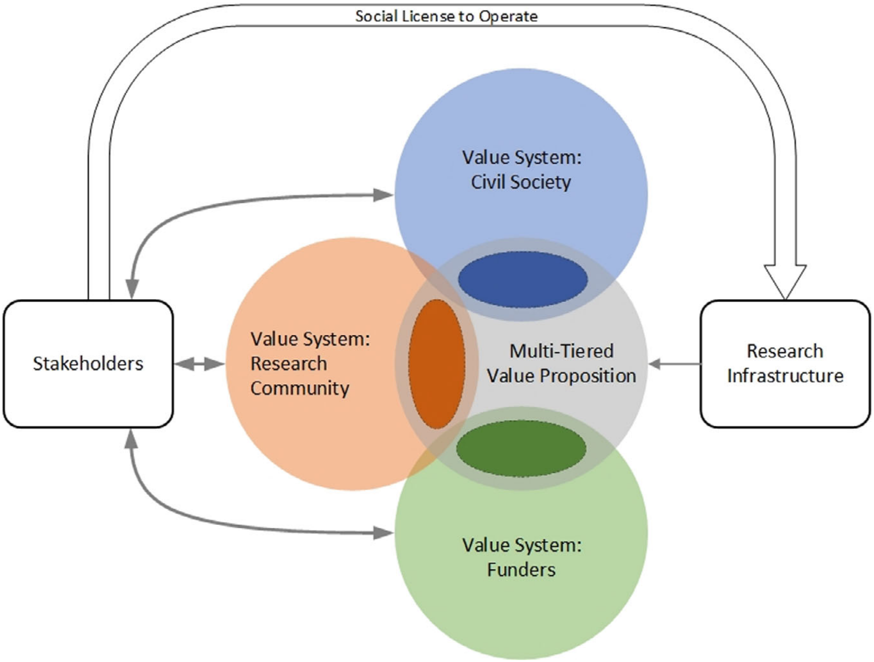

Fig. 3 Value system model for ensuring a 'social license to operate', which reflects the conceptualisation and delivery of a multi-tiered value proposition. The model is generalisable for a range of conceptual licenses, such as 'legal' or 'political' licenses to operate. *Credits* Adrian J. Tiplady

5 Discussion and Conclusion

Ensuring a social license to operate is seen as a critical success factor in the establishment of new research infrastructures, and is a natural evolution of the 'stakeholder inclusive' approach being adopted across the corporate world. Delivery of a social license to operate is dependent on establishing an impact framework that reflects the value systems of the suite of influential stakeholders that may be involved in a specific research infrastructure project. This approach is best achieved through a multi-tiered value system model, described in Fig. 3, which considers the delivery of a multi-tiered value proposition to identified stakeholders as key to delivery of a 'social license to operate'.[8]

By adopting this approach, SARAO has been able to plan for impact—specifically at a local and regional level, where communities are located in the vicinity of such facilities as the MeerKAT and future SKA radio telescopes.

[8] Whilst beyond the scope of this paper, it is worthwhile noting that the concept of a 'license to operate' can incorporate other conceptual licenses, such as 'legal license' or 'political license'. The model is therefore generalised to a broader 'license to operate'.

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Awareness and Attitudes Towards Science. The Case of CERN

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Abstract The chapter highlights the need for public understanding and support of scientific research, especially basic research with no immediate practical applications. It discusses the polarization in public attitudes towards science and emphasizes the importance of valuing curiosity-driven research for societal progress. An experiment conducted in 2022 involving CERN and the FCC project surveyed 8,443 responses from adult laypersons outside the scientific community, expanding on previous surveys in France and Switzerland. Key findings indicate public awareness and generally positive attitudes towards CERN and particle physics research. The public's attitudes vary according to respondents' socioeconomic traits.

Keywords Public support of science · Stated preferences · Citizens' attitudes towards basic research

1 Introduction

Scientific research potentially generates innovations that offer solutions to pressing societal issues [5, 7], thereby ultimately enhancing the quality of life for individuals [2, 3]. The process takes time, is uncertain, and often difficult to understand by citizens.

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Hostile attitudes toward scientific research and the public funding that supports it are reported in the media, especially when the outcomes of research are not immediately tangible by lay-people, such as large-scale investments in basic research without immediate practical application [10].

Indeed, while large-scale scientific projects continue to be on the roadmap of international and national agencies through government funding,[1] hence ultimately by taxpayers, the debate on public engagement with science is still ongoing. Public's attitudes towards science increasingly polarise among people who trust science unconditionally, and others who routinely reject and dismiss scientific evidence [11, 13].

For these reasons, we submit that research institutions need to systematically understand the extent of the citizens' support of their activities. Are citizens outside the scientific community aware of the potential socioeconomic benefits that basic research could generate? According to Flexner [4] society can tackle societal challenges, achieve deeper understanding, and pursue progress only by really valuing and funding the curiosity-driven "pursuit of useless knowledge" in both the sciences and the humanities.

This chapter describes an experiment of public engagement in science conducted to understand better on how laypeople perceive and value investments in infrastructures for fundamental scientific research together with CERN in the frame of the European Commission H2020 co-funded FCCIS project.[2] Specifically, together with the estimation of the socioeconomic benefits directly associated with the Future Circular Collider (FCC) project, in 2022 [1], CERN issued a call to perform a survey in a subset of CERN member states and associated countries to a representative sample of the adult population (aged 18–75) in each country across the following parameters: gender, age, level of education, income, and geographical area of residence (urban vs. rural). Among other questions, the survey aimed to assess the public's awareness and opinions about CERN and its research activity in countries with different types of relationship with CERN, including CERN member and non-member states.

Built on previous similar experiments conducted in France in 2017 and in Switzerland in 2019 [6, 8], the 2022 wave enlarged the scope to seven additional countries: five of them CERN member states (UK, Italy, Germany, Israel, and Poland), and two non- members of CERN, but involved in the LHC research programme and the FCC international feasibility study collaboration (USA and Japan). The fieldwork took place from September to November 2022 and involved 8443 valid responses. In

[1] Example of funding agency /programmes include: the Horizon Europe programme managed by the European Commission DG-RTD, the UK Research and Innovation (UKRI), the National Laboratories (https://www.energy.gov/national-laboratories) of the USA Department of Energy (DOE). As regards roadmap, see (ESFRI, 2021) Roadmap 2021, Strategy Report on Research Infrastructures, European Strategy Forum on Research Infrastructures; retrieved from https://roadmap2021.esfri.eu/media/1295/esfri-roadmap-2021.pdf.

[2] The Future Circular Collider Innovation Study (FCCIS) receives funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754. The information herein only reflects the views of its authors, and the European Commission is not responsible for any use that may be made of the information.

total, including the respondents of the previous surveys in France and Switzerland, 10,448 valid responses were considered in the analysis selectively reported below.

The following paragraphs summarise some of the findings of the experiment related to the public's awareness of CERN, attitudes and perceptions towards particle physics research at the laboratory. The full preliminary findings are reported in Secci et al. [12].

2 Awareness of CERN

Interviewees' awareness of CERN was investigated by asking respondents to indicate international and national organisations that they had heard about among a pre-filled list.

Organisations like NASA, WHO, and UNESCO rank in the first positions, with 84%, 78%, and 68% of respondents having heard about them respectively (Fig. 1). NASA is the most known organisation in Japan (87% of the adult population), the USA and in the CERN member states (83%),[3] followed by WHO with 86% in Japan, CERN member states (80%) and the USA (72%).[4] UNESCO is more popular in the CERN member states (81%),[5] followed by Japan (57%) and the USA (37%).

Focusing on CERN, 41% of the respondents heard about it and its research activity, with some differences among countries. CERN is, unsurprisingly, very well-known in Switzerland, with 81% of surveyed people being aware of it. Awareness is also high in Italy (64%) and to a lesser extent in the other European CERN member states (France, UK, Germany, and Poland). In contrast, the level of awareness, as expected, is the lowest in non-EU countries, namely Israel, the USA and Japan (Fig. 2).

The sociodemographic profile of respondents aware of CERN is illustrated in Fig. 3. Awareness of CERN is higher among the employed compared to the unemployed (42% vs. 30%), among men than women (50% vs. 34%), and among respondents with tertiary education compared to those with primary education (42% vs. 16%). Additionally, respondents interested in science-related topics show a higher awareness than those with no interest in science (50% vs. 29%), which represents the largest difference. Respondents in different age groups, income levels, or living areas (urban and rural) display small to moderate differences in the percentage of awareness of CERN.

While the CERN awareness by gender is likely associated with the well-known gender gap in science (e.g., [9]), showing a scientific interest, also in subjects beyond

[3] Respondents aware of NASA are 84% in Germany, 88% in Italy, 89% in Poland, 84% in the UK, 86% in France, 93% in Switzerland, and 50% in Israel.

[4] Respondents aware of WHO are 76% in Germany, 80% in Italy, 89% in Poland, 80% in the UK, 82% in France, 83% in Switzerland, and 49% in Israel.

[5] Respondents aware of UNESCO are 83% in Germany, 87% in Italy, 63% in Poland, 80% in the UK, 89% in France, 93% in Switzerland, and 39% in Israel.

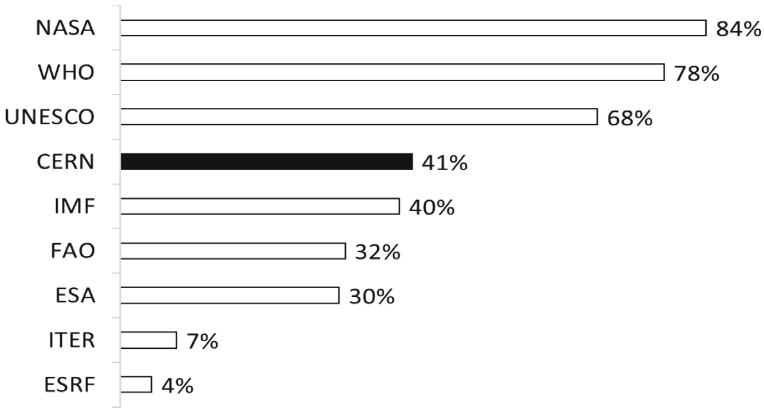

Fig. 1 Awareness of CERN compared to other international organisations. *Source* Authors. Total sample: $n = 10{,}448$ (including France and Switzerland). IMF: International Monetary Fund; FAO: Food and Agriculture Organization of the United Nations; ESA: European Spatial Agency; ITER: International Thermonuclear Experimental Reactor; ESFR; European Synchrotron Radiation Facility Authors elaboration on experiment data

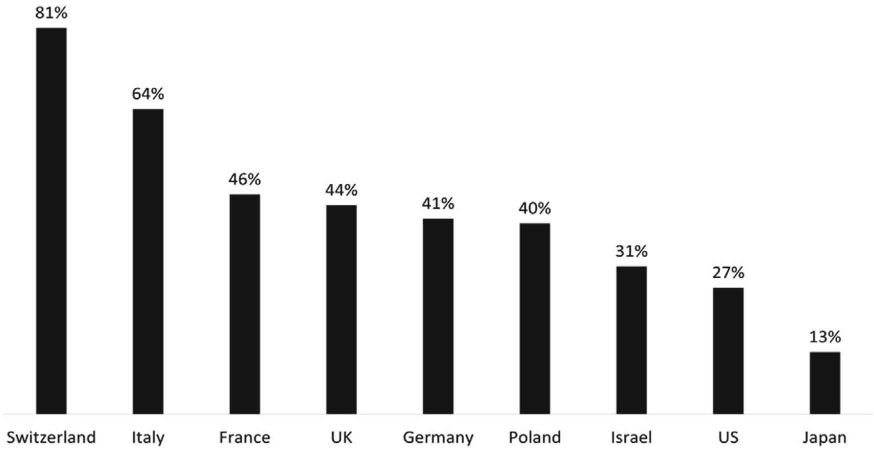

Fig. 2 Awareness of CERN across countries (%). *Source* Authors. Total sample: $n = 10{,}448$ (including France and Switzerland)

physics, triggers the curiosity of people looking for science-related information, including CERN research. High income, occupation status, and education are often correlated, identifying more well-off layers of society. Moreover, living in urban areas is usually associated with easier access to culture, science, and innovation, which might explain a broader awareness of organisations such as the CERN.

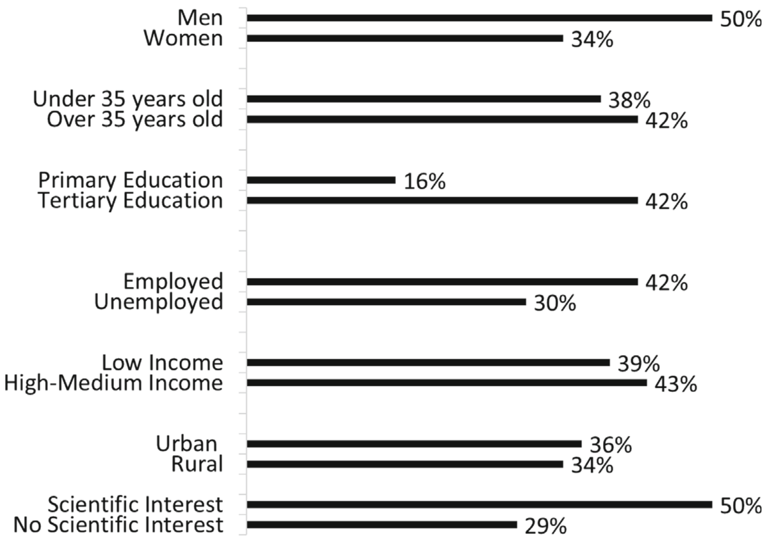

Fig. 3 Share of people aware of CERN across personal selected characteristics (%).Notes: Scientific Interest reflects the share of respondents with an interest in one of the following subjects: biology, physics, astronomy, medicine, and geology (see details in [12]). *Source* Authors. Total sample: $n = 10{,}448$. The category Men represents 46% of the total sample, Under 35 years old 29%, Primary Education 5%, Tertiary Education 33%, Employed 72%, Unemployed 7%, High-Medium Income 61%; Urban 66%, Scientific Interest 59%

3 Opinions and Attitudes About CERN and Its Activity

Respondents were asked to express their level of agreement with a list of statements regarding the scientific research at CERN according to a five-point Likert question from *strongly disagree* to *strongly agree* (Table 1).

The majority of respondents (77%) hold a favourable view expressing positive sentiments towards research activity at CERN. People agree that the societal benefits generated by CERN's research extend to society at large, going beyond the scientific community. According to them, CERN's scientific research broadens society's understanding of the universe, with agreement rates ranging from 79% in Israel to 86% in Switzerland. Respondents also think that CERN contributes to advancing products to enhance the quality of life, including the contribution to new technologies for diagnosing and treating diseases. Similarly, 70% of people believe that CERN's education programs for students and young professionals create value for society and, because of these reasons, CERN's scientific activities should be intensified over the coming decades, according to two-thirds of the respondents.

In contrast, only a minority of the interviewed sample (from 3 to 5%) perceive the societal impact of CERN as being limited to scientists, those residing in the proximity of the laboratory, or viewed research activities at CERN as hazardous to the environment.

Table 1 Percentage of respondents who agree with proposed statements about CERN scientific research

Statements about CERN scientific research	%
CERN's discoveries allow us to enrich our knowledge of the origins and evolution of the Universe	**80**
CERN's discoveries can lead to the creation of products that could improve the quality of life	77
CERN's education programs for students and young professionals creates value for society	74
CERN develops new technologies for the diagnosis and treatment of diseases	68
I am proud that my country is part of the CERN international scientific research projects	67
Research activity at CERN should be intensified over the coming decades	66
Research at CERN has a positive effect on my everyday life	51
CERN's research activities contribute to peace in the world	46
CERN is a humanitarian aid organisation	42

Source Authors. Total sample: $n = 10{,}448$ (including France and Switzerland)

At the country level, Poland (88%) shows the highest share of positive sentiment of CERN research activities, followed by Italy (86%), the UK (84%), while Japan (53%) scores the lowest, mirroring the low level of awareness of CERN.

The survey also investigated what people appreciate or do not appreciate of CERN. To this end, respondents were asked to spontaneously report their first thoughts coming to their mind instead of picking items from a prefilled list.

"*Scientific research*", "*development/innovation*", and "*potential for a brighter future*" are the top three positive items mentioned by respondents with differences across countries. In Poland, the UK, the USA, and Israel, the contribution of CERN to technology development and innovation is appreciated the most; while Italian, French, and Swiss people primarily mentioned "*scientific research*". Japanese respondents mainly focused on *"nuclear research"* attributing to it a negative sentiment. Negative perceptions of CERN can be also associated with thoughts such as "*excessive cost*", "*inadequate safety*", "*insufficient communication/information*", and the "*topic being too intricate or challenging to grasp*".

The sociodemographic profile of the respondents who exhibit positive attitudes towards CERN research activity and who value its societal benefits mostly follows the traits of those respondents aware of CERN (Fig. 3).

On top of that, the above opinions about CERN are also coherent with the respondents' thoughts about the potential roles of scientific research in general (not only related to CERN) since most of the respondents to the experiment point out that scientific research plays a crucial role in enhancing the quality of life and in satisfying human curiosity about the universe's origins and nature ([12]; Chap. 3).

In conclusion, despite the frequent over-exposure in the media of anti-science attitudes, the survey conveys a clear message: there is high support of a large-scale research infrastructure such as CERN. Ongoing work on other aspects of the survey will reveal the determinants and intensity of such support.

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Thinking How to Define and Measure Impacts of RIs

Gelsomina Catalano

Abstract The potential of research infrastructures (RIs) to generate impacts beyond science is widely recognised by policy makers and funding agencies. Hence, the growing demand to be able to measure RIs impacts not only for research but for the society at large. The main challenges associated to this request deal with (i) the definition of RI's impact, (ii) the identification of the variety of impacts which can be generated by RIs of different disciplines and of different types, (iii) measuring these impacts and (iv) exploring the way they are generated. This paper addresses these challenges by suggesting a possible roadmap to guide the conceptualisation and the measurement of impacts of a research infrastructure. Specifically, drawing from recent discussion on socio-economic impact assessments of RIs as well as practices of measurement of RI's impacts, it highlights the variation of impacts which can be encountered across research infrastructures of different types and disciplines and points out to the challenges faced in measuring the different RI's impacts.

Keywords Socio-economic impact assessment · cost-benefit analysis · research infrastructures · impact pathways

1 Introduction

Research infrastructures (RIs) are found to be an essential component of technological and scientific progress: besides improving the quality of scientific research, they enable the access to new knowledge which may find applications in different sectors and affect several domains—such as economy, society and politics—by triggering innovation developments and contributing to tackle societal challenges, such as climate change, health, energy, ageing, etc. [11, 12, 15, 17, 18, 35]. Recently several RIs—operating in the life sciences field—have been in the position to provide relevant data, facilities and knowledge to cope with the COVID-19 emergency [20].

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Hence, the growing demand—from policy makers and funding agencies—to be able to measure RIs impacts not only for research but for the society at large [36].

A first challenge associated to this request is clarifying *what does impact mean.* The OECD [30] suggests that impact refers to an intended or unintended effect generated by RIs' activities and outputs over its lifecycle. In line with the OECD definition, the Horizon 2020 RI-Paths project defines impact as any long-term effect, whether intended, unintended, positive, negative, direct or indirect produced by the intervention. In other words, it is the ultimate changes produced in the society by means of a given action or investment decision [28, 32, 37].

A second and third challenges deal—respectively—with the *identification of the impacts associated to a specific research infrastructure* and *their measurement*. It is widely recognised that this is not an easy task because of the variety of RIs typologies and their related ecosystem: each RI has its own objectives, performs specific activities in relation to a specific discipline and entails interactions with different type of stakeholders [25, 30]. Over recent years, various models have been proposed by different teams with the objective to considering the range of observable direct and indirect effects related to different RIs as well as reflect different information needs of funding institutions, policy decision-makers and science managers. The models proposed by Florio et al. [23] and later by Florio [19] suggest an assessment frame which takes into account the social return of large-scale investments in science against the funds they need (by using a cost–benefit analysis perspective). The RI-Paths project developed a model which instead describes the pathways of materialisation of the socio-economic impacts of research infrastructures and defines a set of indicators and mix of methodologies to assess them. These pathways are intended as the (non-linear) sequence of steps linking the research infrastructure to its direct and tangible outputs, the socio-economic outcomes attributed to that infrastructure, up to more indirect, wider and not necessarily quantifiable impacts. The RI-Paths model boasts a modular structure for being adapted to a broad range of scientific domains and types of infrastructures [28].

Following the conceptual frameworks developed so far and the most recent practices of measuring RIs' impacts, the objectives of this paper are the following: (i) suggesting a possible roadmap to guide the conceptualisation and the measurement of impacts of a research infrastructure and, respectively, (ii) highlighting the variation of impacts which can be encountered across research infrastructures of different types and disciplines and (iii) pointing out the challenges to measure RI's impacts.

2 Conceptualising RIs Impacts

2.1 Identifying RIs Impacts: A User Approach

There is a growing consensus that the notion of impact associated to RI should be comprehensive, thus connecting the different dimensions—not only science but also economics, society and politics—touched by RIs' activities [23, 28, 30]. As suggested by the OECD and RI-Paths definitions mentioned above, impacts generated by RIs may be positive (social benefits) or negative. Amongst the negative impacts, there are obviously the financial costs borne to construct and operate the facility with public funding, but in some cases, there might also include environmental damages to third parties (e.g. occurred during construction phase), pecuniary externalities in the form of change of prices of real estates, etc.

Despite relying on different approaches and methods to measure RIs impacts, the conceptual frameworks developed so far suggest that the identification of impacts must be connected to the RI's mission and strategic objectives since these can directly influence how the RIs impact on society. More specifically, a proper assessment of RIs impact should start with the identification of RI's core missions and related activities as well as the potential stakeholders—direct or indirect users—which can benefit from them. For each group of direct or indirect user, a corresponding impact area can be identified. In turn, for each impact area, a pathway can be traced to describe the way according to which the research infrastructure generates impacts on its direct users firstly, and which of them might expand to the wider society and economy.

The type of missions and strategic objectives of the RIs can be broadly summarised as follows [25, 26, 32]: (i) be a scientific leading RI and an enabling facility supporting advancement in science (e.g. CERN in Switzerland, the Square Kilometre Array, Facility for Antiproton and Ion Research in Germany, European Southern Observatory, etc.); (ii) be an enabling facility exclusively or primarily user/services oriented, for instance by delivering technologically advanced services to users in specific fields (e.g. European Clinical Research Infrastructure Network, the National Centre of Oncological Hadrontherapy in Italy) or by developing and testing prototypes and innovation not yet intended for commercialisation, data repositories (e.g. Diamond, Elixir, Alba synchrotron). Of course, these types of missions are not mutually exclusive and some large infrastructures may combine them.

Traditionally, the production of scientific results and knowledge is identified as the core impact area of all RIs and the scientific community is the main targeted stakeholder category associated with this impact. Indeed, regardless of the core mission and strategic objectives pursued, the main output which can be associated to a RI—either if it pursues its own research or if it provides services/facilities to external users—is the creation of knowledge which is usually embodied by the scientific community in publications, datasets or open science repositories. However, while pursuing its core mission, the RI entails several interactions with additional stakeholders thus offering them numerous possibilities, such as: (i) technology transfer to industries and other research institutes in charge of designing and supplying high-tech instrumentations (e.g. through development or procurement contracts); (ii) learning and skills development to students and researchers involved in scientific programmes; (iii) getting new inspirations for citizens taking part to outreach programmes or (iv) getting answers to big questions of life or solutions to societal challenges for society at large. One should consider that a heterogeneous and various set of direct and indirect users may interact with a RI in multiple ways and with different expectations and objectives. These stakeholders range from those communities directly associated with the research and the services offered by the RI (e.g., scientists and researchers) to academia, industry, consumers of goods and services provided by RIs, government and the general public (citizens and tax-payers). Thanks to these multiple interactions, the RI generates societal benefits which span beyond scientific impacts.

Box 1: RI's Targeted Groups

1. **Scientist and researchers**: they produce knowledge, but are also direct users of the RI. They encompass both inside research staff and outsiders, who are the rest of the research community, including those working in other fields that may use the evidence provided by RI's experiments to produce further knowledge.

2. **Young professionals, junior researchers, and students**: they include, for instance, post-doctoral researchers, early career researchers who spend a period working within the RI or use the RI's facility/tools to carry out their own studies/tests, as well as students, usually at graduate level, involved in training or the preparation of their dissertation or who have access to the facility through a training programme.
3. **Businesses**: they include spin-offs and start-ups, small and medium enterprises, and large enterprises that directly enjoy the services provided by the project and/or benefit from indirect spill-over effects, particularly through procurement and supply chain learning effects.
4. **Consumers**: they are a specific group of citizens directly benefitting from the service/activities provided by the RI. This category may include (i) consumers of RI's goods and services (e.g. patients benefitting from health treatment or residents of a region in which major risks such as floods, earthquakes, and fires are better monitored/forecasted because of the research developed by observatories, stations, or satellites, among others); (ii) general public enjoying RI's outreach activities (both on-site or virtual visitors).
5. **Governments**: it includes policymakers/international organisations which (i) use data/knowledge produced by the RI to design relevant regulations/

strategies in specific fields as well in addressing questions of strategic relevance or which (ii) are involved in international collaborations fostered by the RI.

6. **Citizens**: it refers to those citizens which don't use the infrastructure (non-users) but indirectly benefit from it, e.g., by enjoying solutions provided by the RIs to address societal challenges. Taxpayers—which contribute to fund RI's activities—are a specific group of this category—and they may have a tacit willingness to pay for the RI's impacts (e.g. for its discover potential).

