6 Addendum

6.1 Community

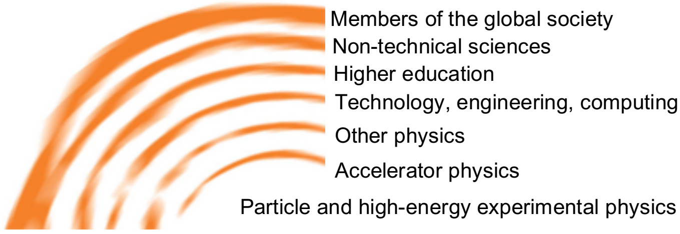

Figure 4: The "onion" model of involvement of and impact for different communities.

The impact on the community can be presented in terms of an "onion" type model, starting with the innermost layer comprising the **core scientific communities**, which need, conceive and use such a facility. Further communities in the European Research Area and beyond, which will benefit throughout the entire lifecycle, starting with the early design phase, include: **other sciences, engineering communities**, **higher education**, **industrial partners**, **researchers from non-technical domains**, and ultimately **all members of society.**

Community	Impact potentials
Particle physics	The FCC-ee has broad physics discovery potential with **an opportunity to attract a world-wide community of more than 20,000 physicists** (see arXiv:1707.03711). It addresses the communities involved with the high energy and precision frontier, electroweak, Higgs and heavy flavour physics as well as the neutrino physics and Dark Matter communities, presently working on the LHC, flavour factories, neutrino and Dark Matter experiments. The theory community is needed to produce Standard Model calculations to match the exquisite precision of FCC-ee measurements. The model builders will be guided by unprecedented precision on masses and coupling constants and the possibility of studying domains of rare processes.
Experimental physics	The detector builders will encounter a vast field of opportunities concerning high precision - low material vertex tracking, large volume tracking and high precision calorimetry with unprecedented micrometric definitions of fiducial volumes, particle identification techniques and ultra-thin detector magnets. Very large tracking volumes might be considered for detection of long-lived new particles.
Accelerator physics	The FCC-ee accelerator with top-up injection and unprecedented beam power will attract the world-wide community from electron storage rings, synchrotron light sources and high luminosity factories. Fully automated operational procedures, integrating luminosity optimisation, clean backgrounds and the energy calibration by resonant depolarisation constitute a wealth of interesting topics that call for the integration of diverse domains of competence.
Other physics communities	The research at the FCC-ee will have implications for astrophysics and cosmology, offering an unprecedented opportunity to federate these scientific fields.
Technology, Engineering, Computing	The project will drive the development of higher efficiency electrical to radio-frequency power conversion. The development of cost-effective high-performance thin-film coated, superconducting cavities needs material scientists and requires expertise from manufacturing experts. Specific engineering areas include precision mechanics, surface treatment, superconductivity, novel materials, electronic engineering and reliability engineering to improve the particle accelerator efficiency. The development of energy efficient cryogenics engages the cold-temperature engineering sciences including mechanical engineering. Electrical engineering communities will be involved in bringing medium voltage DC technology to the market, to conceive lower-loss electricity distribution systems which are more reliable and develop environmentally friendly and sustainable energy recovery and buffering systems. Designers will be needed to develop waste-heat recovery and reuse systems. To design and construct the underground infrastructure in a cost-effective way, the civil engineering community needs to make advances in tunnelling technologies and to develop ways for the recovery and reuse of excavation materials. This work will be carried out as a joint endeavour with material scientists, geologists and chemists.