Source Author elaboration on the basis of different sources [14, 19, 23, 28]

The identification of the activities and the recognition of their actual and potential beneficiaries are, of course, specific to each RI. Having identified the main beneficiaries of a RI, a list of typical benefits can be attached to each group (see the following section for a more detailed discussion). Depending on the RI's nature, some of these benefits may accrue to different types of target groups. The intensity of each benefit may be highly variable across the different typologies of RI and only a case-by-case study can design the appropriate assessment strategy.

2.2 The Variety of RIs Impacts

Evidence from available impact assessment studies reveals that the generation of impacts beyond science are a natural potential of RI rather than a deviation from their inherent nature [19]. A better understanding of the overarching list of impacts generated by a RI and the way they are generated may facilitate a crucial and important change in scientific practices. It can allow to investigate where the RIs is providing its positive contribution and where it is 'failing' to achieve desired results [32].

Building on the conceptual frameworks developed so far and recent socio-economic impact assessments of RIs, six impact areas are likely to be affected by a RI in the pursuing of its missions, specifically:

1. **Scientific impacts**: it refers to the increase in the stock of knowledge occurring both in the specific field of the RI as well as in other scientific areas. These impacts affect *scientists*, being them either external users or internal staff (i.e. producers), as well as *other external users* (e.g. policy makers, firms) of the facility. The impact is channelled through scientific outputs produced within the facility—such as publications, conferences, workshops, datasets—which disseminate new theories, results, methods, data, tools and concepts to scientific and non-scientific users, increasing the total stock of scientific knowledge in a given field. The impact can take the form of a new stock of scientific knowledge which could not have been produced and, therefore, accessed by the community in a 'scenario

without the RI', for instance because of the lack of financial volume needed to develop it, skills, etc. Also, it can result in efficiency gains such as reducing time and effort of users when performing their research or professional activities thanks to an easily, coordinated and integrated access to high-quality knowledge (e.g., database, publication, etc.) as well as reduced transaction costs or productive improvements. These efficiency gains become particularly relevant in the case of RIs pursuing open access research.[1] In such context, this impact can be the result of two mechanisms: (a) wider availability of knowledge resources that makes research cheaper and research success more likely and (b) more fluent collaboration among heterogeneous knowledge actors that amplifies collective intelligence and creativity. Scientific impacts may also be channelled through the creation of networks amongst researchers or multidisciplinary and interinstitutional research collaboration, thus contributing to build consensus of the research community around common priorities, produce common research practices as well as enhance researchers' cohesion and integration under a common label.

2. **Human resource impacts**: it refers to the RI's contribution to the increase of skills and expertise of trained people. This impact concerns *Ph.D. students and postdoctoral researchers* benefitting from training programme and/or learning process and knowledge sharing occurring within the facility between permanent staff and young researchers. It materialises in increasing capacities and skills that ultimately translate into increase in job opportunities and income levels (*salary premium*) for early-stage researchers. This impact is reflected, by one side, in the number of trained people and, by the other, in the actual use that these improved skills can have in the job market.
3. **Economic impacts**: it refers in the RI's contribution to the development of new or improved technological solutions and products as well as to the local and regional economic growth. This impact most often accrues to *firms* being either users or suppliers of the RI and stems from the learning effect and knowledge spill-overs arising from the interaction of the firms with RI staff helping them to solve complex and new technological problems (e.g., through procurement or collaboration contracts). This interaction can produce new technological know-how that can be later applied to new services and products. Also, it can refer to products and services produced by the RI and made available open access to the scientific community and the wider public. They are typically ICT innovations in the form of open-source codes, free software, open data involving broad communities of users, also beyond the scope of scientific research. In some cases, RI-related procurement activities could generate *spatially distributed socio-economic benefits* by contributing to job creation and development of specific economic activities in the region where the RI or the companies supplying it are located. Beyond the localized impacts in the areas where RIs are physically located, the design, building and upgrade of large research infrastructure may involve highly-knowledge-intensive firms located in specialized clusters across the globe. Hence,

[1] For more details see Catalano et al. [7].

the benefits can be more spatially spread.[2] Also, the concentration of people (e.g., permanent staff, engineers, technicians, and early-stage researchers, etc.) linked to a large research infrastructure produces multiple effects on the local economy. This translates in an increase of consumption 'expenditures as well as a higher demand for accommodations (hence, the need of real-estate investments) and local services (e.g. restaurants, bank, shops, transport services), leisure activities (e.g. sport, cultural facilities), etc.[3]

4. **Policy impacts**: it deals with the RI's contribution to the policymaking. This impact most often relates to the production of knowledge (e.g. in the form of data, advancement in scientific research) which is then used by policy makers for the design of relevant regulation/strategies in specific fields as well as for addressing questions of strategic relevance. This impact also channels through discussion promoted by the RI acting as a venue for the building of international partnerships or cooperation to address common challenges.
5. **Outreach impacts**: it refers to the RI's contribution to the wider society. This impact is specifically related to the outreach activities and public awareness which accrue to citizens thanks to scientific dissemination, tourism at RI facilities, traveling exhibitions, media exposure, websites. This impact can be experienced through on-site or virtual visits at RI's facility/outreach products.
6. **Societal impacts**: it refers to RI's contribution to improving people wellbeing. This impact may be channelled through the development of a new technology, a service and/or new body of knowledge which can find specific applications (e.g., a new treatment to address a specific diseases, tools and disaster management systems to facilitate disaster resilience, risk prevention and management for natural risks, etc.) and/or used to understand, raise awareness and/or develop a solution to address societal challenges (e.g. contributing to reach UN Sustainable goals, etc.). The impact results in an improved quality of life of people directly benefitting from the RI's outputs (e.g. *consumers of the health treatment*) or of the society at large (*citizens/taxpayers indirectly benefitting from the solution developed by the RI to address societal challenges, such as climate change, etc.*).

The above list provides a picture of the main socio-economic impacts which can be generated by RI. They are relevant—although with different degree of intensity and definition—for any or most typologies of RIs. Three elements are suggested by the RI-Paths project [28] for highlighting possible differences amongst the impact associated to each RI, such as:

- *The distinction between physical and virtual RIs*: physical research infrastructures have more notable impacts on regional economies (e.g. through improved job opportunities and increased economic activity in a specific location) while virtual research infrastructures are predominately oriented towards providing data-related services (e.g. efficiency gains are among their biggest benefits).

[2] See Crescenzi and Piazza [8] for more insights about a new framework designed to identify and estimate this impact.

[3] See Del Rosario Crespo Garrido et al. [10] for more details.

- *The difference between single-sited and distributed RIs*: the distinction lies in the scale of analysis, geographical coverage and context (diverse locations and nodes). In contrast to single-sited facilities, distributed RIs operate across different national and regional nodes, thus allowing the creation of users networks as well as learning opportunities across them.
- *The difference between RIs operating in social sciences, humanities and arts, and in natural sciences and engineering*: facilities supporting social sciences, humanities and arts have a stronger relative focus on direct contributions to policy making. These RIs are also more likely to have more nuanced benefits in such areas as culture and social inclusion. For distributed data infrastructures in social sciences, humanities and arts there are also less obvious benefits following from the construction and operation (e.g. knowledge transfer) of the facilities than from traditional large-scale facilities in the natural sciences.

The box below builds on the evidence provided by recent socio-economic impact assessment studies and showcases where RI from different fields and of different nature create impacts.

Box 2: The Variety of RI's Impacts: Evidence from the Grounds

1. **Large Hadron Collider (LHC)**: *a physical single-sited research infrastructure operating in the field of physics.* Florio et al. [22] revealed a quantifiable return to society of LHC in terms of scientific, economic, human and cultural value. Specifically, they found that LHC mostly contribute to human capital effects and technological spillovers (each representing around one third of the total LHC benefits). The remaining benefits spill over to scientists and to general public, either in the form a direct cultural effect (a private good) or as a pure public good (a non-use benefit).
2. **National Hadrontherapy Centre for Cancer Treatment (CNAO)**: *a physical single-sited research infrastructure specialised in hadrontherapy* (an advanced oncological treatment). The socio-economic impact assessment carried out by Battistoni et al. [2] showed that the main benefit generated by this RI is a longer or better lives to patients benefitting from health treatments. Additional benefits were found to be typical of research infrastructures and refer to technological spillovers (namely creation of spin-offs, technological transfer to companies in the supply chain and to other similar facilities), knowledge creation (production of scientific outputs), human capital formation (training of doctoral students, technicians and professionals in the field of hadrontherapy) and cultural outreach (students, researchers and wider public visiting the facilities).
3. **European Research Infrastructure for Heritage Science (E-RIHS)**: *a virtual distributed research infrastructure operating in the field of heritage science.* According to the assessment carried out by CSIL in

2019 (in the preparation phase to become a European Research Infrastructure Consortium) the main impact associated to E-RHIS is the improved efficiency (in terms of time saved) and effectiveness (better quality) of the research production in heritage science and related domains. This impact is channelled through the virtual access to the facilities as well as scientific publications. Beyond purely scientific impacts, this RI is found to generate—although to a lesser extent—human capital and outreach impacts.

4. **European Southern Observatory (ESO)**: *a physical distributed research infrastructure operating in the field of astronomy.* A recent publication by ESO [16] showed that ESO's benefits spans across all the dimensions mentioned above. Specifically, ESO has fostered scientific progress with its discoveries as well as enabled the construction and operation (through significant procurement contracts with industries) of world-leading observatories which have pushed the boundaries of engineering. Technologies developed at ESO have found applications in areas such as optics, intercontinental data transfer, medicine, and imaging, sensor and detector technology. In talent development, ESO has played a crucial role in the enrichment and development of highly skilled astronomers, engineers and technical experts which have, then, found career development in academia and different industries. ESO's communication, education and outreach activities has contributed to increase the scientific literacy in society, and inspired more children to engage in science, technology, engineering and mathematics fields. As a collaborative and international organisation, ESO has helped to shape policy priorities in the field of astronomy and brought countries together to develop challenging projects.

Source Author elaboration on the basis of different sources [2, 9, 16, 22]

2.3 The RIs Impact Pathways

Once the impact areas associated to a specific RI are identified, the spreading of effects to its related stakeholders can be described by means of impact pathways. Each pathway represents the chain of events according to which RI's research-related activities might generate effects on its stakeholders' ecosystem.[4] It entails resources, activity, outputs, outcomes and later impacts. Some of these elements fall under

[4] The recent RIPaths project identified 13 distinct impact pathways to be relevant for all types of RIs, although the degree of emphasis may differ. These pathways were grouped across three high-level functions: (i) impacts as a result of RIs pursuing their primary mission—enabling science; (ii) impacts as a result of RIs interacting for problem-solving; (iii) impacts through RI shaping the fabric of science and society [28].

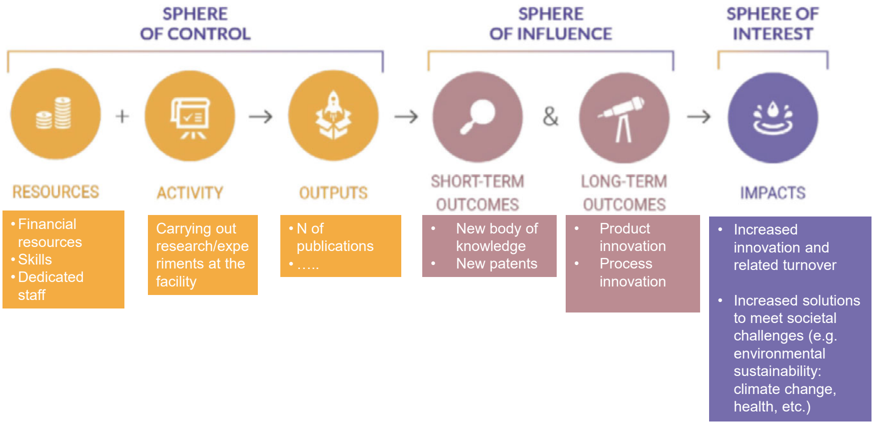

Fig. 1 The logic of impact pathways: the example of public-citation-recognition. *Source* Author elaboration on the basis of *the RI-PATHS Guidebook for Socio-economic Impact Assessment of Research Infrastructures. Deliverable D5.4*. https://ri-paths.eu/deliverable

the direct control of RI managers who are responsible for the implementation of RI's activities. On other elements, although outside their direct control, RIs still have indirect influence by interacting with users and stakeholders' groups. The final stage—represented by impacts—is neither under the direct control nor influence of RI. However, impacts are certainly of high interest to funders, policy makers and hence RI managers as well. Figure 1 shows the example of the specific pathway '*Publication-citation-recognition*' which follows the traditional idea of '*knowledge push*' where RIs generate scientific publications (either directly or via users). These are, in turn, cited by others and eventually become part of a new body of knowledge which can be (conscious or unconscious) used to generate innovations (economic impacts) or address societal challenges.

Impact pathways are usually non-linear and often very complex. They can be interconnected, thus meaning that one pathway may allow to the generation of different ones. In what follows, an example from the *Future Circular Collider-ee* (FCC-ee) study[5] is provided to show how impact pathways may be generated and interconnected (see Fig. 2). For instance, focusing on the pathway publication-citation-recognition (illustrated above), FCC-ee scientific products are likely to be produced and codified in a wide range of scientific products—from scientific publications to presentations, conferences and workshop participation, books and working papers. These can be cited and eventually become part of a new body of knowledge that can also find recognition or interest beyond the High-Energy Physics community as well as spread out into other impact areas, such as industrial spillovers (in the form of patents), or find application and contribute to solving grand societal challenges. Interestingly, the FCC-ee is also expected to generate knowledge advances about the nature and the origins of the universe, which can be considered a 'public good' and

[5] For more details, please see Sirtori et al. [34].

be enjoyed by the society at large (P7 pathway). The example below also shows how the development of free and open-source software (P6 pathway)—depending on the conditions they are delivered (open access versus restricted)—can contribute to the development of new products/technology and addressing societal challenges, thus being connected to P3 and P7 pathways.

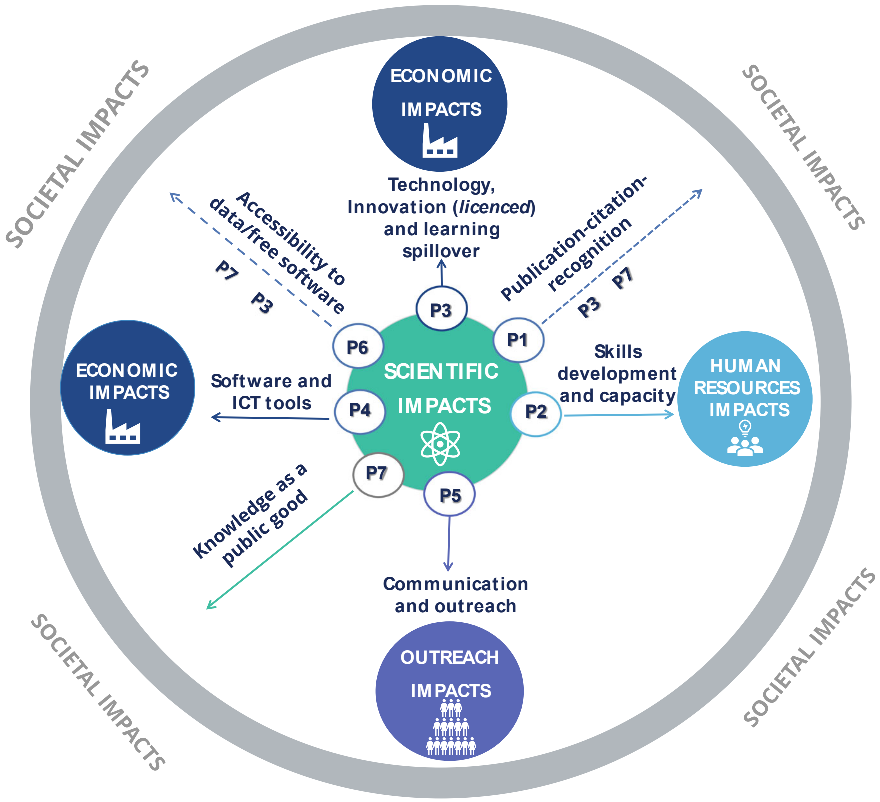

Fig. 2 Example of how FCC-ee create impacts. *Source* Author elaboration on the basis of Sirtori et al. [34] included in the same volume. *Legend* P1—publication-citation-recognition, P2—skills development and capacity, P3—technology, innovation and learning spillover, P4—software and ICT tools development, P5—communication and outreach, P6—accessibility to curated and edited data, P7—knowledge as a public good

3 Measuring Impacts: Approaches and Challenges

3.1 From Indicators to a Model

A widespread solution to measuring impacts is the production of long lists of key performance indicators (KPIs) responding to different information needs of a heterogeneous target audience. Different examples of KPIs have been provided, over the years, by OECD [30], ESFRI [14], Koulocheri [29] and Griniece et al. [27, 28].

While indicators can be useful—from a policy and management perspective—to monitor RI's outputs and outcomes, they fail to provide a concrete assessment of impacts. They often focus on outputs, sometimes outcomes, but hardly ever on impacts. They can inform on the impacts' dimension (e.g. scientific, human, economic, etc.) that may be affected by the RI and on their uptake (e.g. number of users accessing scientific data sets/instruments/tools outside RI, etc.) but they cannot provide a concrete quantification for them or a comprehensive assessment of the investment case. In order to have a complete understanding and measurement of impacts, more complex methodologies should be mobilised. For instance, the specific pathway 'Publication-citation-recognition'—illustrated above—cannot be identified and described by looking at traditional KPIs (e.g. number of publications or patents associated to RIs, etc.). A more complex analysis is needed to assess whether the knowledge created and embedded in publications actually translates in impacts. An example is provided in Fig. 3 showing the results of a patent citation analysis carried out on ALBA synchrotron light source. By relying on bibliometric techniques, this analysis was addressed to assess whether publications stemming from experiments carried out at ALBA beamlines actually contributed to generate patents. The analysis was also combined with a survey to ALBA users addressed to better investigate the relation between the knowledge created and the generated innovation output (e.g. the time lag and the additional research activities needed from the experiment to the development of the innovation output).

Currently, there is no a unique methodological framework in force to assess RIs impacts but a variety of methods are used depending on the *scope of the analysis*, the *type of impacts* that are assessed and the *target users*. These range from macroeconomic modelling to cost–benefit analysis to more qualitative narratives and case studies [25, 28]. Some of them have shown broad applicability while others are quite narrow in their scope and potential informative power.

For instance, CBA could inform governments, research funding agencies, and RIs managers about the value for money of their investments by quantifying the added value to society that RIs provide [25, 31]. Specifically, the incremental approach—adopted by this methodology—allows for the calculation of the net welfare change that is attributable to the RI's investment and express it with a couple of indicators (ENPV and/or benefit/cost ratio) which are easily interpretable. Different impacts

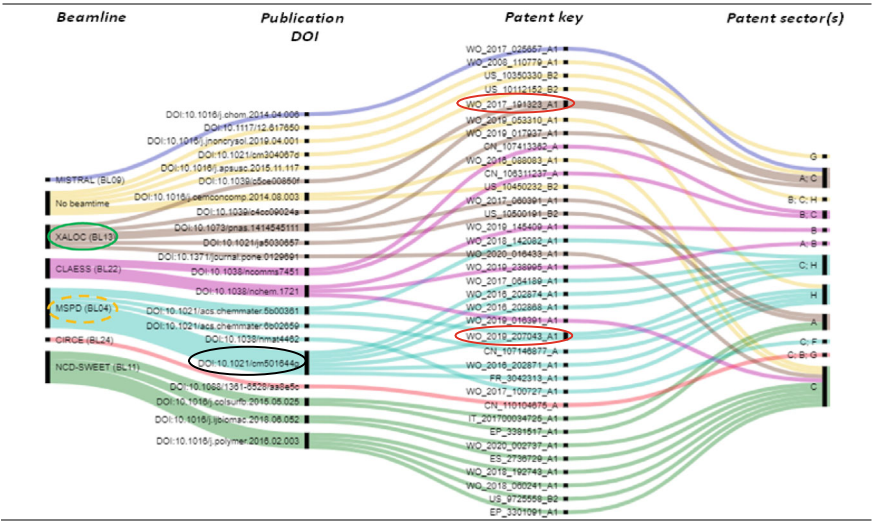

Fig. 3 The pathways from experiments to innovation. *Source* Catalano et al. [5, 6]

mentioned have been measured by using a CBA approach,[6] such as (i) the stock of knowledge output created by the RI in the forms of publications, preprints, conferences, (ii) effect of human resources on the economy (e.g. skilled researchers with high salaries), (iii) the innovation impacts experienced by RI's suppliers (e.g. by means of incremental profits), the cultural and outreach effects generated on virtual and physical visitors of the RI, (iv) the social public value of knowledge created by the RI.

Additional methodologies can be used to enrich the scope of CBA and capture all RI's impacts. For instance, indirect economic impacts on supply chain deriving from an investment in RI can be calculated—both at sectoral, local and national level—by using input–outputs models. Qualitative approaches, such as case studies can be used to obtain a deeper understanding of the benefits accruing to a specific target of stakeholders.[7] Theory-based approaches can be used to describe impact pathways, such as the linkage and sequence of effects or the steps from RI's activities to more indefinite and indirect impacts, which for their nature, are not measurable (e.g. favouring collaboration among stakeholders, impacts on science policy, etc.).

[6] Practical examples of how this approach has been mobilised to assess the different impacts of RIs are provided by Florio et al. [22], Battistoni et al. [2], Bastianin and Florio [1], Castelnovo et al. [3], CSIL [9] and Florio and Giffoni [21].

[7] To this end, information can be collected through the use of a survey, feedback forms, focus groups or interviews etc. For instance, this approach has been used by Sirtori et al. [33] to investigate on the benefits generated by LHC procurement actions on its supplier companies, including the acquisition of technical know-how, the development of new products, from improved organisation capabilities and reputational effects.

None of existing methods, in their formulation, provides a comprehensive and satisfactory measurement of RI's impacts. It would be useful to adopt a model approach which rely on a smart and rigorous combination of different methods (both quantitative and qualitative) to measures all the impacts (both negative and positive) generated by the RI as well as explain the way they materialise.

3.2 Which Challenges and for Which RIs

Evidence from a survey[8] involving 191 research infrastructures—from different disciplines and of different types—showed that collecting data for impacts assessment purposes is a largely widespread practice or will be implemented in the near future. However, as declared by respondents, these practices mostly rely on the collection of key performance indicators which—as discussed above—are better placed to monitor outputs and outcomes rather than measuring impacts. This is likely to suggest that a first challenge deals with the need to have clear in mind the distinction between outputs, outcomes and impacts and to be aware that KPIs represent only a first step towards the measurement of impacts.

Data availability or the relevance of available data are often mentioned as key challenges faced in measuring impacts. In this regard, it is worth pointing out that the collection of data is often bound to scientific and technological outputs (e.g. number of publication, citations, number of procurement contracts, etc.) while it should be strongly tailored to all the *impact dimensions* (e.g. human, societal, etc.) generated by the RI. For instance:

(i) A systematic tracking of scientific publications and citations is the basis for a solid assessment of scientific impacts. This applies to all RIs, since—regardless the type of disciplines represented—they are 'publications-factories'.
(ii) Tracking the number of downloads, identifying the type of organisations which make use of data as well as investigating on the use of these data (e.g. by relying on external consultants for survey, interviews with selected stakeholders, etc.) might be specifically asked to RIs pursuing open access research.
(iii) A systematic tracking of procurement contracts, patents and other innovation outputs may be required to RIs (mostly physical infrastructure) for the assessment of technological impacts. For instance, this action may be required to large physical RI operating in the fields of natural sciences, physics, space or astronomy, and therefore requiring sophisticated developments for their operation.
(iv) A systematic tracking of visitors (both on site to RI's facilities and virtual to RI's outreach products) and doctoral students is the basis for the assessment

[8] The survey was carried out in the framework of the RIPaths project. For details, see Catalano et al. [4].

of cultural and human resources impacts. This is typically required to all RI undertaking training programmes or investing in outreaching activities.

(v) A systematic tracking of RI's contribution to policy discussions or the use of RI's data/information by policy makers to design specific strategies or policy. This action may be required to those RI facilities supporting social sciences, humanities and arts boasting a stronger relative focus on policy making.

The complete set of information needed for assessing RI's impacts may also require to *mobilise dedicated, costly methods*, such as interviews, surveys, case studies. For instance, to assess the impact of RI on innovations—either on firms or solving societal challenges—it is necessary to build a database of RI supplier contract including data on main characteristics of suppliers (local, regional, other domestic, foreign; size; type of product/service provided, etc.) but also carry out in-depth interviews and/or conduct surveys with firms and relevant stakeholders (e.g. to grasp useful insights on the type of innovations developed and how the impact has materialised).

A further debated challenge is related to the *time frame* according to which the different impacts materialise. Indeed, some of them can materialise even before the construction of the RI while some others take some years of operations to start being observable. For example, technological impacts may spill over also during the construction period thanks to the procurement activities, scientific impacts materialise mostly at a later stage when the RI is in full operation while education impacts may last even after the decommissioning. Therefore, a proper assessment of RI's impacts should rely on a long-term perspective, looking at the entire life-cycle of the facility. This allows to describe and assess all the expected/generated impacts, including those spreading far into the future, and to distinguish between short, medium and long-term impacts.

4 Concluding Remarks

The peculiarity of a research infrastructure and its surrounding ecosystem should be taken into account when measuring impacts. This paper showed how to address this complex exercise by providing a roadmap towards the conceptualisation and measurement of RIs impacts and showcasing possible differences across different disciplines.

The overall exercise should be guided by a comprehensive definition of impact, which entails both negative and positive changes in the society. Then, a user's approach can be used to the identification of the specific impacts associated to a research infrastructure. This means that the assessment of the RI's impact should start with the identification of its core missions and related activities as well as the potential stakeholders—direct or indirect users—which can benefit from them.

By following this approach, previous socio-economic impact assessments of RIs and the conceptual frameworks developed so far have pointed out to the identification of six main impact areas, namely (i) scientific, (ii) economic, (iii) human resources, (iv) policy, (v) outreach and (vi) societal. These impact areas are associated to a specific set of stakeholders and can be relevant, although with different degree of intensity and definition, for any or most types of RIs. For each impact area, a pathway can be traced to describe the way according to which the RI's-related activities might generate effects on its stakeholders' ecosystem.

Regardless of the type or discipline of the RI, measuring its impacts can be a complex exercise that involves numerous challenges and hides several pitfalls. First of all, it requires to adopt a model approach which rely on a smart and rigorous combination of different methods (both qualitative and quantitative) able to capture all the type of impacts (both negative and positive) generated by the RI and explain how they may materialise. Additional challenges—which may be faced—deal with data availability and the time frame according to which the different impacts materialise.

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Costs and Benefits of Open Science: Contributing to the Development of a Rigorous Assessment Framework

Gelsomina Catalano, Erica Delugas, and Silvia Vignetti

Abstract The concept of Open Science (OS) is transforming the landscape of scientific research by promoting collaboration, transparency, and innovation. Acknowledged by policymakers and international organisations, OS is integrated into policy agendas recognising its potential to shape the future of research. Despite significant progress, Open Science faces challenges in showing economic impacts, which undermines its maximal adoption. Empirical evidence on positive economic outcomes, such as cost savings and the emergence of new products and collaborations, exist, but there is a scarcity of comprehensive economic impact studies comparing open and closed science. This article advocates for the use of Cost–Benefit Analysis (CBA) as an analytical tool to systematically assess the advantages and disadvantages of OS. CBA, traditionally applied to sectors like transport and health, can provide a structured framework for mapping and evaluating the costs and benefits of OS, contributing to a more informed understanding of its societal desirability.

Keywords Open science · Cost-benefit analysis · Economic impact · Efficiency · Cost savings

1 Introduction

The concept of Open Science (OS) is deeply reshaping the landscape of scientific research production and dissemination. This paradigm shift in research practices is recognised for its potential to accelerate scientific progress, foster innovation, and promote transparency and collaboration. Policymakers, international organisations and the European Union have acknowledged the pivotal role of OS in shaping the future of research and have incorporated it into their policy agendas (e.g. [5, 10, 13]).

The promotion of OS stems from the consideration of its multiple potential advantages. From increased collaboration among scientists to accelerated discoveries in

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companies, from enhanced transparency and reproducibility through public engagement and trust in science by the society, OS benefits extend along impact pathways spreading from the academic to the economic and societal domains. Despite significant strides in the last two decades (see [11]), OS still faces obstacles undermining its full potential. One critical challenge is the lack of comprehensive evidence regarding the economic impacts of OS and how they can be maximised to accelerate its adoption.

Few empirical studies are available measuring positive economic outcomes resulting from the improved accessibility and efficiency of research findings. They typically include cost savings in terms of access, labour, and transaction costs [1, 2, 13]. Beyond efficiency, OS has been credited with facilitating the emergence of new products, services, companies and research collaborations [6].

Yet, the scarcity of economic impact studies comparing open and closed science is a notable issue [9]. Existing literature predominantly discusses positive or, to a lesser extent, negative effects, mechanisms, drivers, and barriers, often relying on theoretical arguments rather than empirical assessments of costs and benefits. This evidence gap has possibly led to inadequately documented high expectations regarding the impacts of OS, especially in the economic sphere.

Cost–Benefit Analysis (CBA) is an analytical instrument to evaluate the societal desirability of an investment decision. It achieves this by examining the costs and benefits associated with the decision, ultimately determining the net welfare change it brings about [4]. Initially applied to traditional sectors like transport, environment, energy, health, and education, CBA has expanded its scope to encompass the economic impact of science [7]. This article explores how CBA can support a systematic mapping and assessment of advantages and disadvantages of OS. Two are the main contributions: (i) helping a rigorous structuring of the analysis and (ii) providing a framework to mapping and assessing costs and benefits.

2 Structuring the Analysis

While OS is often referred to as a movement or a set of practices, for the purpose of a systematic assessment, it is necessary to shift from this theoretical concept to the practical domain of OS projects. Focusing on one specific OS project or initiative is the first necessary condition to run a realistic assessment and draw conclusive evidence on actual impacts. It can be a digital infrastructure such as an open repository designed to grant open access to journal articles, an open data platform providing free access to specific data, or free software that facilitates the processing of data and information. The selected project should deliver specific services, cater to specific user groups, have recognisable boundaries, identifiable resources, traceable effects, and exhibit a defined time horizon.

Additionally, the degree of openness of the project is highlighted as a critical factor influencing impact generation, particularly relevant when identifying the counterfactual scenario. First, the extent of openness is not solely tied to providing open access to scientific information; it also pertains to the feasibility of comprehending, validating, and leveraging such information. For example, if complex data are presented in a simplified format and can be accessed by a broader audience rather than only by scientists with specific technical expertise, the impact is likely to be more direct and extend to diverse beneficiaries. The degree of openness can encompass the accessibility conditions of research outputs. In the case of open-source software, where users have open access to the source code and can make modifications or create routines, it should not be assumed that users have unrestricted free access to the software. Instead, open access to the software code may be available under a subscription payment. Therefore, the degree of openness of a research output is likely to influence the generation of impact.

By comparing what actually occurred with what might have happened under different circumstances, the use of counterfactual enables a better understanding of the causal relationships and consequences of a particular project. For this reason, the selection of the counterfactual scenario is a critical aspect. It involves the definition of what would happen in the absence of the OS project: whether the impact would occur similarly or if the impact intensity would diminish or completely disappear. Once the counterfactual scenario is identified, all costs and benefits are identified and assessed in an incremental way (with-without project scenario). At least two counterfactual scenarios warrant consideration. The first is applicable when an OS project facilitates access to research products that would not have been available otherwise. This acknowledges that the OS project is instrumental in creating and disseminating materials that either did not exist in a comparable form previously or were entirely inaccessible. An illustration is data repositories collecting shared datasets that were previously unavailable, even though their primary sources were accessible. In this case, the incremental scenario aligns with the OS project scenario itself. In contrast, a closed scenario is apt when a scientific product is already shared, but access comes at a cost. This often pertains to scientific journals operating within closed environments, where individuals must pay a subscription fee or the price of individual articles for access. Another example is software usage that is subject to licensing fees. Here, the counterfactual scenario should encompass the costs and benefits associated with the existing status quo, providing a basis for comparison with those related to the OS project scenario to determine the net effect.

Being often hypothetical and not directly observable, the selection of an appropriate counterfactual scenario involves extensive discussions with researchers and specialists involved. This is crucial because determining the counterfactual scenario, in some instances, necessitates robust assumptions. In such cases, it becomes practical to approximate and refer to the next best alternative.

3 Mapping and Measuring Costs and Benefits

3.1 Costs: Actual Use of Resources and Lost Opportunities

Costs in the context of OS projects are defined as resources used in the process of structuring, operating, maintaining, and upgrading the OS project. According to economic theory, every factor of production, such as capital, labour, and knowledge, carries an associated cost. They should be measured through their opportunity costs, representing the value of the next best alternative forgone when choosing a specific resource for a particular purpose. It is advisable to start the measurement of economic costs with financial costs and then correct them as needed to get the shadow costs [8]. The main challenge related to costs is related to their attribution. Attributing costs to a single OS service can be challenging due to complex connections between costs, the involvement of numerous actors, and the common scenario where an OS service is just one component supplied by the same institution.

Three types of social costs can be identified:

- Set-up costs encompass resources associated with the initial establishment of the project. They are tangible and intangible assets, start-up phase expenditures, personnel, and future upgrading that require significant changes in the technical approach. Additionally, resources related to closing down or discontinuing access to a specific database or research tool may be needed.
- Maintenance costs include all resources essential for the operation and upkeep of newly developed or upgraded OS projects. They can be of fixed and variable types, with fixed costs remaining constant regardless of service volume and variable costs fluctuating based on output volume. Socio-economic costs associated with OS adoption, such as additional costs borne by users, for example, the development of the necessary skills, should also be considered.
- Additional socio-economic costs are associated with the preparation phase of materials to be shared on open-access platforms. These costs involve the extra time invested by researchers to prepare materials and align them with platform requirements. Other social costs on the user's side are the opportunity cost of patenting and potential career implications of opening up the developed knowledge instead of protecting it, especially in academic fields where OS adoption is nascent or in sectors where scientific knowledge appropriation can yield significant economic benefits (e.g. pharma).

3.2 Benefits of OS: Efficiency and Enablement Gains

The benefits associated with OS projects primarily centre around efficiency gains, signifying the attainment of the same research or innovation output with reduced input. The concept of cost savings within OS encompasses enhanced production efficiency. It involves saving both time and money due to OS, leading to reduced expenses and resource conservation in the scientific production process. The cost savings benefit, acting as a macro category, comprises four distinct benefits under which various sources and stages of savings emerge for professionals, enterprises, and researchers utilising OS outputs.

3.2.1 Cost Savings

The first type of cost savings is access cost savings, capturing costs avoided when accessing essential knowledge or tools within a closed environment. It refers to avoided expenses associated with accessing proprietary or paid resources, such as subscription fees or licensing charges. From another perspective, this benefit can be seen as the cost savings achieved by not having to replicate, developing it from scratch, the same type of research output that may not be available without payment. In this case, the focus is on valuing the saved production costs (i.e. the Long-Run Marginal Cost method, [7]) rather than the monetary savings. With a focus on the users' perspective, for example when market prices are either unavailable or do not accurately reflect the true economic value of savings, a reliable metric can be the monetary amount that individuals are willing to pay (WTP) to enjoy a specific benefit or avoid a particular cost [3]. Stated preference techniques are employed to determine WTP, allowing the elicitation of people's preferences in hypothetical scenarios.

Storage cost savings is the second type of savings. OS services enable the substitution of private data storage with open repositories or eliminate the necessity to store research outputs. The assessment approach involves a thorough examination of the expenses that are circumvented or diminished due to the utilisation of OS services, providing a quantification of the economic benefits derived from the cost-effective storage alternatives offered by open repositories. The avoided cost method (if a market exists) is suitable for assessing these savings, considering factors like storage space, market prices, or LRMC (if a market does not exist and self-production is the alternative to the OS service).

The third type of savings is related to labour, reflecting the gain in opportunity costs by saving working time through OS knowledge and tools. Shared codes and protocols reduce the need for coding from scratch, enabling users to build upon existing code and save working time. Sharing data mining techniques automates information collection, minimising the manual effort required for data entry. The existence of open data enhances efficiency in finding needed information, as open data is inherently more findable. OS projects also contribute to time savings in designing research projects and writing papers by facilitating the easier circulation of research outputs, reducing duplications of codes, papers, and data. Monetising this benefit involves assessing the time saved by users using methods like shadow wages or WTP.

The last category is transaction cost savings, related to time spent navigating copyright agreements, negotiating access to specific data, or other research outputs.

Open data, protocols, and software can reduce time spent on such procedures. The social value of this benefit is evaluated similarly to labour cost savings.

While these categories often overlap, caution is needed to avoid double counting. These insights contribute to understanding the multifaceted benefits of OS adoption and provide a framework for assessing its socio-economic impact.

3.2.2 Enablement

In some instances, benefits of OS can extend to enablement, encompassing activities that emerge from an open science environment and are less likely to materialise in a counterfactual scenario. Along the causal pathway timeline, enablement benefits are observed to occur subsequent to efficiency gains. However, attributing enablement gains solely to OS is not always justified. Other contributing factors or inputs likely play significant roles in the causal relationship between OS and the realisation of new products and services. Enablement often results from savings in time and money, allowing researchers and enterprises to focus on research tasks that might have been deferred if OS services had not provided access to knowledge.

Enablement benefits stem from knowledge spillovers resulting from the widespread dissemination of research outputs. Scientific journals are a primary medium for the scientific community and industry to stay informed about cutting-edge research, therefore, norms and pricing governing journal access are crucial. OS practices likely expand the possibility for knowledge production within the scientific community through open access and open data, enabling individuals to access and reuse publicly funded research results and data openly. Similarly, enterprises, by accessing OS outputs and utilising OS services, are likely to foster innovation. Additionally, early and easy accessibility to knowledge is likely to enhance the likelihood of patent registrations.

The rapid dissemination of knowledge facilitated by an OS environment provides a notable advantage. Open publications, codes, data, software, and research discoveries can be swiftly and widely shared, fostering a climate of innovation within enterprises. The transparency and openness allowed by OS projects lead to more efficient collaboration and knowledge exchange, reducing research and development costs and enabling exploration of new ideas without the constraints of expensive access fees or restrictive licensing agreements. This, in turn, offers opportunities for more transparent science and allows businesses to pursue innovative avenues that might have been financially prohibitive in a closed system. Enterprises gain the potential to develop novel products, services, and technologies that may not have emerged in a less collaborative and accessible environment.

In cases where enterprises lack the capacity to exploit shared research outputs effectively, OS projects can play a catalytic role in the creation of start-ups and spin-offs, addressing knowledge gaps. These new enterprises emerge to bridge the gap by preparing and processing complex open data, serving as intermediaries to make valuable information accessible to a broader range of industries and professionals.

The economic value of this benefit is typically quantified by measuring the incremental shadow profits resulting from the sale of new or improved products, services, and technologies compared to a hypothetical scenario without OS projects.

Another dimension of enablement gain is associated with patents and other forms of intellectual property rights, providing a significant advantage for enterprises. Using OS services can contribute to an increase in patent registrations for innovative products, services, and technologies by enterprises. When a patent is registered, it generates private returns for the inventor and the potential for knowledge spillover to society. When evaluating this benefit, it is essential to avoid double counting of the expected shadow profit generated by the new product. The marginal social value of patents is typically associated with both a private value (for the enterprise) and an externality (for society). Careful consideration is needed to distinguish and appropriately quantify these aspects in the assessment of the overall social and economic impact of OS projects.

4 Conclusions

Despite the significant progress made by the OS movement, several barriers hinder its full potential. These include the costs associated with openness, insufficient skills in data management, and diverse regulatory frameworks. To develop effective OS policies, a thorough understanding of OS practices and their impacts is crucial. While progress has been made in understanding OS dynamics within the research system, more limited evidence is available on how it affects economies and societies. Existing studies often focus on the OS movement in general, with less clarity on the role of individual OS projects or initiatives. Moreover, many studies assess the impacts of OS without comparing it to non-OS approaches, potentially leading to an overestimation of OS benefits.

Adopting a CBA framework for OS would provide a systematic and comparative assessment of the socio-economic costs and benefits of OS projects. Overall, the framework can contribute to a more nuanced understanding of the economic impacts of OS, facilitating evidence-based decision-making and policy formulation in the realm of scientific research and innovation. Applying CBA to assess the socio-economic impacts of OS requires to focus on direct, more short-term outcomes and impacts, encompassing benefits directly related to the OS project itself. For example, the availability of open data may reduce the time spent on data creation. These short-term outcomes are within the control of the participating organisations and can be upstream (e.g., affecting scientists involved in the set-up phase) or downstream (e.g., impacting end-users). On the other hand, long-term outcomes are influenced not only by the OS project itself but also by additional factors. For instance, the introduction of new e-health technology enabled by open science research may lead to a decrease in deaths caused by strokes, but this outcome requires various additional activities, investments, and factors to materialise.

Assessing long-term impacts falls outside the scope of CBA and necessitates other methods. Broader causal pathways frameworks can provide a more comprehensive perspective on the long-term outcomes of OS projects. The impact pathways identified within the framework of OS practices represent the non-linear sequences of steps connecting inputs to immediate and measurable outputs and extending to more indirect, broader impacts that may not be easily quantifiable. While CBA focuses on causal impacts through an incremental approach, impact pathways offer a progressively broader perspective, tracing the causal chain of OS impacts and identifying the mechanisms and conditions allowing these impacts to materialise. Still, taking into consideration a clear demarcation of the project boundaries, a proper counterfactual and the systematic assessment of both advantages and disadvantages, remain crucial for a proper impact assessment.

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How to Measure the Local Economic Impact of Large Research Infrastructure Procurement

Riccardo Crescenzi and Gabriele Piazza

Abstract While Research Infrastructure (RIs) are designed to address complex scientific questions, their capacity to generate visible economic benefits remains of fundamental importance to the countries that fund them. This chapter introduces a framework to conceptualise, identify and estimate the local economic effects of RI procurement, beyond the boundaries of RI suppliers. The evidence produced with the application of the proposed methodology can be used to showcase the potential economic returns of various RIs. This framework also underscores the importance of connections between local firms and the mediating role of local factors.

Keywords Research infrastructure · Economic impacts · Local economic development · Supply chains

1 Introduction

Can Larger Research Infrastructures (RIs)—such as the Large Hadron Collider at CERN or the International Space Station, bring economic benefits to local communities that fund them?

Answers to this question are central to the use of public funds. Making new discoveries is getting harder, requiring higher inputs both in terms of capital and labour [5]. At the same time, resources are limited, and many alternative possible investments (e.g. local schools or hospital services) with more tangible local benefits compete to attract them. The current macroeconomic situation, with rising inflation and war in Ukraine, has put further pressure on public budgets [12].

In this context, policymakers and citizens alike increasingly look for immediately visible benefits to justify public investment. Understanding the local impact of publicly-funded policies matters for two interrelated reasons. Firstly, the effects of

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public policies are most probably felt at the local level, where individuals and communities directly experience the benefits or drawbacks of these policies. Secondly, local constituencies often feel the direct impact of public policies, which can affect voter satisfaction and influence electoral outcomes. When local needs are not adequately addressed, it can lead to disillusionment with elected officials, decreasing their chances of re-election [22]. Furthermore, when local constituencies feel neglected or negatively affected by specific policies, they might be more inclined to support populist agendas that promise to address their concerns [22].

For these reasons, while RIs are designed to address complex scientific questions, their capacity to generate short-term visible benefits remains of fundamental importance to local communities that fund them.

Beyond the localized impacts in the areas where RIs are physically located [17, 21], research on the socio-economic effects of RIs has looked at procurement as a relevant channel for more spatially widespread and tangible benefits. This is because the design, building and upgrade of these large research projects often involve highly-knowledge-intensive firms that are not necessarily located in the proximity of the RI. Hence, the benefits can be more spatially spread.

The existing evidence on the effects of RI procurement suggests that, on average, firms that work with RIs experience an increase in sales, profits, and probability to patent [3, 6, 14]. However, there could be effects that go beyond the boundaries of the firms and affect the local economy in which these suppliers are located. This is because the procurement for these projects often involves firms in specialized clusters across the globe, creating new value chains similar to those in which MNEs operate. While the first tier of suppliers, particularly for high-tech orders, comprises a limited number of firms, these companies are often linked to a constellation of second- and third-tier suppliers [7]. And these supply chains tend to be spatially concentrated. At the same time, if these effects materialize, there could be some trade-offs. For example, crowding out could occur if these contracts increase local wages, making recruiting harder for other firms [24]. Similarly, there could be a displacement effect if jobs are created at the expense of other local businesses or firms in neighbouring areas [24].

Despite these potential wider effects, we lack evidence on this type of procurement's wider local economic impact. What is the economic effect on an area when a local firm receives a large RI contract? This is the question that this chapter attempts to address.

Estimating these potential local benefits has important policy implications. Positive effects would offer an additional economic rationale for the use of public resources to fund this type of projects, even when the application of new discoveries is not yet clear. In addition, local policymakers could consider this type of investment as another policy tool to improve their local economic performance, putting more effort into helping local firms bid for RI procurement contracts and facilitate the development of supportive eco-systems around the contracting firm.

There might also be implications for the procurement contracts allocation process. The procurement process for RIs often includes some fairness principles: contracts are distributed among the funding states to guarantee a fair return from their national contribution. However, these calculations are based on the value of the contracts and do not consider the potential wider effects on their host economies. Can these potential benefits be incorporated into the procurement process while still pursuing RI's scientific objectives?

Against this background, this chapter introduces a framework to conceptualise, identify and estimate the local economic effects of RI procurement. The rest of the chapter is organized as follows: firstly, we draw on the FDI and Global Value Chain literature to conceptualise and identify the potential local economic benefits of RI procurement. Secondly, we present a research design protocol to estimate the benefits. RI managers and policy practitioners can use this protocol to understand the potential local economic impact of future RI procurement. Thirdly, we report some results of our study on the local economic impact of Superconducting Radiofrequency cavities (SRF) for the European XFEL, which is an application of the framework we developed. Finally, we conclude by discussing the implications of our framework and case-study results for policy and research.

2 Expected Local Economic Effects of RI Procurement

When considering the impact that RI procurement might have on the local economy, we can conceptualize it as a positive economic 'shock'—something that is exogenous and unpredictable—that can have both direct and indirect effects on the local economy.

The first category of effects would include the impact on the supplier. For example, to fulfil the contract, the company might expand its workforce, and as a result, local employment might also go up [24].

The second category includes the effects on other local firms that have so far been overlooked in the RI literature. When thinking about the mechanisms and channels through which RI procurement can affect other local businesses and, consequently, the local economy, the literature on FDI and Global Value Chains (GVC) can offer some insights. Like regional sourcing by MNEs, procurement can be a demand stimulant for local employment [11]. According to this stream of literature, we can identify two main groups of mechanisms: intra-industry and inter-industry effects [9]. Both have a circumscribed regional dimension, meaning they decay with distance. The first group includes demonstration, labour mobility, and competition effects that might be relevant to understanding the impact of RI procurement. Demonstration effects are related to the exposure of local firms to new technology adopted by MNEs [9]. In the realm of RI procurement, there is evidence that suppliers have become more innovative, and this might have similar effects on local firms.

The second channel refers to domestic firms hiring workers who have previously worked for an MNE, who can then apply what they learnt in the new local firm [10]. In the context of RI procurement, staff at local suppliers might move to other local firms after the end of the contract. The third channel is the competition induced by MNEs. Foreign affiliates tend to be more productive and innovative, which might force local firms operating in the same sector to become more efficient or lose market share [9]. This could have a negative effect on employment in the rest of the local sector. Florio et al. [14] demonstrated how RI suppliers become more productive, which could hurt less competitive local firms operating in the same industry.

The inter-industry channel refers to spillovers arising from customer–supplier relationships between domestic and foreign firms. To the extent that the supplier and other local firms in the same sector compete with one another, MNEs might have incentives to prevent spillovers [18].

However, MNEs have a strong incentive to improve the productivity of their suppliers. Therefore, backward linkages—interactions between MNEs and their local suppliers—should have a positive effect on local firms. Javorcik [18] claimed that FDI backward linkages spillovers may take place through (i) direct knowledge transfer from foreign customers to local suppliers, (ii) higher requirements for product quality and on-time delivery introduced by multinationals, and (iii) increased demand for intermediate products, allowing local suppliers to benefit from economies of scale. RI suppliers might have similar incentives, and these backward linkages might positively affect the local economy. Similarly, local firms might also become more productive because they have access to better and cheaper inputs produced by foreign affiliates in upstream sectors, i.e., forward linkages [18].

The empirical literature has found ambiguous evidence on the presence of positive intra-industry effects, with some studies showing a negative impact through the competition mechanism [10]. In contrast, the literature tends to agree on the inter-industry effects through the backward linkage channel [9].

The Global Value Chain literature provides insights into the nature of these backward linkages and their implications for the local economic impact of procurement. Their relational aspect sets these connections within value chains apart from typical market-based spot transactions [2]. Gereffi et al. [15] categorize three primary types of relationships between buyers and suppliers in value chains: producer-driven, buyer-driven, and relational. In a producer-driven relationship, the lead firm maintains significant control over the production process to prevent knowledge spillovers to competitors. The buyer-driven type operates with input purchases made at arm's length through market-based transactions. The relational model emerges in settings requiring high levels of input customization. In such contexts, the connection between a buyer and its suppliers evolves over time. This continuous interaction can facilitate the exchange of tacit knowledge, fostering a mutual dependence between the parties involved.

Regarding RI procurement, the relationship between research organizations and first-tier suppliers resembles the relational type. However, a unique aspect of this relationship is that RIs typically do not manage their proprietary technology due to a commitment to open science, increasing the possibility of knowledge spillovers. While the evidence on other types of buyer–supplier interactions suggests that typical fixed-term contracts pose some challenges to transferring knowledge between the parties involved, Florio et al. [14] demonstrate that this is not the case in the context of RI procurement.

Concurrently, these first-tier suppliers often connect to a network of local second and third-tier suppliers for some of the more labour-intensive parts of the production. Florio et al. [14] argue that in the case of relational governance of procurement, there are benefits also for the other tiers of suppliers. The bonds between the first-tier suppliers and their upstream counterparts tend to be more hybrid, combining elements of the relational and producer-driven type. Arguably, these ties are less restrictive from a resource perspective, enabling this set of firms to seek other market opportunities. Emerging research on value chain resilience suggests that having a diversified customer base could enable second and third-tier suppliers to better withstand idiosyncratic shocks [19]. Diversification can make a value chain more resilient when the shocks are not positively correlated [19]. At the same time, there is a trade-off between exposure and diversification regarding efficiency.

These insights from these two streams of literature indicate that to understand the full scale of these wider effects of RI procurement, one needs to go beyond the relationship between the RI and the first-tier supplier and consider the entire value chain. These impacts are best captured when looking at the entire local economy where the suppliers are located, as the value chain for high-technology manufacturing tends to be spatially concentrated [16].

There could also be an impact on local services. The newly employed within the supplier or in the supply chain might spend their money locally, increasing the demand for local services, and this might lead to an increase in jobs in retail and hospitality [24]. The magnitude of these effects depends on the size of the impact on manufacturing and commuting patterns.

Based on the insights from these streams of literature, when looking at the RI local impact, we would expect a positive effect on employment concentrated in the supplier's sector and primarily activated through the backward linkages channel involving different tiers of suppliers. Beyond the size and duration of the contract, the extent to which the winning bidders use local suppliers will determine the magnitude of the local effect.