	Information and communication technology communities will be involved everywhere. Their activities include simulation algorithms and software infrastructure; parallel and high-performance computing; distributed computing; real-time and embedded systems; mechatronics to conceive new standards and technologies for low-maintenance and easy-to-repair systems in the areas of protection, access, remote handling and autonomous interventions; data acquisition, data visualisation, modelling and operation optimisation,; the introduction of artificial intelligence in machine and detector operation; radiation and fault tolerant systems; environmental information systems; data mining technologies; wireless communications including safety-related functions; data and document management facilities; worldwide computing infrastructures; long-term data stewardship; open access data models and infrastructures and much more.
Higher education	The design and construction of the accelerator and the detectors will offer many opportunities for science teachers and students at master, doctorate and post-doc levels. Eventually the findings from all the scientific activities will enrich the academic curricula: state-of-science today will become state-of-the art tomorrow. This project will enlarge the impact potentials of higher education to highly qualified personnel (HQP) and apprentices.
Industry	A project of such scale must be designed, constructed, operated and maintained with strong involvement of industrial partners from all of the participating nations. Where reasonably possible, a gradual shift towards co-development will lead to a research infrastructure which is sustainable in the long-term on one hand and which has greater impact for industry on the other hand. A specific initiative during the detailed design phase will focus on identifying the fields of cooperation, also elucidating where companies can best profit from enhanced learning to increase their competitiveness and improve the quality of their product and internal processes. One particular area of interest is to develop ways to increase the technology level in the field of civil engineering: novel methods for on-line excavation material analysis and separation, pathways for reuse of the materials by other industries such as chemical and construction are important levers to increase the economic utility in this domain.
Non-technical sciences	This project will engage a variety of scientific communities, beyond physics, technology and engineering domains. Examples include, but are not limited to research in logistics and systems engineering around the world-wide production chain for the particle accelerator and detectors (logistics, operations, sales, HR, procurement, accounting, management and organisation, business administration). Architecture and arts will be involved in surface site development. Media and visual arts as well as museums and marketing experts are needed to efficiently engage the public and to communicate with institutional stakeholders. Radiation protection, technical risk management and waste management experts will facilitate the control of hazards and risks in all areas throughout the entire lifecycle. Environmental and urbanistic sciences will help avoiding, reducing and mitigating impacts. Economics, innovation management and political sciences form another group of non-technical sciences, which have already shown during the FCC study phase that they are essential for the successful preparation of a future project.
Members of the global society	The continued deep exploration of our universe tackles fundamental questions that intrigue everyone: What is the origin of the universe? What is the nature of the matter that we are all made of? Where do we come from? Why is there something and not nothing? This project addresses these questions directly and creates opportunities to engage everyone interested. During the preparatory phase, an effort will be made to intensify such involvement through community science and a modern communications plan. The conceptual study phase has revealed that the greatest challenge is, however, to create interest among people who are unaware. FCC-ee is an opportunity not to be lost for the particle physics and accelerator communities to raise awareness on a global scale and to strengthen the support for continued investment in this research by policy makers, funding agencies and ultimately, by every member of society.

6.2 Timeline

The overall project duration is 18 years, composed of two major parts: the preparation phase spanning 8 years and the construction phase spanning 10 years. The preparation phase includes:

- all administrative procedures with the host states, ultimately leading to the construction permits and delivery of the surface and underground rights of way;
- the consultation process with authorities and public stake holders;
- the development of project financing, organisation and governing structures;
- the site investigations, civil engineering design, tendering for consultant and construction contracts.

The construction phase includes:

- all underground and surface structures;
- technical infrastructure;
- accelerators and detectors, including hardware and beam commissioning.

The implementation timeline for FCC-ee is shown in Fig. 5.

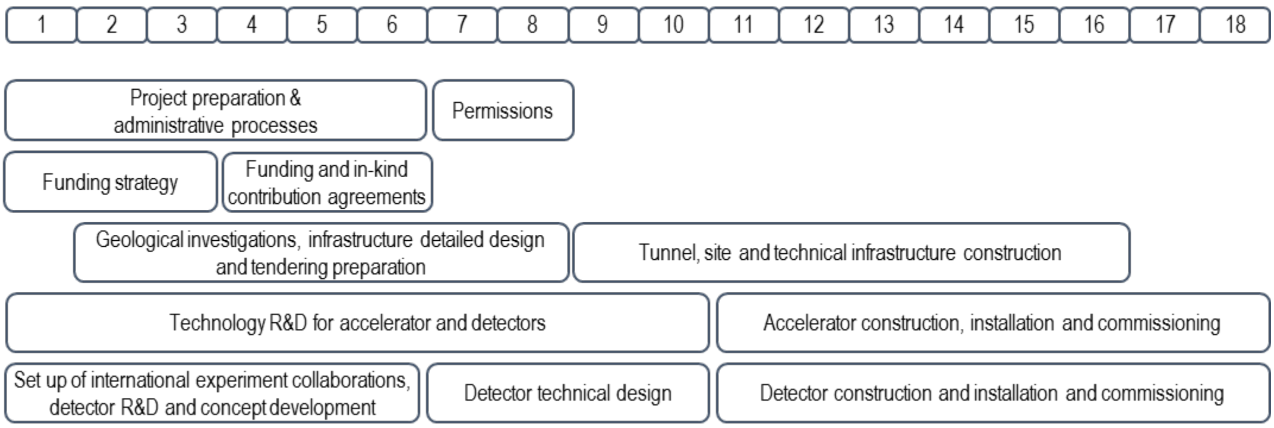

Figure 5: Overview of implementation timeline for FCC-ee, starting in 2020. Numbers in the top row indicate the year. Physics operation would start in 2039.