3 Research Design Protocol

In this section, we suggest the necessary steps in designing studies to estimate, ex-post, the local economic impact of RI procurement.

3.1 Technology

The first step is to select a technology. RIs purchase many different things for their operational and construction activities, from coffee to klystrons. However, to estimate the effect of an RI procurement action, a focus should be put on technologies mainly used by RIs in scientific research projects and that do not yet have wider commercial applications. This makes it easier to confidently attribute the observed impact directly to the specific procurement activity studied and not to other types of private or public demand. When selecting a technology, it is strongly advised to seek advice from RI staff, private sector and economics experts.

3.2 Geography

After choosing the technology, the next step is to select the appropriate geography for the analysis. As is often the case for RIs, producing specialized goods and services may involve a network of firms located in different regions. Therefore, the most appropriate geography choice might vary across various procurement activities.

When picking the geographical unit for the analysis, it is necessary to clearly understand the production and procurement processes for the required product or service. For example, how localized is the supply chain? Interviews with firms and RI staff involved in procurement activities might be the most direct way to gain this information. Existing literature might also provide additional background. As a rule of thumb, the more spatially concentrated the production is, the easier it is to detect any potential local effect.

In some cases, using a functional geography, such as the Labour Market Area that considers commuting patterns, might be more appropriate than using administrative boundaries. The larger the concerned geographical area, the smaller the individual contract is relative to the size of the local economy. This can make it more difficult to detect the effect. Hence, subject to data availability, it is advisable to begin the analysis with the smallest possible geographical unit.

3.3 Synthetic Control Method

To estimate the additional local economic impact of an RI procurement over and above what would have happened in its absence and to establish a causal relationship between the contract and the local economic impact, one must compare the suppliers' area with a suitable counterfactual scenario. In an ideal case, this comparison would involve a "control group" composed of other local areas with similar characteristics. However, this is often not possible. For the most technologically advanced contracts, only a handful of companies in the world are able to supply the product or service. The company's location choice might also be endogenous. In other words, the supplier might have decided to locate or stay in the area because of some local features. Furthermore, the presence of these highly specialized firms might make the industrial profile of the area different from other localities, making it harder to find a control group.

The synthetic control method (SCM), initially developed by Abadie and Gardeazabal [1], is the most suitable approach to address this challenge. It is based on the idea that when the units of observation are a small number of aggregate entities, as is the case for some of the most technologically advanced contracts, a combination of unaffected units provides a more appropriate comparison. The advantage of this method is that it can be replicated for different regions to assess the robustness and heterogeneity of the effects. The appropriateness of this method must be assessed on a case-by-case basis.

Policymakers and RI managers are interested in estimating the potential impacts of future procurement activities on specific local economies. The estimates from this ex-post analysis can be used to indicate the future potential impact of the same or very similar technologies. However, these estimates should be treated cautiously as they assume that the production and procurement processes and costs remain the same. The estimates would need to be adjusted if processes, costs and labour effectiveness evolve.

4 Case Study: The Impact of SRF Cavities Contracts in Italy

4.1 SRF Cavities

The study by Crescenzi and Piazza [8] is a practical example of the application of the research protocol discussed above for the estimation of the local economic impacts of the procurement of a large research infrastructure (the European XFEL in this case) on the local economy (Italian municipality of Schio) where one (of the only two) supplier of a key equipment (SRF cavities in this example) is located.

The design of the case study starts with the selection of a technology whose application is primarily for a research infrastructure (i.e. not a general technology with multiple applications beyond research infrastructure) but likely to generate a visible and identifiable local economic impact in the economy hosting its production. The initial key step involved a set of in-depth interviews with industry experts and scientists that offered a detailed overview on the suitability of different technologies for the study. Based on the evidence collected with these interviews it was decided to focus on SRF cavities: hollow structures made of superconducting material (niobium or coated copper). Three criteria determined this choice.

First, the study required to focus on a technology mainly used in scientific research rather than one with wider commercial use. This makes it possible to reasonably attribute the potential local effect more directly to the RI procurement contract rather than to other possible sources of demand for the same technology. For the same reason, the attention has been focused on technologies developed for RIs that operate in basic research. The selection was further narrowed down by looking at RIs involved in High-Energy Physics (HEP) experiments. The interviews confirmed that SRF cavities are exclusively used for particle accelerators. This allowed the study to isolate the impact of RI procurement: the intrinsic value of this technology lies purely in its technological content and its learning opportunities.

Second, the study needed to leverage a technology requiring close collaboration and interaction between RIs and firms. Both the evidence on RI procurement [14], and the broader literature on knowledge diffusion [4], suggest that this type of relationship is conducive to knowledge transfer, which tend to be diffused beyond the firm boundaries in a localized manner [13]. Interviews with firms and RIs involved in producing SRF cavities revealed that this type of collaboration was in place for most SRF cavity projects.

Third, a technology needed to be selected with a *potential* wider commercial application beyond its primary application for scientific research. This would increase the possibility of the investment affecting the local economy. Although SRF cavities are currently only used in particle accelerators, a recent study showed that High Power Impulse Magnetron Sputtering, a coating technology currently considered for the FCC SRF cavities at CERN, is already employed in some areas of the automotive, medical and communication industries [20].

4.2 The European XFEL

After conducting interviews with staff at various research organizations, the study identified the European X-ray Free Electron Laser (XFEL) as the most suitable case study. XFEL is a research facility located in Hamburg (Germany), where scientists from all over the world carry out experiments using X-ray flashes.[1]

XFEL was selected for two reasons. First, this was the first project in which firms directly produced SRF cavities. Before this production, only the mechanical fabrication was done by companies. In contrast, the surface treatment, the most demanding part of the production, was done by the commissioning research institutes [23]. Secondly, this was the largest deployment of SRF cavities to date—840 SRF cavities in total. In addition, the underlying technology for these cavities has become the standard for other accelerators [23]. The production started in 2012 and ended in 2015, with the first series of cavities delivered at the beginning of 2013. DESY in Germany managed the contracts. The contract was assigned to two companies: Research Instruments GmbH, with one plant in Bergisch Gladbach (Germany) and, another in Dortmund (Germany), and E. Zanon in Schio (Italy).

For commercial reasons, the companies did not disclose the details of the agreements. However, the selling price for each SRF cavity for other projects was said to be approximately € 100,000. This suggests that each contract was worth around € 40 million, a larger contract than most in the sector, according to interviews with industry experts.

[1] Its construction was a joint effort of its partners. The costs amount to 1.25 billion euros (in 2005 prices). Germany covered 57% of these costs, Russia 26%, and international partners covered the rest. Most of the contributions were in-kind.

4.3 E. Zanon and Schio

The study selected as its main focus E. Zanon Physics branch and Schio, a municipality of around 39,000 inhabitants (as of 2021) located in the province of Vicenza, in the Italian Veneto region, for two reasons.

First, as E. Zanon has only one site, it is easier to identify the geography of the production process and potential local effects. Second, all its personnel were involved in producing SRF cavities for XFEL, making it easier to attribute the observed impact to the procurement contract. In contrast, only a third of the staff members at Research Instrument GmbH were involved in this contract. This means that had we focused on Research Instruments GmbH, we would not have been able to isolate the XFEL contract impact from other concurrent projects.

4.4 Local Economic Impacts

The study employed state-of-the-art impact evaluation methods to estimate the impact on the local economy while netting out the estimated impact from any other confounding factors. The core idea of counterfactual estimation is to compare what actually happened with what might have happened if the production of the particular component needed for the RI had not been occurred. This approach helps in understanding the true local effect of procurement, as it isolates its impact from other factors that could influence the economy. By comparing the actual scenario with a hypothetical one (the counterfactual), the study can better attribute changes in the local economy directly to the investment, rather than to other external factors. For stakeholders, such as local governments or national governments funding RIs, the clarity provided by counterfactual analysis can be very beneficial. It helps in explaining the rationale behind economic decisions and in justifying future investments.

The study shows that, as a result of the contract, manufacturing jobs in the municipality of Schio have increased in comparison to what would have happened without the contract. And this positive effect goes beyond the jobs added directly by E. Zanon to fulfil the contract. Every job added by the supplier supported additional jobs in Schio's manufacturing sector and the effects on the rest of the local economy are much greater than those within the boundaries of the firm. When looking at the mechanisms, the study shows that this effect was mainly driven by backward linkages (other local firms supplying inputs for the final products), pointing to the importance of linking local businesses for these benefits to materialize.

5 Conclusions

In this chapter, we presented a new framework to identify and estimate the impact of RI procurement on the local economy in which the supplier is located. The results from this ex-post analysis can then be used to indicate the potential future of procurement activities for RIs yet to be built as well as to showcase the potential economic returns of various RIs.

The study on SRF cavities for the European XFEL has been used as a practical application of the proposed framework, showing that the impact on the local economy is much greater than the direct effect on the supplier highlighted in existing studies. This evidence suggests that by only looking at the impact on suppliers, the socio-economic impact of these projects would be underestimated. In addition to the scientific benefits, policymakers should consider these wider economic effects when evaluating such investments. While other types of investments might achieve similar local economic impacts, RI procurement, particularly when high-tech, can also push the frontiers of manufacturing and engineering and potentially the local technological capabilities.

This framework underscores the importance of connections between local firms and the mediating role of local factors. For local policymakers aiming to maximize these potential effects, a key strategy involves bolstering these linkages, both within individual localities and across different areas. A starting point in this process would be to map out the local supply chain and potential linkages with other areas. While most local areas may lack specialized firms capable of fulfilling the technical requirements of high-tech contracts, many others will have companies that could serve as second or third-tier suppliers in these supply chains. Given the internationalization of supply chains, understanding the spatial distribution of the entire production process for different technologies would also be beneficial for RI managers who want to ensure that most of these wider benefits accrue to funding member states. In addition, dedicated programmes to multiply economic benefits in the economies hosting RI suppliers might include incentives for using local suppliers or programs that help local businesses scale up to meet the demands of the RI supplier. Local suppliers might not initially meet the quality or scale requirements of larger firms. Public policies might need to support skill development, technological upgrades, and capacity building for local suppliers. By linking local businesses in this way, an economy can also become more resilient. Diversification in a local economy, achieved through robust backward linkages, can protect against economic downturns that might affect one industry or sector disproportionately (as seen in Schio). Backward linkages often facilitate the transfer of skills and technology from first tier RI suppliers to smaller (second tier) local suppliers. This can lead to an overall enhancement in the productivity and competitiveness of the local business sector.

The advantage of the approach proposed in this chapter is that it can be applied to other cases to better understand the heterogeneity of such effects. For example, it can be reproduced to examine whether smaller and less technologically intensive contracts can also impact the local economy in which the supplier is located. It would also be helpful to understand the mediating role of regional features. For instance, are these local effects larger in less developed regions? This could offer insights into whether RI procurement can be used as a policy tool in economically underperforming areas and help build more evidence on the local economic effects of these projects.

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Building CERN's Future Circular Collider—An Estimation of Its Impact on Value Added and Employment

Gerhard Streicher and Johannes Gutleber

Abstract This chapter explores the potential economic and employment impacts of constructing the Future Circular Collider (FCC), a next-generation particle accelerator being developed by CERN. The FCC project aims to build upon the existing accelerator complex near Geneva, extending into the Haute-Savoie region and introducing an unparalleled research facility for the global scientific community. By integrating a high-intensity electron-positron collider and a high-energy hadron collider, the FCC is designed to push the boundaries of particle physics throughout the twenty-first century. Beyond its scientific aspirations, the project has the potential to create significant economic value through direct and indirect employment, technology transfer, and innovation spillovers across sectors. The analysis presented in this chapter examines the anticipated impacts on regional and international economies, highlighting the benefits of such a large-scale infrastructure in advancing scientific frontiers while also delivering tangible contributions to society, innovation, and employment growth. Through advanced modelling and projections, the chapter estimates the FCC's potential to act as a catalyst for economic development, further solidifying Europe's leadership in high-energy physics research.

Keywords Future circular collider · CERN · Particle physics · Economic impact · Employment · Research infrastructure · Value-added · Innovation · Technology transfer · Scientific progress · Regional development · High-energy physics · Economic modelling · International collaboration

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1 Introduction

CERN, the European Organization for Nuclear Research, is hosting an international collaboration that develops scenarios for a new circular particle collider-based research infrastructure. The so called “Future Circular Collider” (FCC) would be located in the vicinity of CERN’s main sites (Meyrin, canton of Geneva, Switzerland, Prévessin, department Ain, France), connect to the existing particle accelerator complex and extend significantly into the Haute-Savoie department region (see Fig. 1). Hosting subsequently an intensity frontier electron–positron and an energy-frontier hadron particle collider, this research infrastructure has the potential to contribute substantially to the discipline of particle physics and the understanding of nature’s workings at the sub-atomic level with a research programme until the end of the twenty-first century.

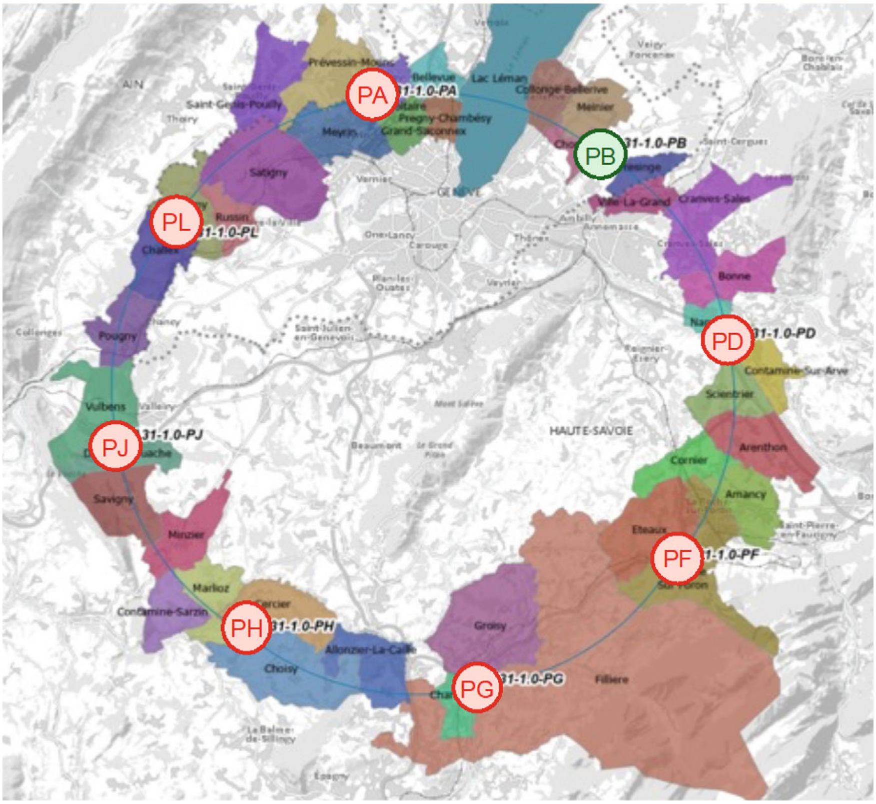

Fig. 1 Working hypothesis for a new future circular collider with a circumference of more than 90 km and eight surface sites that connects to the existing CERN particle accelerator complex. *Source* Placement scenario for the new particle-collider based research infrastructure developed in the frame of the FCCIS H2020 co-funded EU project. *Credits* FCC study/CERN

Such a research infrastructure can also contribute to scientific and technological progress in many areas that will be needed to construct and operate such a facility. This boundary-pushing effect can be felt in unrelated areas as well: the World Wide Web was conceived at CERN around 1990, leading to the take-off of the Internet, until then known as ARPANET, a computer network used primarily by US-American academic institutions.

Apart from science-changing insights and technological developments, there are more immediate economic benefits likely to arise from this project: the opportunities for firms to contribute to the installation and operation of this machine and the jobs that go along with these opportunities. The purpose of the following chapter is to contribute to an effective and continuously improving open platform to estimate such effects in order to help launch a policy development process to make scientific research infrastructures in Europe more resilient.[1,2]

2 Investment and Costs

The FCC's scientific potential comes with a sizable price tag: In total, investment and operation costs over a 25-year lifetime (10 years of construction followed by 15 years of operation[3]) are estimated at more than 21 bn CHF[4] (in 2019 prices[5]) (Table 1).

These expenditures are linked to tangible economic spill-over effects, even excluding scientific effects[6]: FCC-related CAPEX represents sales opportunities for firms, as does OPEX.[7] Employees engaged in the FCC programme earn wages, which

[1] There will be other incremental benefits from the FCC, from possible advances in fundamental research leading to practical technological progress to individual researchers' career opportunities, in and out of science. However, these aspects do not feature in the present analysis, but are dealt with in a separate segment of the integrating FCC socio-economic impact study. Interim results can for instance be looked at in Bastianin (2021).

[2] For the full report, see Streicher [8].

[3] 15 years of operation (plus 2 years of "scientific research and data processing with already collected data") for a setup with two "experiments".

[4] Investment volumes and operational expense are based on CERN estimates developed between 2019 and 2021, as were all assumptions on structural details for the investment and operation phases.

[5] Cost adjustments based on inflation, GDP and other economic indicator forecasts are not meaningful when capturing the impact generation potentials on large time scales. Therefore, this work chose to report on "current cost and effects" based on actual costs and effects generated today. This helps the reader to get an immediate understanding of the relation between investments and the connected effects. Incremental socio-economic benefits reported on FCC in a comprehensive study uses a social discount rate of 2% to compare the expenses and impacts over a long-time scale, as is best practice in this field of economics.

[6] Consensus among economics researchers exists that a monetary value of the core scientific mission cannot reliably be estimated, since it is unrelated to economic activities and the specific effects of the knowledge increase on economic activities cannot be foreseen.

[7] OPEX = Operational Expenditure; costs that a company incurs for running its day-to-day operations.

Table 1 FCC-related investment and operation cost estimates (CAPEX and OPEX)[8]

		Investment volume	Annualised volume
		[mn CHF]	[mn CHF/a]
FCC-related investment			
Total investment	2031–2050	12,097	605
Core phase	2031–2040	10,709	1071
Upgrade phase	2041–2050	1,388	139
FCC-operation			
FCC OPEX	2041–2055	2,950	199
FCC personnel	2028–2057	5,400	180
Total	2028–2057	21,100	700

Source FCC study preliminary cost estimates (2021). Totals are rounded; 2019 prices

are partially spent on consumption and represent therefore again potential sales for firms. The existing CERN installations are already today a major tourist attraction with up to 170,000 visitors per year before the pandemic. In the run-up to the FCC, visitor facilities will be upgraded and expanded to allow for a total of 300,000 visitors per year, inducing further effects for the regional tourism sector.

For the purpose of the estimation of the economic impacts on employment and value added, the project can be divided into distinct phases (see also Table 2):

- The initial, **core investment phase**, planned to span the decade between 2030 and 2040, when the underground infrastructure and surface technical infrastructures are constructed and the particle collider and the experiments are installed.
- A second **upgrade investment phase**, that is interleaved with the operation period in the subsequent decade, in which the particle collider is periodically updated to reach ever higher collision energies, as specified by the envisaged physics research programme.
- The **operation phase** during which the machine will be used for scientific research starts after 2040 and lasts until approximately 2055. Operating in a baseline scenario with two experiments and a possibility to install four experiments (not covered in this analysis), this period will last for 15 years ("FCC OPEX" in Table 2); however, scientific research personnel will still be active for 2–3 years after the end of particle collider operation to analyse the data gathered in the course of the experiments ("FCC Personnel" in Table 2).
- During the operation phase, the FCC will generate value added directly by virtue of paying wages and through the depreciation of the original investment ("FCC direct" in Table 2).

CAPEX = Capital Expenditure; purchases of significant goods or services that will be used to improve a company's performance in the future.

[8] See Footnote 4.

Table 2 Summary of economic effects and linkages related to FCC construction and operation, annualised over FCC-related construction and operation 2028–57[9]

	Investment / consumption period	Investment / consumption volume	annualised invest./cons. volume	Average annual Value added effects [Mio. CHF]			Sum total	Avergae annual employment effects [persons]			Sum total
				Direct	Indirect	induced		Direct	Indirect	induced	
Investment related											
Total Investments (I + U)	2031–2050	12,097	403	179	206	86	471	2600	3400	1700	7700
Initial Investments	2031–2040	10,709	357	160	184	75	418	2400	3000	1500	6900
Upgrade Investments	2041–2050	1388	46	19	22	11	53	200	400	200	800
Operation related											
Direct FCC	2041–2057	0	0	255	0	0	255	5700	0	0	5700
OPEX	2041–2055	2956	99	40	50	27	116	400	700	500	1700
Living-related for resident personnel	2028–2057	9180	306	149	106	368	623	1600	1600	5200	8400
Visitors	2028–2057	3900	130	46	67	61	174	700	1000	800	2500
Total	2028–2057	28,133	938	669	429	541	1384	11,000	6700	8200	26,000

Source Own calculations with ADAGIO based on CERN data

[9] In all tables, results on value added are rounded to the nearest 50 if value > 500 and to the nearest 10 if 20 < value $\leq$ 500 and to 1 if value $\leq$ 20. Values on employment are rounded to one decimal. Sums are rounded independently, rounding errors are not compensated.

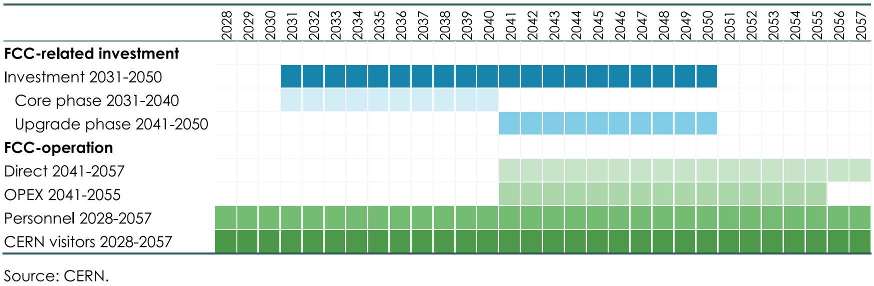

Fig. 2 Schedule of the FCC-ee project for the purpose of economic analysis of the employment sector. *Source* CERN

- During those phases and including partially the "design phase" that is assumed to start around 2028 when the first project-related, relevant investments take place, between 4000 and 11,000 persons will work for the project, not all of them on-site. The induced **consumer spending** of the resident FCC personnel will contribute to the economy of the region and beyond.
- A visitor facilities development programme that is already starting with the inauguration of the "Science Gateway" at the CERN headquarters in 2023, will permit gradually to increase the annual **visitor numbers** from the current 150,000 to around 300,000. A survey by CERN (see [5]) showed that visitors typically stay for an average of 4 nights spending around 1000 CHF per person, thus significantly contributing to the local economies of the western part of Switzerland in the Auvergne-Rhône-Alpes region in France

Figure 2 depicts the different phases used for the economic analysis of the employment sector in chronological form.

Those outlays—spending on FCC investment and operation as well as visitors' expenditures—are in turn associated with opportunities for firms in terms of turnover and employment. Further impact pathways exist and could be evaluated, subject to resource availability for such studies.

3 Model and Method

The method of choice to estimate value added and employment associated with some investment project is Input–Output Analysis (e.g., [7]). IO analysis is based on Input–Output tables, which split up the total economy into economic sectors (corresponding to commodities, i.e. goods and services) and compile the flows of intermediate inputs and outputs (one firm's inputs are another firm's output) between these sectors from statistical sources like surveys, tax records, or trade data. In the case of multiregional IO tables, these flows additionally distinguish between sectors in different regions, thus following the flows between sectors in different regions—the global value chains.

By recording the flows of intermediate products between sectors (as well as the employment associated with these flows), the method takes into account the total production process beyond the **direct** purchase of the final investment item from a contractor, including all **indirect** effects at the level of this contractor's suppliers and their suppliers.[10] Thus, IO analysis highlights the entire global value chain set into motion when an investment good is purchased. In addition, IO analysis can also be used to estimate the **induced** effects that are linked to the consumption and investment connected to the wages and profits generated in the course of this production process, resulting in the simulation of a "Keynesian economic multiplier".[11] This economic cycle brings about a widening of the economic effects, both in sectoral and regional terms (purchases of intermediate products from other sectors as well as other regions).

To estimate these effects, we use ADAGIO, a multiregional IO model developed at WIFO.[12]

ADAGIO—A Global Dynamic Input-Output Model

ADAGIO is an Input-Output model, distinguishing 43 countries (the EU 27 plus 16 of the major economies) and 64 sectors and commodities. At its core, it is a full representation of the flows of goods and services between these 64 sectors in the 43 countries (plus the Rest-of-the-World), tracing out the "global value chains" connected to any (idealized) commodity that is produced or consumed in the model countries. This allows ADAGIO to simulate the effects on output, value added and employment of some "demand shock", new demand that for example arises from the FCC project.

To make use of this model, we first convert the investment plan into demand for model-compatible investment commodities.[13] The main beneficiaries in terms of sales are construction (with almost 40% of the investment volume), electronic, electrical and mechanical equipment (with more than 40%). As in this explanatory stage of the project, the individual contractors cannot be known, we must make assumptions about where these commodities are sourced: For a broad regional structure of the origins of the FCC parts and inputs, we make a "fair share" assumption which reflects member countries' contributions to the CERN budget to determine the total

[10] IO analysis allows to follow—in a statistical way—the, say, metal components of a machine via the production of its metal products and the production of the metal itself all the way back to the mining of the iron ore and coal.

[11] Induced effects constitute **multiplier effects**: by working via value added, they amplify the initial direct and indirect effects.

[12] FOR technical details of FIDELIO, ADAGIO's predecessor which was developed for and with the EU's Institute for Prodpective Technology Studies IPTS, see Kratena et al. [6]

[13] FOR details on this as well as all details on all the other calculations, assumptions and results, see Streicher [8]

amount for the contracts awarded to the firms of each member state (allowing for some deliveries from non-members of crucial components which cannot be sourced from member states). Additionally, assumptions about which goods and services are purchased from each member are based on each country's economic and technological strengths and specialization. In economic terms, this specialization is reflected in a country's export structure—if its firms are especially competitive at producing some specific commodity, then it should lead to this commodity having an above-average share in the country's total exports. Thus, if France has a relative advantage in, say, machinery, apparent from an above-average share of machines in its exports, then we assume that France also has an above-average share of machines supplied for the FCC. In this way we ensure that FCC investment goods are sourced from the member states where they are produced most efficiently. However, one must consider that the distribution of specialisation is evolving. Evidence from previous studies on the LHC project also showed that a project of the FCC scale can induce an acceleration of technology development in a country [4] and thus also influence the evolution of regional specialization.[14] A careful analysis of the needs and a policy development together with participating nations and industrial partners is therefore required during a project preparatory phase.

In the regional dimension, expenditures by resident staff and visitors are easier to pinpoint: apart from mobility-related services (e.g. spending on non-regional transport), almost all purchases take place in the region on both sides of the Swiss-French border. Figure 3 shows today's distribution of the persons who participate in CERN's projects and operation activities. As ADAGIO operates at the national level only, we assume a 50:50 split of visitor expenditures between France and Switzerland as well as a 75:25 split of living expenditures by resident personnel between France and Switzerland [1].

Having specified the procurements in the regional as well as the sectoral dimension, we can use ADAGIO to estimate the global effects on production, value added and employment that are linked to the construction and operation of the FCC under the assumption of today's economic performance and specializations of nations.

[14] A systematic monitoring system of key economic variables of contractors (turnover, employment, export share, R&D expenditures, etc.) before, during and after their involvement with the FCC would allow for the analysis of such specialisation at the level of individual firms, thus helping to better understand such knowledge-driven developments.

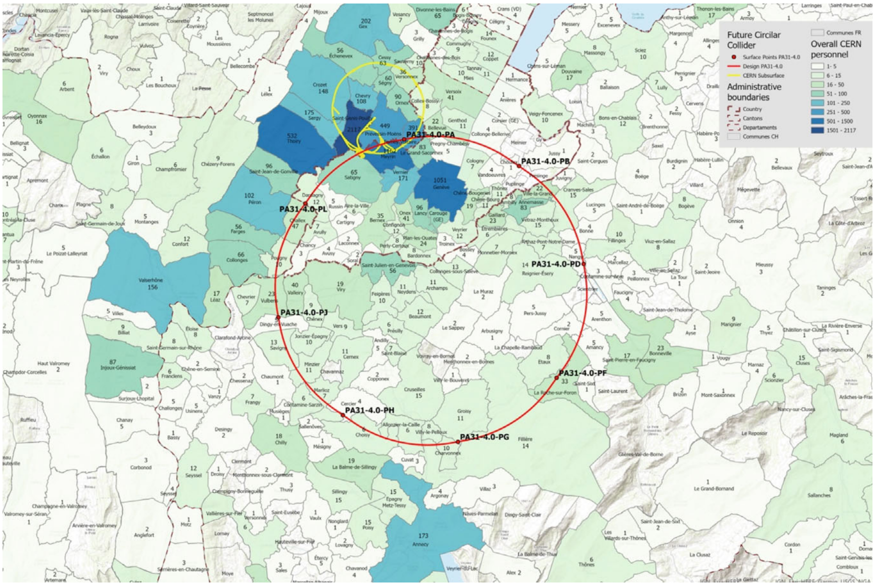

Fig. 3 Places of residence of current CERN employees, resident users, resident contractors. The yellow structures indicate CERN's current particle accelerator complex. The red ring indicates the perimeter of the FCC. It is likely that today's distribution of residents (two third in France and one third in Switzerland) experiences a shift towards the Haute-Savoie region (three quarters in France and one quarter in Switzerland). *Credit* FCC Study/CERN

4 Results

Table 2 reports the average annual effects over the project's 30-year period for the investment as well as the operating phases.

Over the 30 years of FCC construction and operation, about 28 bn CHF of expenses (on average about 940 mio CHF per year) are estimated to occur. Thereof, about 21 bn CHF relate to the construction and operation. The average annual spending of 940 mio CHF is connected with an estimated 1, 4 bn CHF of world-wide value added, filling 26,000 jobs. This means that in addition to about 6000 directly project-related science, engineering, administration, and management jobs, more than 20,000 jobs are secured to provide the goods and services for the construction and operation of the FCC, as well as for the goods and services that are consumed by FCC personnel and visitors. Most of the job opportunities (and value added) are generated during construction; Fig. 4 shows, how the estimated number of jobs linked to the construction and operation of the FCC develops over the whole period. It is important to note that the economic analysis cannot pinpoint the national location of these jobs; rather it is based on the above-mentioned assumptions on the distribution of direct contracts between the CERN member states. For any more accurate estimation, an organisation model and project structure need to be drawn up that permit analysing

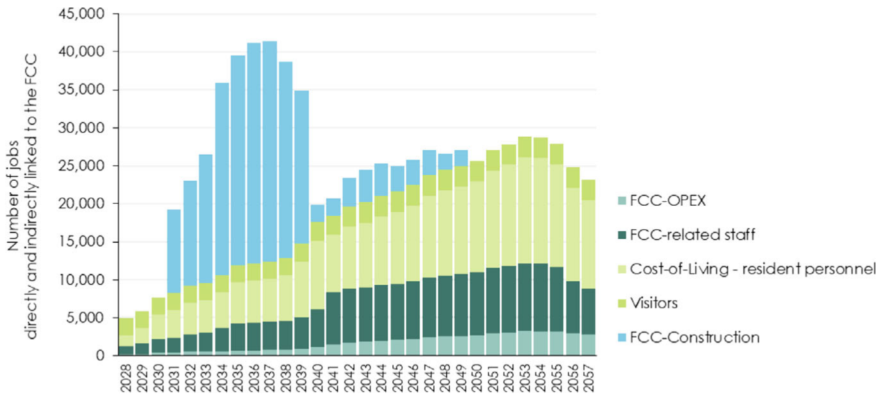

Fig. 4 Summary of annual employment effects related to FCC construction and operation (world total). *Source* Own calculations with ADAGIO based on CERN data

the effects and locations of employment related value-added in detail (e.g. wages, taxes, insurances).

Under the current national specialization assumption, the countries that benefit most from the CAPEX and OPEX spending are Germany, United Kingdom, France, Italy, the USA and Spain. This is not surprising as we assumed in a first analysis that direct contracts are proportional to a country's contribution to the CERN budget and these countries are the biggest contributors.[15] Immediately after these countries, however, China would profit most from an FCC project, although it is not a member of CERN, and therefore only a very small share of the direct contracts was considered to be awarded to firms from this country. This discrepancy between China's share in the initial investment and in the induced value-added highlights its prominent role in the global value chain. In contrast, the major share of the economic effects of spending by resident personnel as well as visitors remains in France and Switzerland, the host countries.

5 Discussion

In this report, we covered some aspects that go beyond the narrowly defined purpose of a value-added analysis for the FCC construction and operation; these include for instance the touristic aspects, but also the induced effects from the cost-of-living expenditures of FCC personnel. However, this is certainly not exhaustive, and a multitude of additional effects and developments with links to the FCC remain to be identified (and estimated), whose economic potential however could not be explored

[15] For the USA, which is not an official member of CERN, the effect can be traced to the assumption of a contribution to the experimental research operation programme.

here.[16] Some examples for which dedicated economic impact studies could be carried out and for which socio-economic strategies and policies could be developed include, but are not limited to:

- Global co-operation on a technologically advanced project like the FCC creates a special environment in which personal and institutional networks can thrive, laying the foundation for future collaborations on scientific or commercial endeavors. While the overall value-added figures of an FCC project would not significantly differ from a conventional infrastructure investment project (e.g. a train or road tunnel, a bridge), a scientific research infrastructures represents an investment choice that leads to sustained returns over its entire lifecycle (and probably beyond) with strategic development opportunities that strengthen the economic competitiveness and cohesion of the participating nations in (among others) high-tech co-developed products and services, increased markets and competitiveness of participating companies, development of underdeveloped sectors in a country to increase specialisation and most importantly, the sustained development of highly qualified and academic workforce, which are known to be key drivers of the economic development.
- FCC contracts with their exacting specifications on size and quality push the limits for many suppliers, even for those that would not be counted as "high tech"; For many suppliers, this also pays off commercially by improving their (future) profit potential.[17]
- However, concentration on the direct returns from such a project—even if those can be sizable, as this analysis has shown—is somewhat short-sighted: The participation of specialised regions on the one side and the development of key specialisations on the other side outweigh individual national short-term returns on annual membership fees. The academia-industry-third sector co-development approach is by far more relevant for scientific research infrastructure developments. It has been confirmed very recently that the key ingredient for industrial spillover effects is the relationship between the research infrastructure and the contracted company [2].[18] This overarching appraisal approach leads to governance and control over key technologies for the communities of participating nations, by increasing their share in global value chain effects (while at the same time strengthening their resilience towards detrimental exposure to the same global value chains). Acting as a group, they have stronger hand in setting the conditions for global participation and creating strategic advantages through a common market. As outlined above, the sustained training of early-stage career professionals in an international

[16] Some of them were dealt with in other reports on the FCC, such as the impact on science as well as individual careers within and outside science or the impact of technological challenges on suppliers to the FCC.

[17] Gutleber et al. (2021) conclude in Chapter 4.3. that "1 Euro spent for LHC procurement generates on average 15.3 Euro of additional revenues and 2 euro of additional profits for the supplier" (or even 20 resp 3.11 Euro in the case of a high-tech procurement contract).

[18] As a matter of fact, the EIB uses the "Internal Economic Return Rate" (IERR) as the key parameter to judge if an investment is not acceptable, fair, good, very good or excellent [9].

and mobility-oriented ecosystem is a key investment multiplier that works across generations.

- Given the dimensions of the subsurface structures housing the FCC, innovative solutions to manage the excavated material must be developed and brought to market to avoid disposal and negative effects connected to such a process. This approach has positive impact potentials on an entire industry sector that is today still largely relying on disposal and thermic truck transport with significant nuisances and carbon footprint. Typically, many conventional infrastructure projects have a low overall project budget compared to the investment needs for developing and bringing to market circular-economy technologies. Therefore, the innovation processes as well as the evolution of the legal and regulatory frameworks are still slow. The FCC is sufficiently large and long lasting to make a difference in this sector. Recently established cooperation with the "Metro Lausanne" (Switzerland), the Lyon-Turin Tunnel (TELT), the SAFER[19] of the region Auvergne-Rhône-Alpes and leading companies in the field demonstrate the necessity and validity of this impact pathway.
- The FCC can trigger the development of more efficient electrical distribution systems, refrigeration systems, heat recovery, supply and storage systems, with benefits for the whole economy and society. The supply of low-grade (40 to 45 degrees Celsius) waste heat for heating, aqua cultures and aquaponics, thermal applications, biogas production and as a baseline for food and chemical industries is an intriguing case with significant economic value-added potentials. Recently in 2023, CERN cooperation partners Ginger Burgeap (France) and NTNU (Norway) started to analyse the market potentials and develop solutions around CO2 as a transport medium for heat networks and storage systems. Regionally, a project like the FCC can act as an infrastructure development catalyser, since its size and duration are large enough to justify the works from which the environment in which the project is embedded will benefit.
- As in the past (e.g. with the World Wide Web), FCC-related work is likely to advance the state-of-the-art in software applications, from business information systems to general software libraries. Examples that have already been analysed are digital libraries (the CERN-operated Zenodo, which is based on Invenio), collaborative tools (Indico) and particle-matter interaction modeling tools that find application in life-sciences and space technologies.
- Part of the up to 11,000 people would contribute to the regional economy through their consumption spending. With the installation of four instead of two experiments, the effect would even be more pronounced. However, the project would also be an important economic player in the region beyond these induced effects. With respect to the current impacts that CERN generates, the FCC's perimeter of economic effects would be enlarged.

At a general level, the results presented in this report show that the "costs" that a scientific research infrastructure development project like the FCC entails are directly

[19] Link to the SAFER in France.

connected with "economic impacts", in terms of supply opportunities for firms and employment opportunities for scientists and non-scientists alike. By concentrating on a core set of transmission mechanisms only, these results constitute a lower bound for the expected economic effects. Numerous drivers and effects were not included at this initial stage in the analysis. Therefore, even though the narrow economic linkages of the construction and operation of the FCC are not larger than would be expected for a conventional infrastructure project of this size, the potential for spillovers into quite unrelated areas of technology and business are certainly much more pronounced—for example, only few projects would have the FCC's touristic attractiveness, not to mention its technological Open Innovation potentials.

It is important to highlight that the economic effects of large-scale scientific research infrastructures are sustained over long periods of time and are not limited to individual nations, but rather for communities and for a group of participating nations that acts collaboratively as a "whole". The focus on the involvement of persons at the early stages of their careers leads to impactful societal and economic development if the eco-system foresees an effective transfer of these trained people into the "ecosystem" of participating nations, supporting mobility. Marie-Curie actions at CERN and within the framework of CERN managed projects have given evidence for these effects with the quantitative evidence for a lifetime salary premium for those people with respect to their peers who are not exposed to a comparable experience [3]. However, a dedicated and targeted international early career programme would be needed to assure the appropriate competence transfer from science to industry, ideally involving directly the private and third-sector partners. Such a system would have a natural place in the framework of a EU research programme, but, however, does not yet exist. The effort of proposing and running numerous individual small training projects is high and does not yield the same effects as a single, uniform programme that targets research infrastructures such as the FCC and comparable organisations (e.g. ESO, SKA).

By estimating the regional structure of the effects linked to the construction and operation of the FCC, the analysis has also shown that the connection between contributions to a CERN project, direct contracts and indirect benefits is not always clear-cut. For example, the USA and China, which are not CERN member states and who therefore do not contribute annually to its budget, are estimated to have sizable economic benefits due to their prominent roles in global value chains. This finding could form a basis for negotiations between CERN and such countries on intensifying and formalizing mutually beneficial collaborations in the future. The direct, indirect and induced economic effects based on the analysis of the internationally recognized and widely used Input–Output method could also inform the definition of adequate annual contributions to a project like the FCC.

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The Value of a Collaborative Platform in a Global Project. The Indico Case Study

Irene del Rosario Crespo Garrido, María Loureiro García, and Johannes Gutleber

Abstract The rise of collaborative platforms has revolutionized the way individuals and organizations interact. The impact perimeter embraces interpersonal communication, knowledge sharing, and collective problem-solving. Indico, a web-based platform providing a free event management system, designed, implemented, maintained, and operated by CERN is a prime example of such type of platform. It provides a range of features and benefits for organizations and individuals hosting events of any kind. Indico improves work efficiency by streamlining the event management processes, reducing manual effort, and saving time. It also leads to sustainable practices and cost savings by eliminating paper-based processes and minimizing physical infrastructure requirements. It enhances accessibility by offering virtual event options, enabling wider participation, and promoting inclusivity. The platform fosters interdisciplinary knowledge sharing and collaboration among event participants by serving as a persistent and durable repository of presentations, articles, minutes, and writeups, including publication and protection mechanisms. Making event-relating materials available online contributes to knowledge dissemination and advancing research and professional communities. Additionally, Indico can further contribute to environmental sustainability by reducing carbon emissions through virtual events and reducing the use of paper. The data management and reporting capabilities of Indico enable data-driven decision-making for future events and resource allocation. This article reports on the socio-economic value of the Indico platform. The presented work used the stated preferences approach to estimate the socio-economic value that can be expected from a collaborative platform that a future large-scale international research infrastructure will require and put in place for its purposes.

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The approach taken to monetarize the socio-economic impact produced by the platform is the Choice Experiment Method. The monetary values obtained amounts to about 3.1 billion CHF discounted for a period of 29 years (2028–2057).

Keywords Indico · CERN · LHC · Open-source · WTP · Economic impact · Social impact

1 Introduction, Motivation, and Goal

The advent of collaborative platforms has transformed the way individuals and organizations work together, enabling efficient communication, knowledge sharing, and collective problem-solving. Collaborative platforms provide a virtual space for users to collaborate, share resources, and co-create content, fostering teamwork and synergy. As these platforms continue to gain popularity, it becomes increasingly important to understand their value and impact on individuals, organizations, and society.

The value estimation of a collaborative platform encompasses a wide range of factors, including productivity gains, cost savings, innovation, knowledge creation, and social capital. By leveraging technology to facilitate collaboration and information exchange, these platforms have the potential to unlock significant value across various domains.

CERN has been promoting the Open Science movement [9] since its inception as an intergovernmental organization. This has led to the development of open-access tools and platforms that can be used by any individual. Among them is the Indico[1] collaborative event management platform, used in an ever-growing user community by several different institutions around the world.

The motivation of this analysis is to elucidate the socio-economic potential impact that emerges from collaborative software platforms and tools that large-scale, worldwide distributed scientific research programs such as CERN's Large Hadron Collider [8] require and eventually trigger.

The goal of this study is to use an existing platform (in this case Indico) as a factual example to estimate the quantitative socio-economic impact potential of a software platform that a new large-scale research infrastructure, the Future Circular Collider [1] will require.

Indico [10] is a free event management system, designed, implemented, maintained, and operated by CERN. It provides comprehensive tools and features for planning, organizing, and executing various types of events. It is designed to streamline event management processes and enhance the overall event experience for organizers,

[1] Indico is an Open Source Software, freely available to the world, online available at https://getindico.io.

speakers, attendees, and participants. Indico offers a wide range of functionalities to support event planning and management. These include:

- Registration management: Indico allows organizers to create customizable registration forms, manage attendee data, and process registrations efficiently. It supports different registration types, such as early bird, regular, and group registrations.
- Abstract submission and review: For events involving presentations or research papers, Indico provides a submission and review system. It enables authors to submit abstracts, facilitates a peer-review process, and helps organizers in selecting and scheduling presentations.
- Program scheduling: Indico offers features for creating and managing event agendas, including sessions, multiple tracks, and speaker assignments. It allows organizers to easily update and communicate any changes in the program schedule to attendees.
- Speaker and presenter management: Indico provides tools for managing speakers and presenters, allowing organizers to collect and manage speaker profiles, bios, presentation materials, and session assignments. It ensures smooth coordination and communication with speakers before and during the event.
- Attendee communication: Indico offers various communication channels to interact with event attendees, including email notifications, event announcements, and targeted messaging. This helps organizers keep participants informed about updates, changes, and important event details.
- Virtual event support: Indico has adapted to the changing landscape of events by providing virtual event options. It supports virtual conferences, webinars, and live-streamed sessions, allowing participants to join remotely and interact with speakers and attendees virtually.
- Analytics and reporting: Indico provides data management and reporting features, allowing organizers to gather insights into event attendance, participant demographics, and engagement. It helps in evaluating the success of an event, measuring impact, and making data-driven decisions for future events.
- Integration capabilities: Indico integrates with various third-party tools and services, such as video conferencing platforms, room reservations, payment gateways, and content management systems. This enables seamless data exchange and enhances the functionality of the platform.
- Cost-effectiveness: Indico eliminates the need for expensive event management software licenses or hiring dedicated event planners and office administration personnel, making them accessible to the individuals and organizations who manage their events directly. Far from other free event management tools, Indico does not intend to generate revenue through optional premium features, advertisements, or partnerships with service providers, allowing it to offer its functionality utterly free of charge to its users. The need for the international organization to self-organize their global research programs that are set up as collaborative endeavors assure long-term maintenance, support, and continued development of

the platform. This benefit spills over to all other users of the platform that in total today exceed the original user community.

Indico simplifies and automates event management tasks, streamlining processes, and improving efficiency for organizers and participants. It offers a user-friendly interface, customizable options, and flexibility to adapt to different event types and sizes.

This article explores the benefits qualitatively produced by the Indico platform, and then transforms them into a quantified estimate of the socio-economic impact of the Indico platform, based on a method of choice experiment conducted through a survey distributed in different countries.

2 Indico Socio-economic Benefits Pathways

Indico offers several socio-economic benefit potentials for organizations, event organizers and participants, and the wider community outside the core user community. Some of the impact pathways include for instance:

- Increased efficiency: Indico streamlines event management processes, automating tasks such as registration, abstract submission, scheduling, and communication. This improves overall operational efficiency, reducing manual effort and administrative burden. Event organizers can allocate their time and resources more effectively, focusing on delivering a high-quality event experience.
- Cost savings: By using Indico, organizations can achieve significant cost savings. The platform eliminates the need for paper-based processes, reducing printing and shipping expenses. Additionally, it minimizes the need for physical infrastructure such as venue rental management, reducing costs associated with event logistics. Virtual event options provided by Indico can further save on travel and accommodation expenses for participants.
- Increased accessibility and inclusivity: Indico enhances the accessibility to events by providing virtual options. This allows individuals who may have limitations in attending physical events, such as mobility issues or geographical constraints, to participate remotely. It promotes inclusivity, enabling a wider range of participants to engage with events and share knowledge regardless of their location.
- Knowledge sharing and collaboration: Indico facilitates knowledge sharing and collaboration among event participants. Through features such as discussion forums and real-time communication tools, attendees can exchange ideas, ask questions, and build connections with peers. This fosters collaboration, interdisciplinary dialogue, and the potential for new research collaborations and partnerships.
- Networking opportunities: Indico creates networking opportunities for event participants, both in-person and virtually. Attendees can connect with experts, researchers, industry professionals, and peers who share common interests and

goals. These connections can lead to future collaborations, career advancements, and knowledge exchange.

- Knowledge dissemination: Indico supports the dissemination of research findings, abstracts, and presentations beyond the event itself. Making event materials available online enables broader access to valuable knowledge and research outputs. This promotes the transfer of knowledge, encourages further research, and contributes to the advancement of scientific, academic, and professional communities.
- Economic impact: Successful events facilitated by Indico can have a positive economic impact on local communities. Events attract participants from different regions, driving tourism, hotel bookings, and spending on local services such as transportation, restaurants, and retail. This economic boost can benefit various sectors and contribute to local economic development.
- Environmental sustainability: Indico contributes to environmental sustainability efforts by providing virtual event options. Virtual events significantly reduce carbon emissions associated with travel, as participants can attend from their locations. Additionally, Indico's paperless approach reduces paper waste, promoting eco-friendly practices.
- Data-driven decision-making: Indico's data management and reporting capabilities enable event organizers to collect and analyze event attendance, participant demographics, and engagement data. The data can be used to improve event planning and measure the impact and success of events. It facilitates evidence-based decision-making for future events and resource allocation.
- Community development: Indico being an open-source project, encourages community involvement and collaboration. Users can contribute to its development, report bugs, suggest enhancements, and share their experiences with the platform. This fosters a sense of community, promotes knowledge sharing, and allows the project to evolve and improve over time.

To be able to estimate the quantitative socio-economic value that Indico generates, we designed and carried out a survey-based study based on the choice experiment method. The subsequent section sheds light on this approach.

3 Assessing the Willingness to Pay

We used the choice experiment method [12] to evaluate the socio-economic value of Indico by estimating the Willingess to Pay (WTP) [3] among private sector users in five countries: Spain, Italy, France, Germany, the United States, and the United Kingdom. Similar methodologies have been utilized by [2, 6, 13, 14] in their respective studies.

The choice experiment method is a survey-based approach used in economics and social sciences to measure individuals' preferences for different goods or services and estimate their willingness to pay, thus elucidating the true underlying value that

Table 1 The exchange rate used in this study

The exchange rate used for the study, November 11, 2022	
1 $	0.97 €
1 £	1.14 €

the good represents for its consumers. It is commonly employed to evaluate the economic value of environmental and healthcare projects, public goods, or policy changes. It allows researchers to capture the heterogeneity in preferences within a population and provide insights into the factors that drive decision-making.

In a choice experiment, respondents are presented with a series of choice scenarios that involve multiple options or alternatives. Each one is described by a set of attributes or characteristics, and each attribute can take different levels or values. The respondents are asked to choose their preferred option or alternative from each scenario or rank them based on their preferences.

This method allows researchers to quantify preferences, understand trade-offs between attributes, and predict people's likely choices for different scenarios. It can provide valuable insights for product development, policy formulation, market segmentation, and resource allocation decisions.

We surveyed to gather data from participants in these individual countries as a basis to assess Indico's socio-economic impact. The survey included a sample of 2100 respondents, with 350 individuals from each of the six countries. The target group for the survey comprised employees above 18 years of age working in companies from the private sector with a minimum of 50 workplaces and who regularly use conference, workshop, and meeting management software. To ensure consistency, the monetary values obtained in various currencies were converted to euros, using the exchange rate as of November 11, 2022, reported in Table 1.

The survey findings are presented in two different sections. The first section provides an overview of the respondents' profiles, outlining their characteristics and demographics. The second section delves into the outcomes of the respondents' answers and willingness to pay, which was obtained using the choice experiment method.

3.1 Respondent´s Profiles

Out of the 2100 participants, 1089 individuals were men (51.86%), 1009 individuals were women (48.04%), and 3 participants identified as a different gender (Fig. 1). The respondent profile shows a nearly equal distribution between men and women aged 30–65.

The data presented in Fig. 2 and Table 2 depict the educational attainment and current occupations of the respondents. To ensure a diverse and contrasting sample, a wide range of occupations has been deliberately selected. Notably, most respondents reported that other occupations primarily stem from the medical field.