The underground and surface civil engineering construction can be completed in less than 8 years. The first sectors would be ready for machine installation about 4.5 years after the start of construction.

6.3 Construction and Operation Costs

6.3.1 Capital Cost

A cost study was performed for the FCC-ee based on the conceptual design. The capital cost for construction of the project is summarised in Table 1. This cost includes all equipment for operation at the Z, W and H working points. Operation of the FCC collider at the $t\bar{t}$ working point will require later installation of additional RF cavities and associated cryogenic cooling infrastructure with a corresponding total cost of 1,100 MCHF.

Table 1: Summary of capital cost for implementation of the FCC-ee project for the Z, W and H working points.

Domain	**Cost [MCHF]**
Collider and injector complex	3,100
Technical infrastructure	2,000
Civil Engineering	5,400
TOTAL cost	**10,500**

The **total construction cost amounts to 10,500 MCHF** (for Z, W and H working points) as shown in Fig. 6, dominated with 51% or 5,400 MCHF by civil engineering. The capital cost for the technical infrastructures is 2,000 MCHF corresponding to 19% of the total construction cost and the remaining 30% or 3,100 MCHF corresponds to the accelerator construction.

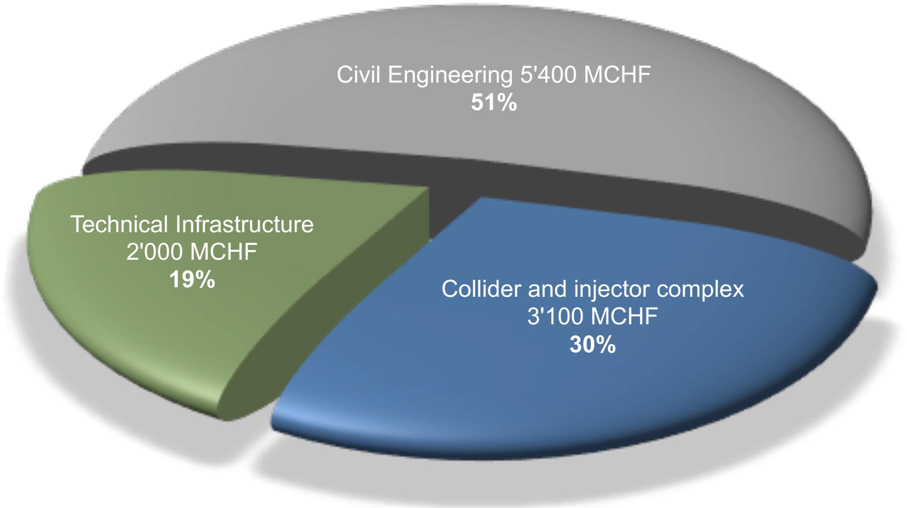

Figure 6: FCC-ee capital expenditures per project domain.

The cost estimates for the accelerators (collider and injector complex) and the technical infrastructure are based on machine and system inventories. The cost estimate for civil engineering is based on an analysis of construction methods for underground and surface structures, the associated material quantities and unit prices, derived from several recent large-scale tunnel and civil engineering projects in Central Europe. The precision of the overall cost estimate is at ±30% level.

It should be noted that both civil engineering and general technical infrastructures can be fully reused for a subsequent hadron collider FCC-hh.

The capital expenditure can also be related to the physics goals: Taking the H mode running as an example, **with 5 ab^{-1} accumulated over 3 years**, the total investment cost corresponds to **10 kCHF per Higgs boson produced**; for the Z running with **150 ab^{-1} accumulated over 4 years** the total capital investment cost corresponds to **10 kCHF per 5×10^{6} Z bosons**, the number of Z bosons collected by each experiment during the entire LEP programme.