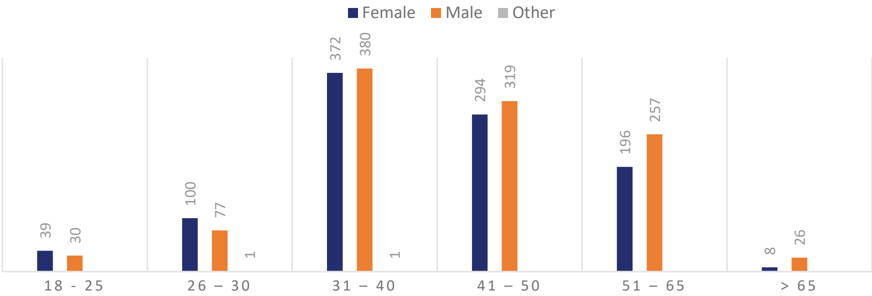

Fig. 1 Age range of the respondents by gender

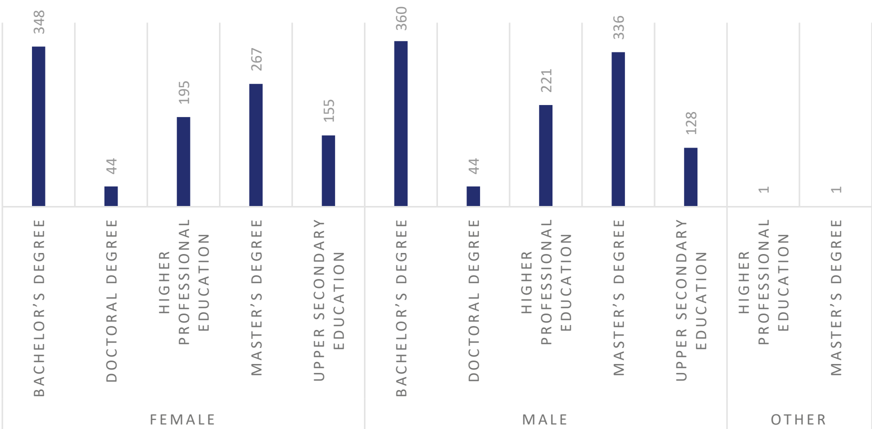

Fig. 2 The highest level of education of the respondents in terms of gender

When respondents were asked about their gross salary, the majority of participants (excluding 51 respondents) disclosed their annual income. The data reveals that most respondents earn more than € 45,000 per year. The distribution of income ranges within the sample is depicted in Fig. 3.

The results are presented by categorizing the respondents based on their event management use patterns and familiarity with meeting and conference management tools and software. Some survey participants are well acquainted with these tools and software and use them extensively in their professional lives. The findings for this group are illustrated in Figs. 4 and 5.

We observed that the majority of respondents actively participate in events using these tools or software. A smaller group of respondents has the profile of an event organizer (Fig. 6).

Table 2 Occupational status by country

Job title by country	France	Germany	Italy	Spain	UK	USA
Administrative employee	3	80	110	105	82	72
Computer engineer	4	18	12	11	12	38
Consultant		15	13	8	6	2
Data analyst/statistician	13	8	1	5	8	8
Director	24	28	12	37	16	35
Engineer	135	35	22	23	7	13
Executive			1		1	
Freelance/I have my own company	20	4	7	2	9	8
Manager	8	31	33	22	140	132
Other, please specify:	1	3	1	5	5	2
Researcher (including student and post-doc)	1		5	3	6	4
Retired	25	2		1		
Teacher/professor	11	11	32	18	13	8
Technician/employee	15	113	98	108	45	28
Unemployed	90	2	3	2		

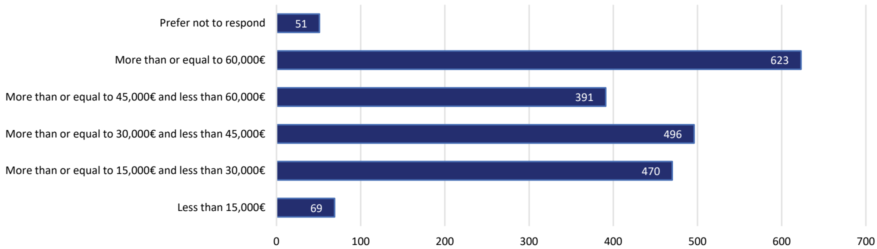

Fig. 3 Annual gross income of the respondents

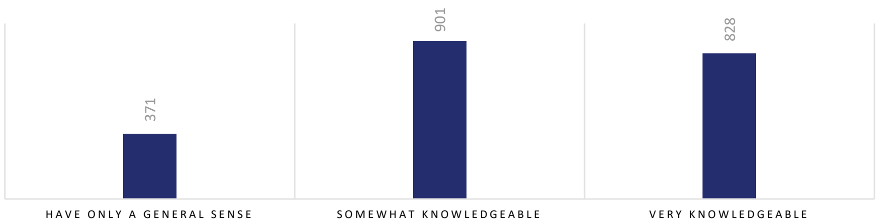

Fig. 4 Knowledge of meeting/conference management tools/software

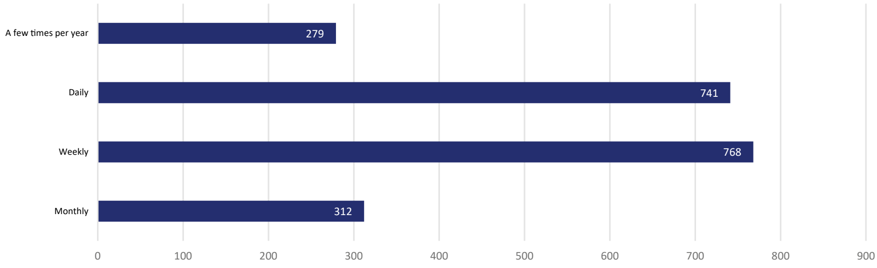

Fig. 5 Use meeting/conference management tools or software in your working life

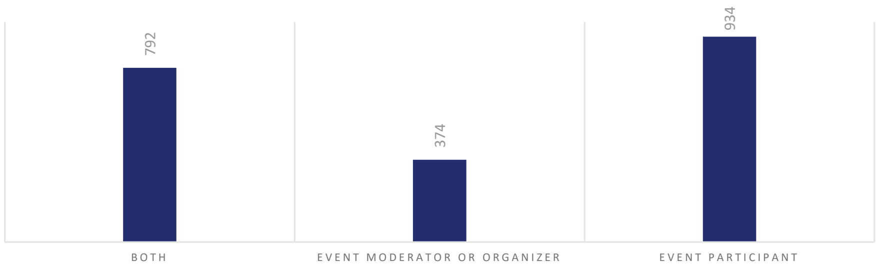

Fig. 6 User profile type

3.2 Respondents' Preferences and WTP for an Event Managed with Indico

During the survey, two types of questions were asked to gauge respondents' WTP as a measure of the value they attributed to the common good. These questions were presented after providing an overview of the Indico tool, including its features and functionality.

The initial query received a straightforward response, employing financial indicators. Upon observing Fig. 7, it becomes apparent that a significant number of participants are amenable to paying between 150 and 900 euros for each managed event.

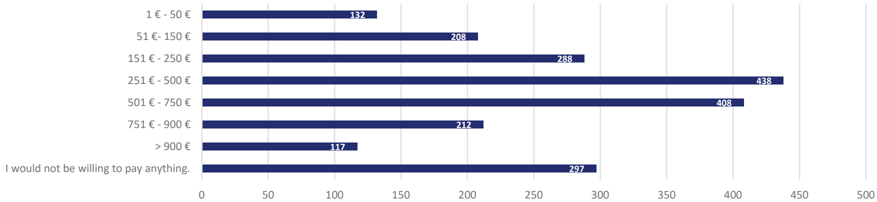

Fig. 7 Willingness to pay for the management of a single event in the Indico tool

Respondents were requested to provide justifications for their answers. The majority expressed the opinion that the selected price is reasonable considering the need to ensure the security of events and documents. This recurring response was expressed in various forms throughout the survey. A summary of these justifications based on value ratios is presented in Table 3.

Based on the outcomes of the initial question, we ran an OLS regression model intending to obtain results and to show which variables directly influence choice, the following variables were employed. The dependent or endogenous variable selected was the WTP. The independent or explanatory variables considered in the model are shown in Table 4.

The results of the regression model using the aforementioned variables are shown in Table 5.

The model demonstrates the influence of age, salary, and the user's role as a moderator/creator of events and participants on the decision of WTP. After removing variables that have no impact on the model, the estimated average WTP for organizing an event supported by Indico is reported to be 405.53 €.

Table 3 Justification for the choice made

Response value ranges (€)	The rationale for the answer
50–150	Good service
151– 250	I like that it is organized and professional
251–500	The platform is very good I like high-quality services like this Because it helps me at work
501–750	Very good platform
751–900	Effort matters Because it is elite
> 900	High-quality platform According to the description, it is a full options service with very excellent features, therefore I choose this price range

Table 4 Independent or explanatory variables of the regression model formulated

The independent or explanatory variables	Variable formulation
User type	Dummy variable: 1 = event moderator or organizer and both, 0 = event participant
Gender	Dummy variable: 1 = male, 0 = female
Age	Age of the respondents
Salary	Salary of the respondents
Level of education	Dummy variable: 1 = master's degree and doctorate level, 0 = other

Table 5 Parameters used for the calculation of willingness to pay

Independent or explanatory variables	Estimate	Std. error	t value	Pr(>|t|)
Constant	399.7496526	32.9159997	12.145	$< 2e^{-16}$***
User type	77.7775385	14.4968565	5.365	$8.98e^{-08}$***
Gender	– 19.0559329	13.5783103	– 1.403	0.161
Age	– 4.5484464	0.6488828	– 7.010	$3.21e^{-12}$***
Salary	0.0032059	0.0002921	10.977	$< 2e^{-16}$***
Level of education	– 15.4176452	14.8222870	– 1.040	0.298

Signif. codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Num of observations = 2100

3.2.1 Choice Experiment Method

Following the initial questions concerning the WTP, we carried out a choice experiment. Participants were provided information about the basic features of the Indico tool, including the names and contact details of speakers and participants, event materials, a comprehensive agenda with time indications, video conference links, speaker and participant invitations, and event access management. The attributes that respondents were queried about in the choice experiment are shown in Table 6.

To elicit respondents' preferences, we designed six distinct sets of questions, each offering four options. Three of these options presented varying combinations of the three attributes, considering the price attribute. The fourth option allowed respondents to express disagreement with the preceding three options. Table 7 shows one of the sets of questions.

Using the obtained results and based on the study [11], a conditional logistic regression model was conducted. This regression model is a statistical method used to analyze data with a nested or matched structure, particularly in cases where the outcome variable is binary or categorical. It is commonly employed in matched case–control studies or when there is a clustering or dependency within the data. The conditional logistic regression model extends the logistic regression model by accounting for the matching or clustering structure of the data. It allows for the estimation of the association between predictor variables and the outcome variable while controlling for the dependencies within the groups or clusters. It assumes a logit

Table 6 Attributes of the choice experiment included

Attributes	Choice
Price per event	(A) 250 € (B) 475 € (C) 750 €
Registration form and room reservation	Yes or no
Abstract submissions and publications review	Yes or no
Customizing the event page	Yes or no

Table 7 One question of the choice experiment method

	Indico option A	Indico option B	Indico option C	Indico option D
Price	250	475	750	Neither option A, B nor C is preferred
Registration, payment form, and room booking	Yes	No	Yes	
Abstract submissions and publications review	Yes	Yes	No	
Customizing the event page	Yes	No	No	
Please, choose one option	☐	☐	☐	☐

link function, where the log odds of the outcome variable are linearly related to the predictor variables. The model estimates the conditional odds ratios or conditional probabilities of the outcome variable based on the values of the predictor variables, taking into account the within-group dependencies.

The conditional logistic regression model is based on the premises of the random utility model (RUM) and can be represented by the following Eq. (1):

$$U = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \varepsilon \quad (1)$$

In this equation, U represents the random utility of the outcome variable given the predictor variables, β_0 is the intercept, also referred to as the constant term, β_1, β_2, …, β_p are the coefficients associated with the predictor variables X_1, X_2, …, X_p, respectively. The Random Utility Model (RUM) [4] is a concept commonly used in economics, particularly in the field of choice modeling and consumer behavior analysis. It is a framework that attempts to explain how individuals make choices among various alternatives by considering the utility they derive from each option.

The central idea of the RUM is that individuals make choices in a way that maximizes their expected utility. Utility refers to the satisfaction or preference that individuals derive from consuming goods or services. Each alternative is associated with a certain level of utility, and individuals choose the alternative that provides them with the highest expected utility.

Conditional logistic regression is widely used in various fields, including epidemiology, medical research, psychology, and social sciences when analyzing data with a nested or matched structure. It allows researchers to examine the relationship between predictor variables and the outcome variable while accounting for the dependencies within the data. The results of the regression indicate that all variables are statistically significant and thus have importance in the choice decision.

After formulating the conditional logistic regression model, the coefficient for the price variable must be negative, as it is used to calculate the "marginal Willingness to Pay" (MWTP), based on [5]. MWTP refers to the maximum amount of money an

Table 8 The output model

Independent or explanatory variables	Coefficient	exp(coef)[2]	se(coef)[3]	z[4]	*p*-value
Bid	$-2.385e^{-03}$	$9.976e^{-01}$	$5.464e^{-05}$	-43.64	$< 2e^{-16}$
Abstract submissions and publications review	$7.331e^{-01}$	$2.081e^{+00}$	$2.481e^{-02}$	29.54	$< 2e^{-16}$
Registration form and room reservation	$8.624e^{-01}$	$2.369e^{+00}$	$2.347e^{-02}$	36.75	$< 2e^{-16}$
Customizing the event page	$4.999e^{-01}$	$1.649e^{+00}$	$2.467e^{-02}$	20.26	$< 2e^{-16}$

Likelihood ratio test = 3942 on 4 df, p = $< 2.2\ e^{-16}$
Num of observations = 50,400

individual is willing to pay for an additional unit of a good or service. It represents the incremental value or utility that an individual derives from consuming one more unit. MWTP is an essential concept in economics and is used to measure consumer preferences and demand. It helps determine how much consumers are willing to sacrifice in terms of monetary value to obtain an additional unit of a particular good or service. MWTP can vary among individuals based on their preferences, income levels, and other factors. It also plays a crucial role in determining the demand curve for a product or service, as it represents the maximum price consumers are willing to pay at each quantity level. Economists and businesses analyze MWTP to understand consumer behavior, set prices, and make production decisions. By understanding how consumers value additional units, businesses can optimize their pricing strategies and allocate resources efficiently. The output model is shown in Table 8.

According to the findings obtained using the model, participants are willing to pay an extra 307.38 € for the "Abstract submissions and publications review" feature in their events. Conversely, the "Customizing the event page" feature is perceived as the least valuable, 209.60 €, while the "Registration form and room reservation" feature is considered the most valuable, 361.59 €. On average, respondents expressed a Willingness to Pay an additional 292.86 € for each additional feature added to the basic event. Based on these findings, it's evident that a tool like Indico would be well-received within the market.

[2] The term "exp(coef)" represents the exponential function applied to a coefficient in statistical analysis. It is commonly used to interpret the effect size or relative change associated with a one-unit increase in the predictor variable.

[3] The term "se(coef)" refers to the standard error of a coefficient in statistical analysis. It is a measure of the variability or uncertainty associated with the estimated coefficient. The standard error provides an indication of how much the estimated coefficient is expected to vary across different samples from the same population. A smaller standard error suggests a more precise estimate, while a larger standard error indicates greater uncertainty in the coefficient estimate.

[4] The z-score is a measure of how many standard errors the coefficient estimate is away from zero. It helps assess the statistical significance of the predictor variables in the model by comparing the estimated coefficient to its standard error.

4 Socio-economic Value of Indico

The survey results have played a crucial role in determining the monetary value associated with the socio-economic impact of the Indico tool for the FCC observation period 2028 -2057. The study focused on selecting institutions that have adopted the Indico tool for their purposes already today. In an effort to encompass communities beyond the core users, a deliberate attempt was made to exclude organizations that largely overlap with the LHC particle physics community. Table 9 presents the organizations and infrastructures that have been included in the study, along with the annual number of events they host using the Indico tool. The values within the cells represent the annual count of events organized by each organization. The column on the far right displays the total sum of events managed by each organization yearly.

Considering that, except for the United Nations using the tool mostly for conferences (90%), Indico is primarily used for lecture or meeting events. By excluding the category of "Submission of abstracts and review of publications," which is predominantly associated with conferences, the survey results indicate a WTP of 571.19 € per event. The model incorporates two additional assumptions: First, the number of events is projected to increase by 20% annually from 2028 to 2040, using the reference period of 2014–2022. Second, from 2041 to 2057, the growth in events is estimated to be 5% per year, considering that the user community of the platform will eventually stabilize.

$$SEV = \sum_t \frac{(Numberofevents_t \times 571.19€)}{(1 + SDR)^t} \tag{2}$$

Upon evaluating formula (2), the resulting overall discounted potential for socio-economic impact is assessed at 571.19 € per event, applying a social discount rate (SDR) of 2%, based on the study [7], yields a total of 3.1 billion CHF for the entire observation period and 107 million CHF discounted annually. Considering the great adaptability of this tool in generating various types of events, it is essential to recognize that the results presented here represent a cautious situation, based on the current usage patterns of the tool. If we were to cover the full spectrum of event combinations that can be achieved with the Indico tool, the results would undoubtedly be expanded, leading to a higher socio-economic impact result.

5 Conclusions

Collaborative platforms offer numerous valuable benefits for individuals and organizations, providing a centralized space for efficient teamwork and a range of communication tools. These platforms streamline workflows by centralizing documents, files, and project-related information, eliminating time-consuming tasks like file searches and coordination of updates. With simultaneous document access and collaboration,

Table 9 The organizations and infrastructures considered

Year	WWU Münster	SISSA	SKAO	Maths CNRS	EGO	United Nations	ESA	UU	CTA	STFC	RIKEN	FUSENET	EGI	INAF	IHEP	Sum events
2014			33	280			17	78	235		338		384	31	672	2068
2015		2	31	264		1973	32	86	204		359		348	125	679	4103
2016		2	50	673		3910	36	89	221		261		335	145	925	6647
2017		11	35	869		4354	38	123	372		218		333	69	844	7266
2018		7	30	855	7	4636	36	105	392	17	252		603	127	1268	8335
2019	30	7	54	924	28	5083	44	113	376	81	306	1	571	194	1652	9464
2020	144	10	53	731	58	2486	29	122	541	104	289	4	485	315	1899	7270
2021	517	4	48	744	154	1807	31	152	596	186	343	10	324	459	2325	7700
2022	571	13	53	1289	170	3270	34	232	683	196	331	8	245	420	2431	9946

version control is improved and redundant efforts are reduced. This heightened efficiency enables teams to accomplish tasks more swiftly and effectively. Among these platforms is Indico.

Indico, developed by CERN, is a robust event management tool specifically designed to cater to the needs of scientific and academic communities. Its extensive features and functionalities are tailored to the requirements of organizing and managing events within these domains. With its user-friendly interface, Indico simplifies event creation, scheduling, and registration management, streamlining the entire event management process. It provides comprehensive support for handling complex agendas, parallel sessions, and diverse event formats, ensuring seamless coordination of scientific conferences, workshops, seminars, and more. A noteworthy strength of Indico lies in its integration with scientific collaboration tools and services, including for instance the CERN Document Server (CDS[5]). This integration allows for the effortless incorporation of scientific papers, presentations, and related materials into event listings and agendas, enhancing accessibility to scientific knowledge and promoting efficient information sharing within the scientific community. Indico offers advanced features for abstract submission and review, enabling effective management of the scientific content of events. It supports a peer-review process, where researchers can submit abstracts and reviewers can evaluate and provide feedback on submissions. This functionality streamlines the selection of presentations and posters, ensuring a high-quality scientific program. Moreover, Indico provides comprehensive collaboration and communication tools for event participants, such as discussion forums, messaging systems, and document-sharing capabilities. These features facilitate networking, collaboration, and knowledge exchange among researchers, scientists, and attendees. The platform's flexibility and customization options allow organizers to adapt Indico to their specific event requirements. It can be configured to support different workflows, languages, and branding, providing a tailored experience for various scientific communities and institutions. As a specialized event management platform developed by CERN, Indico effectively addresses the unique needs of scientific events. Its integration with scientific collaboration tools, advanced abstract submission and review features, and comprehensive collaboration tools make it an invaluable resource for organizing and managing events within the scientific and academic domains.

The objective of this study was to showcase, for the first time in the platform's history, the socio-economic impact of a collaborative web-based platform that is required by a global scientific community and which spills over into further user communities using a choice experiment method conducted through a survey. The estimation of the evolution of the use base was chosen based on the actual past evolution of the user community. The observation period 2028–2057 for the estimation of the future socio-economic impact potential was deliberately chosen to capture the impact potentials for a new, large-scale research infrastructure that will require the same kind of collaboration, the Future Circular Collider.

[5] CERN Document Server, online available at http://cds.cern.ch.

The findings from the study indicate that the average WTP for the attributes selected in the survey for such an event management tool is approximately 293 €. Based on the established WPT 571.19 € per event, a socio-economic impact of 3.1 billion CHF using a social discount rate of 2% is reported for the period 2028–2057.

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The Value of an Open Scientific Data and Documentation Platform in a Global Project: The Case of Zenodo

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Abstract Open Science is a movement aimed at promoting public access to all scientific research products, without barriers or restrictions. Open Data refers to the practice of sharing research data in a way that assures that the research is accessible, reusable, and reproducible for everyone. Leveraging these two principles, scientists can validate results, and findings, conduct new research, and promote scientific progress. Open data also enables interdisciplinary collaborations and the exploration of research questions beyond the original scope of the data. The most appropriate means used for implementing Open science and open data are digital, collaborative technologies. One notable example of a platform facilitating information dissemination is Zenodo, a free virtual repository based on the CERN developed Invenio software suite. Zenodo serves as an open access and open data platform, offering researchers, scientists, and individuals a centralized, durable, reliable, scalable, free, and accessible space to share, publish, and preserve their research outputs. Zenodo provides various features and benefits that foster knowledge advancement and collaboration within the research community. By promoting open access, Zenodo enables the global dissemination of research findings, eliminating obstacles such as geographic and financial constraints. It is challenging to accurately capture the impact of scientific dissemination, both social and economic. This is particularly the case for a free, "catch-all" repository, which permits any user to supply and access non-reviewed information. This report provides a quantitative estimate of the monetary value that a virtual repository represents based on a multi-component model in which the different parts of the system are quantified using appropriate distinct methods. This study uses the virtual repository Zenodo as a reference case for the ex-ante societal impact analysis for the Future Circular Collider (FCC) at CERN, assuming that in the lifetime of such a new research infrastructure, at least one comparable development will be required due to the collaborative nature of scientific physics

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research with particle accelerators and colliders. Our results indicate a discounted socio-economic impact potential of about 2.8 billion CHF for an observation period of 29 years, from 2028 to 2057.

Keywords Zenodo · CERN · LHC · FCC · FCCIS · OpenAIRE · Open science · Open-access · Economic impact · Social impact · Virtual repository

1 Introduction

Open Science (OS) [1] is a movement that aims to transform the way scientific research is conducted, disseminated, and accessed. It advocates transparency, collaboration, and inclusiveness in the scientific process, to accelerate scientific advances and maximize their societal impact. By removing barriers and fostering accessibility, OS strives to liberate knowledge and cultivate a more inclusive and efficient scientific community.

Typically, access to reliable scientific research results has been limited to those who subscribe to paid journals. This hinders the flow of knowledge and impedes collaboration among researchers. OS aims to change this model by promoting open-access publishing, which makes research articles and the underlying data freely available to all. In this way, scientists, students, and the public can access and benefit from the latest scientific discoveries. Nevertheless, the information provided is free of charge and is funded. For Open Access articles in peer-reviewed journals, this happens typically through institutional funding of the publication process (e.g. SCOAP3 collaboration[1]). In the case of a free virtual repository, it happens through the institutional funding of the system development and operation (e.g. CERN and OpenAIRE[2]).

OS adopts the long-known principles of open-source and free software. Open-source software refers to any freely available, but not necessarily free-of-charge software, allowing researchers to view, modify, and distribute it. In the context of open science, open-source tools help the sharing of scientific work, methodologies, and computational models. Free software is openly available and free of charge. Opening data involves sharing it in structured, documented, and reusable formats, allowing other researchers to validate findings, perform additional analyses, and conduct further research. This practice drives transparency, reproducibility, and

[1] SCOAP3 is a partnership of over three thousand libraries, funding agencies and research centers in 44 countries, regions, or territories and three intergovernmental organizations. It supports OA publishing in a set of journals at no cost for authors. In addition, existing Open Access journals, books, and monographs are centrally supported, removing existing financial barriers for authors and allowing a free and easy scientific discourse in High-Energy Physics. Each country, region or territory contributes in a way commensurate to its scientific output in the field.

[2] OpenAIRE (www.openaire.eu) is a pan-European infrastructure for research.

collaboration while facilitating interdisciplinary research. Eventually, the concept helps accelerate scientific progress.

OS encourages open peer review, which makes the review process transparent and accountable. This makes reviewers' comments and identities openly accessible, encouraging constructive feedback and scientific discourse. Open peer review improves the quality of published research, in addition to developing a sense of community and collaboration among researchers.

Citizen Science [2] is another integral facet of OS, promoting active public participation in scientific research. This term defines the involvement of the public in scientific research projects, engaging so-called "citizen scientists" in various aspects and phases of the research process, such as data collection, analysis, and interpretation. Citizen science projects can cover a wide range of disciplines, such as ecology and the environment, as well as medicine, astronomy, or social sciences. This approach promotes public engagement, scientific literacy, and equal participation in the research process.

Despite OS's wide range of benefits, it also faces major challenges. The traditional publication model and current academic reward systems can stand in the way of the transformation to open science. The non-enforcement of a review process and the absence of community-based quality processes (for instance implemented in Wikipedia[3]) lead to an inflation of products and an issue of referencing credible, reliable, and accurate information. Concerns around intellectual property, privacy, and data security need to be raised to ensure a judicious sharing of research results. In addition, achieving cultural and systemic changes in the scientific community requires collective efforts and ongoing advocacy.

Virtual repositories are a suitable channel to capture and make information available openly and freely. These repositories, also known as digital repositories or online repositories, are digital platforms and systems to store, manage, and provide access means (organize information, search information, link information) to a wide range of digital content, such as documents, files, datasets, images, and multimedia. They serve as a centralized location for preserving digital resources in durable and reliable ways, making them easily findable, referenceable, and accessible to users. Virtual repositories are designed to facilitate the storage, retrieval, and sharing of digital content, providing an efficient solution for managing large volumes of information. They usually include search functions, metadata management, version control, and access control mechanisms to ensure the organization and security of stored content.

The purpose of the study presented in this report is to analyze and quantitatively estimate the socio-economic potential of a free virtual repository in monetary terms. The work is motivated by the fact that a Future Circular Collider (FCC) [3–5] is assumed to require during its lifetime at least one comparable information management infrastructure to satisfy the needs to a worldwide collaborative scientific research activity as was the case with CERN and the LHC program so far. The solution may be a new type of information management platform, but it may also be the continued development and use of the virtual repositories such as the "CERN

[3] Quality process of Wikipedia: https://en.wikipedia.org/wiki/Wikipedia:Quality_control.

Document Server" and "Zenodo" built on the Invenio[4] software that has been developed at CERN for this purpose. This study takes the Zenodo virtual repository as a case for the investigation that provides ex-post socio-economic impact data as input for the ex-ante socio-economic impact study for the FCC.

The report first gives an overview of the Zenodo open and free virtual repository. Then it presents the approach to elucidate and quantify the socio-economic impact potentials that can be associated with this platform with an outlook on the FCC program period. To conclude, the results of a survey conducted to estimate the common good value of the repository via a willingness to pay (WTP) approach are presented.

2 Zenodo: An Open Virtual Repository

Zenodo [6] is a free virtual repository and open-access data platform that allows, researchers, scientists, and individuals to share, publish, preserve, find, reference, and access information. The underlying software and the system were developed by CERN. The virtual repository is managed by the OpenAIRE (Open Access Infrastructure for Research in Europe) project. The name Zenodo derives from Zenodotus, who is said to have been the first librarian of the Library of Alexandria.

The Zenodo source code is openly accessible. It is based on the Invenio digital library, which is also an open-source project managed by CERN. Work in progress is openly shared on GitHub; anyone can contribute to any aspect, but the source is controlled by CERN. Metadata is openly available under a CC0 license, and all content is accessible through open APIs. This engaging process promotes that any individual or institution can have access to the platform to either use it as is or tailor it to its needs under the condition that the original name, Zenodo is not used. The Zenodo deployment at CERN is the EU-recommended repository for all EU co-funded research project results. Anyone in the world can freely deposit information on this platform that is hosted on CERN's computing infrastructure. Zenodo is integrated into the European Open Science Cloud (EOSC).

Zenodo offers researchers a user-friendly, reliable, and scalable platform for sharing and preserving virtually unlimited amounts of research outputs. Its commitment to open access, long-term preservation, version control, and integration with other platforms makes it a valuable tool in the research community. The following are some of the key features of Zenodo:

- **Open access**: Zenodo follows the principle of open access, meaning that the research outputs shared on the platform are freely accessible to anyone without paywalls or subscription requirements. This promotes the dissemination and accessibility of research worldwide.

[4] Invenio is a free and open-source software developed by CERN for building digital repositories and information management systems. https://invenio-software.org.

- **Wide range of research outputs**: It supports various types of research outputs, such as datasets, software, papers, posters, presentations, and multimedia files. This flexibility makes it suitable for different disciplines and research fields.
- **Open access and preservation**: The virtual free repository follows open access principles and makes research results publicly available. It assigns a Digital Object Identifier (DOI) to each uploaded item, ensuring persistent and citable links across versions. Zenodo also guarantees long-term preservation, ensuring that shared research results remain accessible and discoverable for the foreseeable future.
- **Integration with other platforms**: Zenodo integrates seamlessly with other research infrastructures and platforms, such as ORCID (Open Researcher and Contributor ID), GitHub, and EOSC. This allows researchers to link their Zenodo profiles to their ORCID IDs and connect their code repositories directly to Zenodo for versioning and archiving.
- **Version control and DOI**: The platform supports version control, allowing researchers to upload multiple versions of their research results. Each version receives a unique DOI, ensuring proper citation and referencing. This feature allows researchers to update and improve their work while maintaining previous versions.
- **Licensing**: The platform facilitates collaboration by allowing multiple collaborators to be associated with shared research output. In addition, it offers several licensing options, including open licenses such as Creative Commons, which allow researchers to define the conditions under which their work can be reused or shared.
- **Discovery and citation**: The virtual free repository ensures that research results are findable through its search interface and its integration with other indexing services. It promotes the use of standardized metadata and encourages proper citation of shared research results, contributing to the scholarly record and recognition of contributors.
- **Statistics and metrics**: Zenodo provides usage statistics and metrics for uploaded articles, allowing researchers to track the impact and visibility of their work.
- **Community support**: The platform has an active community of users and developers who provide support, guidance, and feedback. The platform regularly incorporates suggestions and updates from users to improve its functionality.

It is impossible to talk about Zenodo without discussing the FAIR principles. These principles emphasize data management and sharing, aimed at promoting the findability, accessibility, interoperability, and reuse of research data.

2.1 FAIR Principles

The FAIR principles were initially proposed by [5] to address the challenges associated with data sharing and reuse in the scientific community. They are a set of guiding principles that promote the Findability, Accessibility, Interoperability, and

Reusability of research data. They were developed to address the challenges associated with data management and sharing in the scientific community. The concept emerged as a response to the growing volume of scientific data and the need to unlock its potential for advancing research and innovation. These principles aim to ensure that data is effectively managed, shared, and utilized by researchers, institutions, and organizations. Each of the principles will be explored in more detail below:

- **Findable**: Research data and resources should be easy to find, both for humans and machines. To achieve findability, data should be assigned persistent identifiers (such as DOIs), and metadata should be provided to describe the data and its context. The metadata should be sufficiently rich and standardized, enabling effective data search, retrieval, and linking.
- **Accessible**: Research data and resources should be openly accessible to both humans and machines. This principle emphasizes the removal of barriers to access, enabling unrestricted access to the data without requiring unnecessary permissions or restrictions. Open access facilitates broader use, analysis, and validation of research outputs.
- **Interoperable**: Research data and resources should be structured and represented in a way that enables their integration and interoperability. Interoperability allows data from different sources to be combined and reused effectively. It involves the use of standardized data formats, vocabularies, and ontologies that promote compatibility and facilitate data integration and exchange.
- **Reusable**: Research data and resources should be well-described and provide sufficient context and documentation to facilitate their reuse. This involves providing clear and rich metadata, including information about the data's provenance, methods of collection, and conditions of use. Licensing and permissions should be clearly defined to enable others to understand and comply with the terms of reuse.

Adhering to the FAIR principles means that research data and resources become more valuable and usable for both researchers and the broader community. FAIR principles support open science practices, enhance collaboration, enable data-driven discovery, and promote reproducibility and transparency of research. They are fundamental to maximizing the impact and potential of research results and fostering a culture of openness, sharing, and innovation in the scientific community.

3 Estimated Value of Zenodo's Socio-economic Impact Potentials

This section sheds light on the quantitative estimation of the socio-economic impact potentials of the Zenodo repository as an example of an OS platform.

To our best knowledge, no studies exist so far that monetize the value of the impact potentials of this type of infrastructure. A comparable analysis has been carried out in 2021 on the Benefit/Cost of the entire OpenAIRE infrastructure [5]. Several studies analyze the impact of open-source software such as [2, 6–8] among others, but none provides a ready-to-use prescription or guideline for the elucidation of the quantitative socio-economic value of an open and free data platform. Due to a lack of an existing method to capture the quantitative value, we had to devise a viable set of complementary methodologies to estimate the values of the individual segments of the platform.

This study aims to answer the question: What is the estimated value of the socio-economic impact potentials produced by open scientific data and documentation platforms, taking the Zenodo case study as a reference? We provide one possible lower limit by formulating an economic model based on the expected net present value model.

3.1 Methodology

Knowing what a virtual repository is and the benefits potentials it comes with at the scientific and social levels, we conceived an econometric model to provide an estimate of its socio-economic impact value, based on the sum of estimated socio-economic impact values of individual segments of the platform for which we use models. Eventually, this estimation is compared with the revealed common good value that has been approximated with a Willingness to Pay survey.

The monetary equivalent value has been estimated through the expected Net Present Value (NPV) adopting an observation period 2028–2057, i.e., ex-ante given continued use and further development in the frame of the FCC program, based on the past, known evolution of the platform. This financial metric is used to calculate the present value of the future investment. Both, the benefits, and costs of an investment are estimated, and a social discount rate (SDR). It is used as a measure of the avoided cost and therefore as an investment decision criterion to update the collections and payments and to know how much will be gained or lost with such an investment. Reference [9] sheds light on the use of this financial metric in socio-impact analysis, demonstrating its efficiency and optimal results. A project holds social value when its benefits consistently outweigh costs over time, indicated by a positive Net Present Value (NPV). When considering benefits (B_{ti}) and costs (C_{ti}) occurring at different instances represented by time *ti*. Below is the formula (1) used for the final calculation of the socio-economic impact study, where SDR represents the social discount rate.

$$NPV = \sum_{i}^{t} \frac{B_{ti} - C_{ti}}{(1 + SDR)^{t}} \quad (1)$$

One first issue that arises in setting up the econometric model is the chronology to which we are exposed. Setting up an economic model for such a long period means that we are faced with the possibility of very large and unforeseeable changes in future years. For this reason, several assumptions have been implemented in the model to be able to address future changes in the economy and to be transparent about the presented results and how they have been devised. The assumptions considered are:

- The reference period considered for the study, 2028–2057, has been established by an expert panel of economists in the EU project Horizon 2020 research and innovation action "Future Circular Collider Innovation Study" (FCCIS), in which this work is carried out, to homogenize the criteria among the other studies developed in the same project.
- The base year is 2021 and the discount rate is 2%, established by [10].
- The exchange rate EUR/CHF used in the analysis is 1 € = 1.07 CHF, representing an average exchange of the year 2021.
- It is assumed that data archived in Zenodo will grow until 2040 and then remain constant. This development assumes that twenty years from now, virtual repositories will be fully integrated into research domains, which means that their user base will be mature and will therefore only grow marginally. Our estimates aim to be conservative lower-bound limits for socio-economic value and therefore we assume a constant use base rather than a marginally growing one.
- For the computation of the benefit value from the online use of the repository (explained in detail below), the value of the time visitors spend on the platform must be estimated. For this study, the time value is set to 0.30 €/min. This value has been extracted from the Eurostat database based on the average salaries per minute of researchers in EU countries in 2018 [11]. The average salaries per minute have been updated to 2021 using the GDP deflator following the methodology applied by [12].
- For estimating the economic benefit of downloads made in Zenodo it is necessary to establish a monetary value per download. This monetary value has been set at 7 € per download. The choice of this value will be explained in detail below.

3.2 Description of Relevant Variables

The resulting expected net present value between the years 2028 and 2057, taking 2021 as the base year, was obtained by subtracting the discounted estimated costs of the infrastructure from the sum of the discounted estimated benefits of the free virtual repository. The variables chosen to formulate the model, as well as the monetary values, were:

3.2.1 Development and Operation Costs

The virtual repository's annual development, maintenance, and operation costs have been known since 2012. The value is rather modest since Zenodo is a "by-product" of developments carried out at CERN to manage the knowledge produced in a global high-energy and particle physics community of almost 20,000 people over several decades. Physical assets required for the development and operation such as computing and data management infrastructures, networks, offices, end-use devices, and even travel represent a marginal cost in a common effort of a community of nations. In other words, the cost base, platform, and deployment can de facto be considered a gift to society.

The cost level for 2022 has been maintained in the analysis. Consideration should be given to the fact that the creation of a virtual repository requires mainly an initial budget to bootstrap the development, but as the architecture is settled, a working code base is available, and the repository becomes operational the expenditure starts to decrease and only the salaries of the software engineers and technicians has been noticeable in the accounting. Given this assumption and observing the long timeline applied to the study, an annual incremental cost of 4% has been applied from 2023 to 2057 to account for cost increases additional features, and code consolidation. The future budget estimated with formula (2) corresponds to three full-time equivalent individuals working on the development of the virtual repository every year.

$$Total\ Cost = \sum_{i}^{t} ((Cost_{t-1} \times 4\%) + Cost_{t-1}) \tag{2}$$

3.2.2 Data Storage Benefit

One of the noteworthy impacts of the platform is the assurance of long-term preservation and accessibility of information. This aspect can be captured by estimating the value of the persistent data store segment of the virtual repository. As the repository is free, estimating the monetary term is challenging, but not impossible. Currently, several information platforms apply prices for the preservation of scientific documents and data. Repositories such as Arxiv [13] and IEEE Xplore [14] store text documents. Zenodo also stores datasets, software, video, images, and files in HTML or archives for instance in ZIP format, differentiating itself from other repositories. For that reason, we chose the international repository Dryad [15], which provides functionalities approaching Zenodo as a comparable reference to establish the monetary value of the impact produced by this variable. Dryad is an international open-access repository of research data, especially data underlying scientific and medical publications (mainly evolutionary biology, genetics, and ecology). Dryad is a general-purpose curated repository that makes data discoverable, freely reusable, and citable. Dryad's scientific, educational, and charitable mission is to provide the infrastructure necessary to promote the reuse of scholarly research data.

Dryad publishes a price list [16] for the storage of these files that were used as a reference to establish a monetary value for the case study. The prices established by Dryad for uploading files to its repository are as follows:

- For less or equal to 50 GB the price is 111.72 € per document.
- For more than 50 GB it charges 46.55 € for each additional 10 GB.

A conservative approach has been adopted, considering previous years of available data, to implement an annual growth rate of 10% for data storage under or equal to 50 GB and 3% for data storage over 50 GB. Using the formula (3) the total estimated benefit was obtained.

$$
\begin{aligned}
Data\,storage\,benefit = & \sum_{i}^{t} (((Data \leq 50\,Gb_{t-1} \times 10\%) + Data \leq 50\,Gb_{t-1}) \\
& * 111.72\,€) \\
& + \sum_{i}^{t} (((Data > 50\,Gb_{t-1} \times 3\%) + Data > 50\,Gb_{t-1}) \\
& * 46.55\,€)
\end{aligned} \tag{3}
$$

3.2.3 Online Use Benefit

The purpose of this variable is to measure, through the time users spend on the web platform, the impact potential of the use of an open-access repository by users via a web browser.

The actual past and current time of web usage are captured using Piwik's web interaction activity recording. This free and open-source web analytics tool used by Zenodo and other platforms for its metrics, measures the time users spend during each visit to the free virtual repository. Using this method, we were able to establish an average interaction time per unique visit of 4 min. The annual increment of individual users for the analysis period is 10% until 2040. The percentage increase is based on a moderate growth of the deposited information observed in recent years. We set the monetary value estimate of time for interacting with the web interface to 0.30 € per minute, based on the average salaries per minute of researchers in EU countries [11].

$$
\begin{aligned}
Online\,usage\,benefit = & \sum_{i}^{t} (((unique\,visitors_{t-1} \times 10\%) + unique\,visitor_{t-1}) \\
& \times 0.30\,€ \times 4\text{ min})
\end{aligned} \tag{4}
$$

3.2.4 Download Benefit

The monetary value of downloads is another variable that we considered as a measure of the socio-economic impact potential. It allows measuring the impact of using information stored in the virtual repository.

Table 1 Common average prizes to access information in research repositories and paid scientific journals

Repository or scientific journal	Average item price (€)
Science Direct	31
IEEE Xplore subscription fee	6.22
Nature subscription fee	7.7
Springer	29.95

We assigned a monetary value of 7 € for an individual download, irrespective of its type, contents, and size. We chose this value after comparing the prizes to access information in several repositories and paid scientific journals (Table 1).

Our original estimations pointed to an average value of 30 € per download, however, Zenodo does not feature content and format quality assurance and peer reviewing, which is the main cost driver of paid information resources. Two relevant paid platforms, the non-profit IEEE Xplore digital library, and the commercial Nature platform, see Table 1, both offer the possibility of an individual subscription, which facilitates the estimation of the value per user and download. Estimating the costs of quality management with experienced copy editors and reviewers of scientific publications and deducing it from the individual subscription costs brings the price estimate to 7 € on average, considering the IEEE Xplore and Nature prices as a reference.

The second assumption for the estimation of the value of this variable is that we do not have an unambiguous figure for individual downloads, but only for all downloads of an information set. A single document or data set may be downloaded by the same user multiple times. If it is downloaded only a single time it may also be consumed multiple times by the person having downloaded the information or further shared the information. Zenodo cannot distinguish individual downloads. Consequently, there exists no reliable method to estimate the use of the information by counting downloads only. Therefore, we decided to consider a simplified approach, counting only a single download as consumption per individual record stored in the repository over the entire lifetime of that information record, taking as a reference the number of documents evaluated in the data storage variable.

4 Results

The results of the study have shown that open-access virtual repositories, considering Zenodo as a case study, promote social benefits that when transformed into monetary values, bearing in mind the assumptions mentioned above, yield the results (Table 2).

The combined discounted socio-economic impact of all model variables results in an estimated monetary value of about 2.8 billion CHF from the period spanning 2028 to 2057, considering a SDR of 2% [10]. This translates into an annual average value of approximately 97 million CHF discounted.

Table 2 Discounted monetary values of model variables from the period 2028 to 2057

Model variables	Discounted values (CHF)
Development and operation costs	10,917,550
Data storage benefit	1,309,037,916
Online use benefit	1,426,391,881
Download benefit	81,998,069

5 Assessing the Use and Perception of Zenodo in the Scientific Community

In addition to the study described above, we designed and surveyed with the purpose of estimating the use and perception of the Zenodo virtual repository in the scientific community. Elucidating the common good value of a virtual repository by using the Willingness to Pay (WTP) approach helped us to verify and fine-tune our monetary value estimates and assumptions.

We administered the survey to a random sample of the international scientific Future Circular Collider (FCC) study collaboration, which federates more than 150 universities and research centers worldwide, active in many diverse disciplines of science and engineering. Respondents were asked about their use and knowledge of the Zenodo free virtual repository, as well as their willingness to financially contribute, with a view to establishing a monetary value for the data storage, the online use, and the download of information. WTP in economics is a metric that refers to a consumer's willingness and ability to pay a certain price for a product or service [17]. It can vary depending on factors such as individual preferences, perceived value, affordability, and market conditions. This metric was previously used by [18] to contingently assess citizens' attitudes towards CERN. The survey indicated clearly that the question on willingness to pay (WTP) would be used to assess the added value of an open data platform for the scientific community and that no intent exists to make the platform a paid service. Despite this fact, as will be shown later, a significant number of respondents misinterpreted the survey intent as an attempt to test for introducing a service fee. This required us to identify such respondents and exclude their responses from the evaluation. However, the strong reactions are also a sign for the high value of Open Science and free access to scientific research results, thus supporting at the same time the socio-economic value of such platforms.

Finally, we obtained a sample of 182 valid responses, which include the ones who reported a zero WTP. The larger part of the respondents were men, aged between 30 and 65 years with a doctoral degree and working in physics research.

It is noted that the survey was aimed primarily at the scientific community and therefore biased by this community. After all, the Invenio software emerged from this discipline. This means that administering such a survey to a more heterogeneous set of actual or potential users could lead to different results when including people from substantially different disciplines such as life sciences, social sciences, economics, law, and business administration. It is therefore not surprising that the respondents have an overwhelming number of Ph.D.'s (81%) or other university degrees (Fig. 1). 157 of the 182 respondents work or have worked in research centers, as is the case of one of the retired respondents. Of those who report working in scientific research, 31% work at CERN. A suspicion of a CERN bias due to the amount of respondents working at CERN could, however, be ruled out after analysis of the data.

It was surprising that 53% of the participants in the study did not know about Zenodo when they were contacted, despite the large set of persons working at CERN and being involved in the FCC study. From our experience of using the WTP method in previous investigations, the fact of not knowing the subject for which a person is asked to financially participate explains an overall low willingness to financially participate. People need to know a service or system, understand its functions and services and need to have experienced at least once its potential benefits to be able to attribute a monetary value reliably to it (Fig. 2).

Out of the 51% of respondents who do not know Zenodo, only 18% consider using it in the future. On the other hand, of the 86 respondents who do know Zenodo, 59% use the repository routinely for professional reasons. All the respondents who do know Zenodo are in favor of sharing their data for free because they believe that knowledge should be accessible to everyone.

Figures 3 and 4 show the respondents' WTP levels. 48% of respondents state a zero WTP to have unlimited data storage on Zenodo for scientific information. 57% respond with a zero WTP for unlimited access to scientific information. When asked for their main reason, 97% of respondents say that "*access and use of the virtual repository should be free of charge and that it goes against the principles of the OpenAIRE movement*". This shows that the respondents misunderstood the survey, thinking that they were asked how much they would pay in case a service feed would be introduced for the use of Zenodo, rather than how much is it worth to them. This

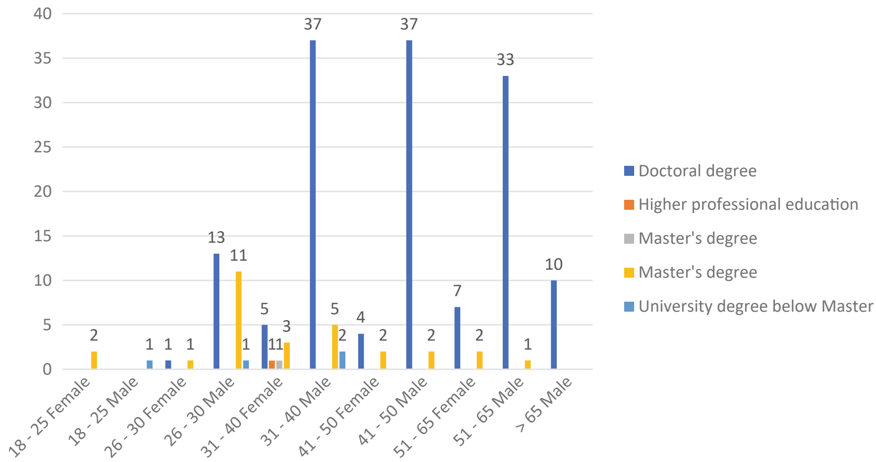

Fig. 1 The highest level of education of the respondents in the function of gender and age range

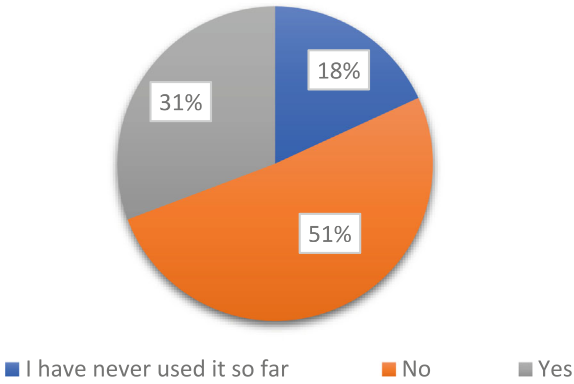

Fig. 2 Previous use of the virtual repository based on the question "Have you used Zenodo before?"

exhibits a limitation of the WTP survey approach. On the other hand, the results demonstrate that people generally favor scientific research being shared openly and freely, as mentioned above.

For the WTP analysis of the survey, we considered only the valid responses with WTP values above 0 € and respondents who indicated 0 € for reasons that make clear that they have understood the purpose of the survey (i.e., the goal to elucidate the value for the respondent). This approach is consistent with the recommendations found in the literature [19] not to exclude zero value responses, on condition that the arguments for answering with zero demonstrate the correct interpretation of the question. All other respondents have been removed from the analysis.

Next, we established an OLS regression model to obtain overall respondents' willingness to pay and to elucidate, which variables directly influence it, based on testing different dependent or endogenous variables. The independent or explanatory variables considered in the model are as shown in Table 3.

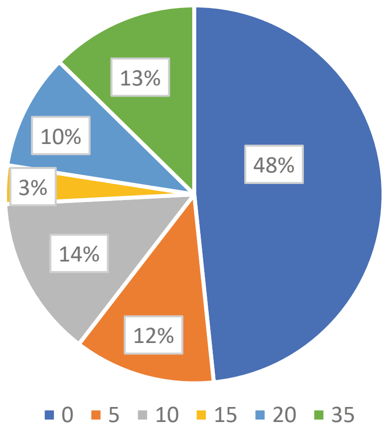

Fig. 3 Willingness to pay levels in euros per year for unlimited data storage in Zenodo for scientific information

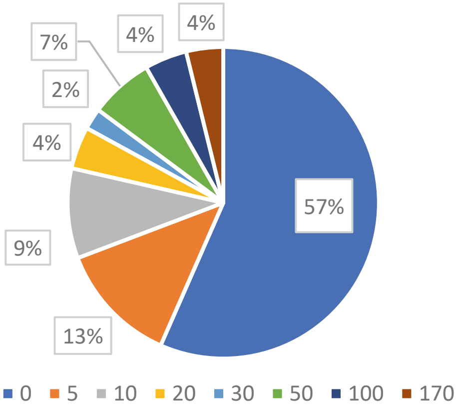

Fig. 4 Willingness to pay levels in euros per year for unlimited access to Zenodo

Table 3 Independent or explanatory variables of the regression model formulated

The independent or explanatory variables	Variable description	Mean	Standard deviation
Respondents' salary	This value is taken from the Glassdoor[5] database. The average salary, in euros, considered is that of a researcher in the country of residence the survey provides	53,313.1526	20,899.5773
Gender	Dummy variable: 1 = male, 0 = female	0.8517	0.3716
Age	Age of the respondents	44.12	12.97
Education background	Dummy variable: 1 = natural sciences, mathematics, and statistics, 0 = other	0.8297	0.3769
Level of education	Dummy variable: 1 = doctorate level, 0 = other	0.8077	0.3952
Type of occupation	Dummy variable: 1 = employed and retired, 0 = working at CERN	0.7253	0.4476
Knowledge = respondent knows the repository	Dummy variable: 1 = yes, 0 = no	0.4725	0.5006
Use = respondent uses the repository	Dummy variable: 1 = yes, 0 = no and never used	0.3077	0.4628

[5] For more information: https://www.glassdoor.com/.

Using the variables outlined in Table 3, the results shown in Tables 4, 5, and 6 were obtained.

The results of the three models shown in Tables 4, 5, and 6 indicate that only the variable "previous knowledge of the platform" has the effect of influencing the users' decision on their WTP. The Variance Inflation Factor (VIF) [20] of the models is in the range of 1.03 and 2.12, which shows that the variables are moderately correlated.

The outcomes related to this important variable reveal that with each additional person informed about the Zenodo virtual repository, there is an observed willingness to pay an average of 14.47 € for downloading a document, 7.56 € for accessing unlimited storage, and approximately 20 € for utilizing a combination of features within the Zenodo virtual repository.

Using the derived estimators for each variable, we conduct the calculation to determine the respondents' WTP for each formulated model. The ensuing outcomes

Table 4 Parameters used for the calculation of WTP for downloads

Independent or explanatory variables	Estimate	Std. error	t value	Pr(> |t|)
Constant	37.9119	14.9497	2.536	0.0121*
Respondents' salary	– 0.0002	0.0001	– 1.616	0.1080
Gender	1.08336	8.3251	0.130	0.8966
Age	0.1776	0.2398	0.740	0.4600
Education background	– 12.6918	8.3757	– 1.515	0.1315
Level of education	– 10.5984	7.9794	– 1.328	0.1859
Type of occupation	– 3.8330	6.4212	– 0.597	0.5513
Knowledge	14.4725	8.1126	1.784	0.0762
Use	– 7.7266	8.9129	– 0.867	0.3872

Signif. codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Num. of observations: 182

Table 5 Parameters used for the calculation of WTP for data storage

Independent or explanatory variables	Estimate	Std. error	t value	Pr(> |t|)
Constant	5.8896	4.5539	1.293	0.19763
Respondents' salary	– 0.0000	0.0000	– 0.549	0.58358
Gender	2.4828	2.5359	0.979	0.32892
Age	0.0569	0.0731	0.779	0.43714
Education background	– 2.7106	2.5514	– 1.062	0.28954
Level of education	0.1043	2.4306	0.043	0.96581
Type of occupation	– 1.6363	1.9560	– 0.837	0.40399
Knowledge	7.5617	2.4712	3.060	0.00257**
Use	– 2.0401	2.7150	– 0.751	0.45343

Signif. codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Num. of observations: 182

Table 6 Parameters used for the calculation of combined WTP

Independent or explanatory variables	Estimate	Std. error	t value	Pr(> |t|)
Constant	43.8015	17.9429	2.441	0.0156*
Respondents' salary	– 0.0002	0.0001	– 1.486	0.1392
Gender	3.5662	9.9919	0.357	0.7216
Age	0.2344	0.2879	0.815	0.4164
Education background	– 15.4024	10.0527	– 1.532	0.1273
Level of education	– 10.4940	9.5771	– 1.096	0.2747
Type of occupation	– 5.4694	7.7069	– 0.710	0.4789
Knowledge	22.0342	9.7369	2.263	0.0249*
Use	– 9.7668	10.6975	– 0.913	0.3625

Signif. codes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$
Num. of observations: 182

Table 7 Results of the WTP models

Willingness to pay for a function	Model output monetary value (€)
Willingness to pay for a single download	17.34
Willingness to pay for a single data storage	8.87
Combined willingness to pay for a publication on the platform	26.21

are outlined, showing respondents' WTP for each segment defined in the survey (Table 7).

6 Conclusions

Open Science is a paradigm shift in the way scientific research is conducted and shared. It promotes transparency, collaboration, and accessibility by making scientific knowledge and data freely available to the public. The dissemination of information that promotes open science can be carried out through many means of dissemination, but virtual repositories are key enablers of open science.

In this study we presented an estimation of the monetary value that an open and free virtual repository represents for the society, taking the Zenodo platform as an example. We conceived a methodology that applies to any open platform for scientific data and documentation. It consists of decomposing the task of quantifying the socio-economic impact potential into individual segments of the repository and establishing models based on past and factual observations and reliable references. The assumptions are verified with a common good value analysis based on the WTP approach.

The total discounted estimated monetary value of the socio-economic impact potentials of a virtual repository for the period 2028–2057 amounts to about 2.8 billion CHF. This value must be compared to the total discounted estimated cost of developing, maintaining, and operating the platform, represented by a marginal value of about 11 million CHF, for the same period. It must be considered that this initial socio-economic value analysis is a first and lower-bound estimate and that the true value potential is most likely significantly larger as annual accounting data of the IEEE Xplore shows.

The results demonstrate therefore convincingly that large-scale, fundamental science projects contribute to society rather than take from the society. The value added generated by useful by products of fundamental scientific research and management of international science collaborations dwarfs the investment costs.

The insights garnered from this study furnish us with the basis to articulate specific recommendations aimed at amplifying the influence of advancements like Zenodo:

- **Enhance investment in development**: It is recommended to bolster investment in the advancement of free and open virtual repositories. This will serve to enhance functionalities and overall quality, thereby rendering the platform more appealing to a broader spectrum of users.
- **Incorporate quality management features**: Introducing quality management attributes is advised. These could include provisions for both anonymous and identified comments on deposited content, potentially incorporating a voting mechanism and facilitating moderated comments.
- **Boost awareness and adoption**: Investment in augmenting awareness and usage of the platform is crucial. Our study underscores that the perceived value among individuals is intrinsically tied to their familiarity and utilization of the platform.

We propose that the financial burden for these initiatives should be borne by stakeholders with an interest in fostering such infrastructures. This could involve international and national science funding agencies, as opposed to the organizations responsible for platform development, operation, and utilization. This objective can be accomplished by offering targeted funding to key communities for leveraging Zenodo's capabilities.

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Collaboration Between Science and Industry: Future Research Directions for Big Science Organizations

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Abstract Over the last few decades, science-industry collaboration has in large part been studied through the lens of universities, as key sources for industrial innovation. Surprisingly, relatively little attention has been paid to Big Science Organizations (BSOs), also known as large scale research infrastructures, despite them playing a great role in science, technology and innovation policy. Research has been conducted on both actors and their collaborations with industry, resulting in two streams of research. While the stream on University-Industry Collaboration (UIC) is rather established in quantity and quality, Big Science-Industry Collaboration (BSIC) research is yet an under-developed area, and there is a clear imbalance in the literature between the two streams. However, attention to BSOs is gaining traction, and as such, deciphering what can be learned and applied from UIC and what can be further studied in BSIC can be conducive. The objective of this work is thus to present a comparison of these two streams, with the aim of identifying some of the core differences between them, as well as to produce an agenda for future BSIC research. A review of UIC literature reviews is compiled, along with a systematic review of the BSIC literature to date. The results of this study have demonstrated many similarities between the two streams of research, where both streams have covered the same themes, and in most part, the same topics. Differences have arisen in subtle ways, such as through definitions of concepts, organizational perspectives, or differences in the temporal periods of collaboration studied. Various areas are highlighted for future research.

1 Introduction

With growing pertinence of technological innovation on economic development [12], much attention has been paid by government to the role of science in industrial innovation over the last several decades [30, 39, 46]. Today, science-industry collaboration is considered a standard means in science, technology, and innovation policy [47]. Often

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studied through the lens of universities, we have been seeing an increase in attention to collaboration between BSOs and industry [20], resulting in a stream of research of its own. BSOs are research facilities designed to support top-level research. BSOs differ from universities in size and research opportunities, in offering large-scale facilities with novel instrumentation and computing systems to researchers from around the world [3, 40].

As greater attention to BSIC emerges in science and innovation policy, and the stream of research on the topic matures, it is pertinent to determine what can be learned and applied from the already evolved stream of research on UIC, as a highly related topic. Evolving the recognition of the role of science-industry collaboration in innovation, this systematic literature review compares the two streams of literature: UIC and BSIC. Given the large number of studies on UIC throughout the years, and the relatively small number of BSIC studies, only literature reviews of UIC are reviewed in the current study, to achieve a general overview of all topics and findings in a comparable manner to those of the BSIC literature. This systematic literature review was conducted along two encompassing questions:

1. How do the topics and findings of the UIC and BSIC literature compare?
2. What do the similarities and differences between the two streams mean for future research?

Six themes were identified in the literature: organizational characteristics, success factors, individual characteristics, processes, policy, and commercialization. Each theme comprises of a variety of research topics, and most topics studied are found in both streams of research. The differences in topics and findings unveil some of the distinctions between the two streams. Those distinctions then begin to uncover an appropriate research agenda for BSIC research, as a developing research area.

2 Methodology

A systematic review of the two areas of interest: the UIC review articles and the BSIC literature, up until the end of 2022, was performed. While there are delimitations to reducing the UIC stream to review articles, where less popular themes, topics, or findings may be overlooked, it does provide a general overview of the research over the years, appropriate for comparison with the aim of this study. The search process outlined by Tranfield et al. [42] is followed for both streams of literature and is detailed below.

Using Harzing's Publish or Perish, a series of relevant titles and keywords were searched for in the Web of Science, Scopus and Google Scholar databases. This yielded a total of 89 UIC reviews, and 115 BSIC articles after removing duplicates. Non-peer reviewed articles were also removed from the samples. Whereas the BSIC literature is comparatively underdeveloped, and key terms not consistent, this search includes one additional step of identifying missing articles via a reference list search of the articles found. Six additional articles were found.

Table 1 Selected literature

UIC reviews	BSIC literature
Agrawal [1], Ankrah and Omar [2]	Autio et al. [3, 4]
De Wit-de Vries et al. [10]	Bastianin et al. [5]
Figueiredo and Fernandes [13], Galvao et al. [15]	Bianchi-Streit et al. [6]
Govind and Küttim [16], Lima et al. [21]	Byckling et al. [7]
Maresova et al. [22], Marinho et al. [23]	Castelnovo et al. [8], Cavallo et al. [9]
Mascarenhas et al. [24]	Deák and Szabó [11], Florio et al. [14]
Mendoza et al. [25], Miller et al. [26]	Hallonsten and Christensson [17], Lauto and Valentin [18]
Nsanzumuhire and Groot [28]	Li-Ying et al. [19], Nordberg et al. [27]
Passos et al. [29], Perkmann et al. [31]	Puliga et al. [36], Vuola and Hameri [45]
Pertuz et al. [32], Pesti et al. [33]	
Piva and Rossi-Lamastra [34], Prigge [35]	
Rybnicek and Königsgruber [37], Sjöö and Hellström [38]	
Thune [41], Valentín and Sánchez [43]	
Vick and Robertson [44]	

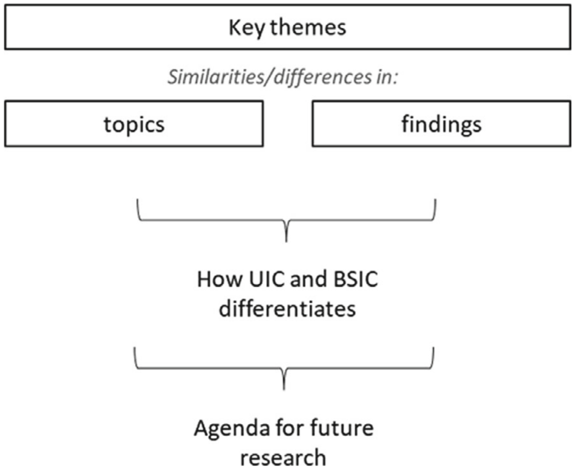
This procedure yielded a total of 65 UIC reviews and 52 BSIC articles that were then screened by abstract. To be included in the final sample, the articles must meet the ensuing criteria. The articles must be published in a scientific journal; must be in English, and; must be primarily about UIC/BSIC—thus excluding the contextualization of countries within UIC/BSIC. This abstract screening left us with 24 UIC reviews and 15 BSIC articles (ranging from 1976, the year of the first relevant article, to 2022), as listed in Table 1.

We then read and synthesized the remaining articles. Our objective was to identify the overall themes that are researched in the complementary domains, and to establish (1) the similarities and differences in topics researched, and; (2) the similarities and differences in findings. In combining these objectives, we are then able to identify how UIC and BSIC differentiate as fields of research. From that, an agenda for future research in BSIC is established, as visually represented in Fig. 1.

3 Findings

The six themes discovered in the literature cover a range of topics and findings, some similar between the UIC and BSIC streams, and some different. Those topics and findings are briefly described here.

Fig. 1 Conceptual model



Organizational characteristics

Many UIC studies have focused on the implementation of university technology transfer offices [1, 31]. The studies evolve to include a focus on skillsets or absorptive capacities within the partner organizations, and when focused only on the firm, firm size, structure, and support/internal policies are taken into account [32].

The BSIC literature expands to a BSOs physical characteristics—one with pioneering facilities providing for a strong development environment [7, 36]. It is generally agreed that BSOs ought to accommodate and foster firm innovation to the best of their abilities, which includes supporting liaison activities [17, 36, 45]. The BSIC literature recommends that firms ought to enable more than corporate venturing, but spin-outs as well; and further, that they should provide wider network access to their R&D employees [36, 45].

Success factors: Risks, benefits and best practices

The risks and benefits are studied from the university's perspective in UIC, though some benefits for firms are outlined in passing. For best practices, the studies take into consideration both the university and firm, and in small part, third parties. Best practices for both universities and firms have to do with compatibility: understanding one another's missions, writing contracts for clear governance, management of collaboration teams, and encouraging personal relationships [32, 35, 37, 38]. Best practices for third parties are also mentioned in the UIC literature, as local, non-governmental funding, tax incentives, and support structures or network facilitation [15, 37, 38].

The BSIC literature under this theme is primarily oriented towards benefiting the firm. For instance, the best practices for BSOs are: publish procurement rules to bid evaluation, procedure simplification, technical dialogue, and relationship maintenance [8, 9, 19]. Firm benefits include profits and improvements to processes [3, 6, 8, 14], new products or commercial opportunities [3, 5, 8, 45], market growth [3, 6, 8], and enhanced networks and reputations [8, 36, 45]. BSO benefits are often brief mentions of improved scientific instrumentation [8, 17, 19, 45]. The risks however are underexplored in this stream of research, though firms are advised not to engage in BSIC for financial profit [7, 36]—but for knowledge transfer.

4 Individual characteristics, roles and interactions

The UIC stream focuses on the academic perspective only, though in two levels: the student and the faculty member. Students are often involved through scholarships or contracts, and often with positive results in commercial outcomes and academic freedom [21, 41]. For faculty members, the literature considers research productivity with and without alignment to commercialization.

This theme is relatively underrepresented in the BSIC literature, though there are mentions of the importance of individual motivation [3] and networking [45], and of course, skill development throughout collaboration [4, 27].

5 Processes, mechanisms and challenges

The processes identified in the UIC literature generally follows some set of stages of collaboration and technology transfer that consists of search, evaluation, approach, strategy, development, and exploitation [13, 15, 25, 29]. Knowledge exchange can occur through formal or informal exchanges [10, 23, 25, 28, 44]. The challenges often highlight intellectual property (IP) management, bureaucracy, resource barriers, knowledge boundaries [2, 28, 44], willingness, or network accessibility [15, 23, 28].

BSIC too acknowledges mechanisms of collaboration [4, 9], specifically such activities as: technology transfer programs or boundary organizations [4, 9, 18], tendering [4, 8, 18], co-inventing and patenting [9, 17, 19], and; industry testing [7, 9, 11]. The challenges identified consist of lack of human capital and resources [7, 19], and governance structures and procurement rules [8, 9, 19].

6 Policy

Patenting is a popular topic within UIC policy research, at university and federal levels [1, 2, 15]. Recently, an interest in the economy of knowledge production and socio-economic processes of contemporary innovation systems has emerged [15, 21, 24, 26].

Policy has been critiqued as being underutilized for innovation impact in the BSO context [3, 18, 36]. A popular recommendation is to incentivize technology transfer programs, to support industrial spillover [4, 11, 18, 36]. Vuola and Hameri [45] has found that BSO members are seeing various positive impacts on national innovation as a result of BSIC.

7 Commercialization

Within UIC, university environments with high competition are found to be associated to commercialization, as is university quality, and peer pressure among the staff [25, 31, 33]. Recent literature considers the social innovation aspect of commercialization, such as innovation clusters and universities as business incubators [33].

The commercial benefits in the BSIC literature are defined in a series of studies as outcomes with long-term impacts to knowledge transfer for the firm [3, 6, 18, 19, 45].

These findings are summarized in Fig. 2.

8 Discussion

The literature on UIC and BSIC has demonstrated both similarities and differences, both in topics and in findings. This review highlights areas that can be explored in further research as the findings suggest that there is more to be learned in BSIC, even with the knowledge that we have gathered from the UIC literature. Figure 3 demonstrates a variety of topics that are under-explored, or unexplored, as inspired by the comparative findings of the two streams of research reviewed.

Overall, the UIC literature has shown us that BSOs can afford to be more introspective when it comes to research on all levels, but it is particularly lacking on the individual level. This includes possible research on how human capital and individual networks, and even individual motivation can enhance BSIC and perhaps commercialization, not only be a result of it, given that BSOs have a concentration of exceptional people already [7]. Further research could also investigate the BSO scientists' personal gains from collaboration, whereas the UIC literature indicates that there may be positive findings, which could then act as an incentive for scientists to involve themselves in BSIC.

On the organizational level there is much to be explored, from both the BSO and firm perspectives. First off is the emergence of the industry contact officers as in-house intermediary support structures. Differing from technology transfer offices, least by name, little is known about them from a management research point of view given their recent development. Also lacking are studies on risks to BSOs—where generally BSIC has to do with instrumentation development or maintenance, differing from UIC research, risk assessments and mitigation could reasonably be expected to differ from the UIC findings. This overall focus on instrumentation has

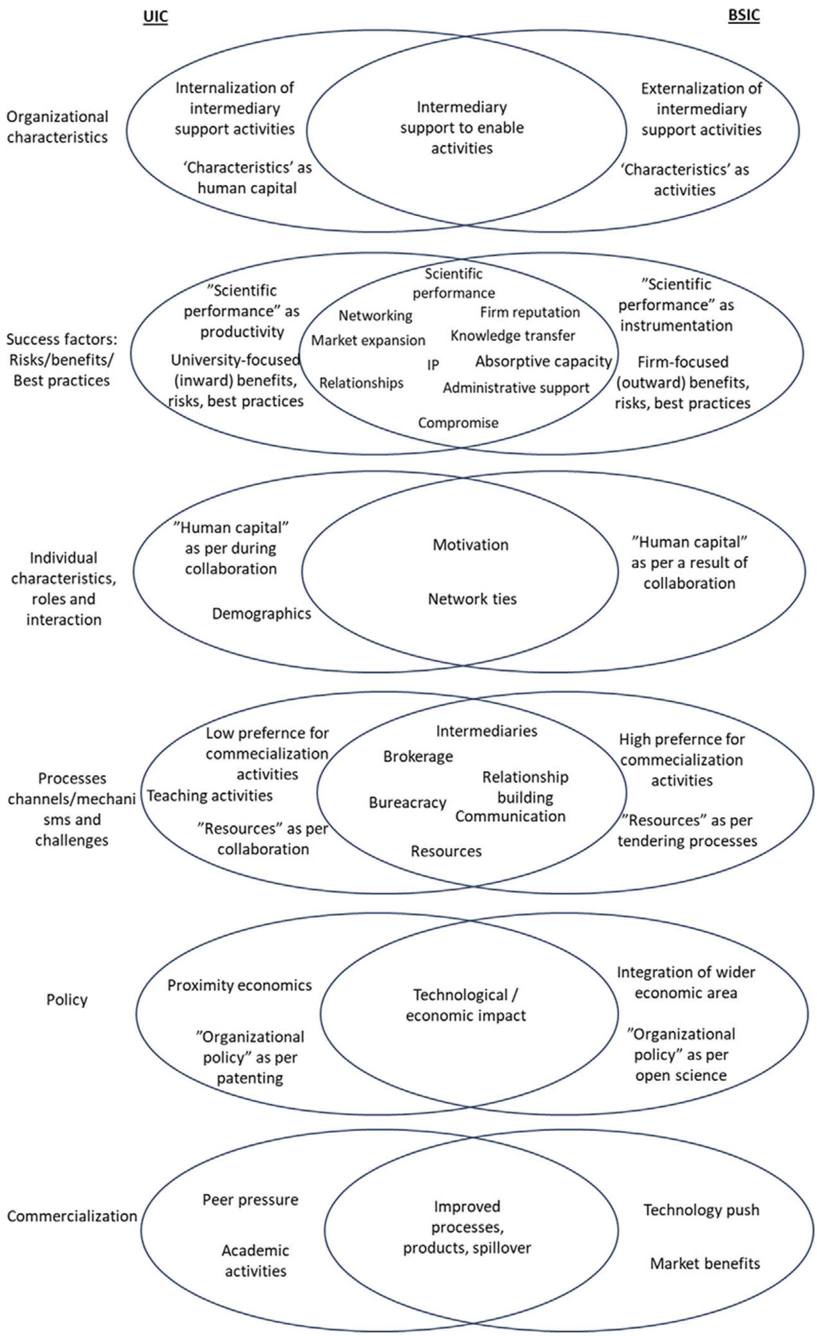


Fig. 2 Summary of similarities and differences of topics and findings within UIC and BSIC literature

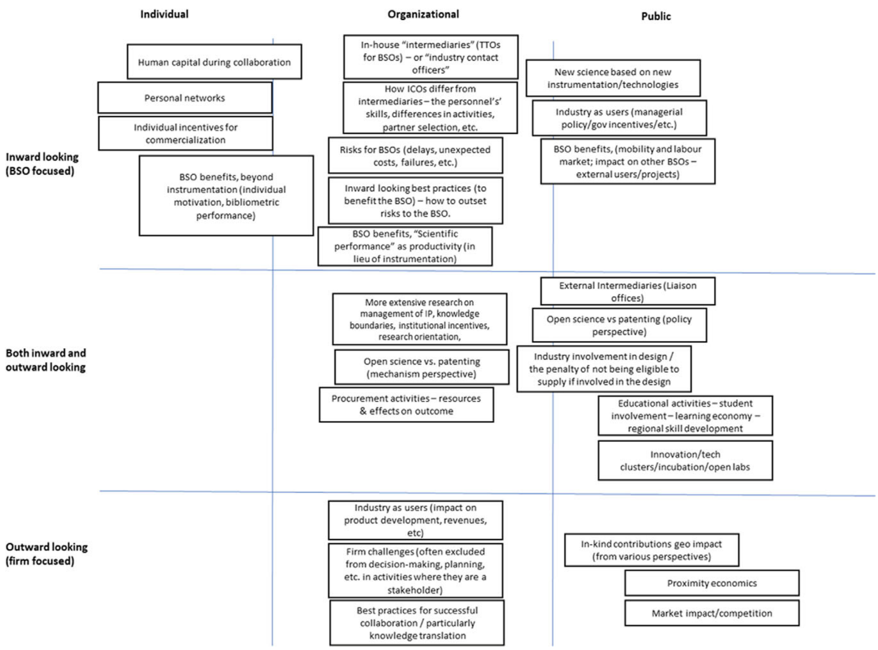


Fig. 3 Topics for future BSIC research, as organized by level of study and perspective

delimited research from the firm perspective as well, where little has been conducted on firms as users of BSOs, which has the capacity to open the doors to new insights on product development and commercialization.

On the public level, research concerning the societal impacts resulting from new science based on new instrumentation and technologies, that were enabled by BSIC, is scarce. Understandingly much of the scientific outcomes are published in the natural sciences domains, however there are significant societal impacts that sometimes occur as a result to such scientific research that ought to be explored within innovation policy research, such as by popular example the world wide web coming out of CERN. From another angle, activities involving universities, BSOs and industry, together, may be of interest. Given the often intrinsic links between universities and BSOs as research institutions and actors in the innovation system, and their differences in structures, there is room to explore such dynamics and activities.

9 Concluding Remarks

The interactions between science and industry as a means of economic advancement through innovation has for the most part been studied through the lens of UIC. Attention to BSOs as another potential source of innovation is increasing in science, technology and innovation policy. Although they have many similarities to universities in terms of their mission to produce scientific knowledge, BSOs offer complex instrumentation allowing for a much wider scope of ground-breaking research. Correspondingly, the potential effects a BSO can have on industry has the capacity to generate a wider scope of novel innovations, than with UIC. Although the guidelines outlined by Tranfield et al. [42] were followed in this systematic literature review, some limitations should be considered in the current study. These limitations include a lack of coherence of terminology in the BSIC literature as a relatively newer area of research, creating difficulty in the article search process. Furthermore, while a review of UIC reviews does provide a suitable overview of research done on UIC, some findings may have been overlooked. Nevertheless, we believe that the literature search and the review in itself was able to better differentiate the literature on these two types of scientific actors and contribute to the field of study with a strong agenda for future BSIC research.

The results of this study have demonstrated many similarities between the two streams of research, where both streams have covered the same themes, and in most part, the same topics. Differences have arisen in subtle ways, such as through definitions of concepts, organizational perspectives, or differences in the temporal periods of collaboration studied. In some cases, the findings of the topics studied have been found to differ between the two streams. In such, many areas have emerged as understudied—or not yet studied—in the BSIC stream that may be of interest to science, technology and innovation policy scholars.

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