6.3.2 Operation Cost

Operating costs are a major factor for any research facility and design efforts need to be made from the early concept stage to enable sustainable operation. History of large-scale technical infrastructures reveals a trend of steadily decreasing normalised operating costs: While at the peak of LEP operation CERN had 3,300 staff members, in the LHC era the laboratory's staff complement has shrunk to 2,300 employees, even though the LHC together with its injectors is a much more complex machine. This decreasing number of personnel is a manifestation of progress in technology, operation and maintenance concepts.

This optimisation trend is expected to continue for the FCC-ee with major improvements in the areas of automation of operation, monitoring, inspection and repair activities. Even though the FCC-ee is nearly four times larger than LEP and has two separate vacuum systems, the total number of different elements in the machine is increasing by less than a factor 2. Consequently, the number of component series does not scale with the size of the machine and the associated operation and maintenance costs will not do so either. An increase in the absolute number of components goes along with a growth in the maintenance, repair and restore effort required. However, this fact does not necessarily imply higher complexity, i.e. dynamic system behaviour leading to significantly higher operation and mitigation costs should not be a consequence. The training and experience requirements for maintenance personnel are further optimised by the use of industry-based standardised, modular designs for accelerator components. The detailed technical design phase will, however, focus on ensuring that the operation of such a machine is sustainable in the long term.

<u>Sustainable maintenance:</u> The machine design will place **an emphasis on conceiving the individual systems and subsystems such that they can be monitored, maintained and repaired by service suppliers as much**

as reasonably possible. Experience with this approach for particle accelerators and imaging devices for healthcare applications has been gained over more than 15 years. Examples include the remote maintenance of power converters and the servicing of superconducting devices including cryogenic refrigeration infrastructures. The effects of this approach are 1) the possibility to re-negotiate operation and maintenance along the operation phase and, thus, to profit from an ever improving understanding of the infrastructure's operational behaviour, 2) the possibility to engage financial resources only when needed and with the possibility to reduce them when no longer needed at the end of the machine operation, 3) the creation of "local economic benefits" in the contributing nations and regions due to the financial revenues over sustained time periods for different companies and a long-term education effect for highly qualified personnel.

Modular design: Investing early-on in modular designs of basic components and equipment to be installed will enable streamlined operation, service and repair. The successfully demonstrated concept of a vertically integrated "column" that will be replicated many times is the underlying principle of this approach, leading to a scalable system. Thorough analysis with potential industrial partners and the consequent application of best practices will be one of the requirements in the preparatory work plan. One key topic in this approach is the reduction of, and facility-wide agreement on, standard interfaces at all levels (e.g. mechanical, electrical, fluids and their parameters, communication and software). A dedicated activity for interface management is the key to cost-effective production and testing, installation and long-term sustainable operation.

In-kind, collaborative operation: The LHC experiments have already indicated the way in which long-term operability of an experiment can be achieved through a committed involvement of the international collaborating institutes. Intensifying and extending this concept to the entire particle accelerator and experiment infrastructure is an essential lever to fully engage the entire community in this project. Particle accelerator experts and equipment specialists exist in numerous academic institutes around the globe. Operating a world-class particle-collider creates a unique learning experience for scientists and engineers at all levels and age categories. It is also one essential way to reduce the operating budget through the assignment of in-kind contributions to the operation, maintenance and repair. Information and communication technologies in twenty years from now will permit the distributed monitoring and root-cause analysis of numerous systems. Through unified supervisory control infrastructures, it should be straightforward to operate the technical infrastructures of all experiments with a single set of trained personnel and to share the task across the globe. The CMS "remote operations center" pioneered by FNAL in the US is a first step in this direction.

The **electric power consumption** is one of the operating costs, but the analysis of the conceptual design indicates that it is not the cost-driver. In order to arrive at a long-term, sustainable highest-luminosity particle collider, the FCC-ee conceptual design already integrates a number of energy reduction measures:

- Use of **power-saving two-in-one magnet designs for arc dipoles and quadrupoles**.
- A **booster-ring for continuous top-up**, more than doubling the availability of the collider rings for luminosity production, thus **leading to a sustainable physics programme**, which can be completed within 15 years.
- Use of superconducting radiofrequency cavities based on **thin-film coating technology at 4.5 K with a higher energy efficiency** than bulk superconducting materials at 2 K.
- Development of **high-efficiency klystrons** to increase the effectiveness of electrical to RF power conversion.
- Using **medium-voltage DC electricity distribution** to optimise the size of the powering infrastructure, enabling the introduction of renewable energy and storage systems and supressing the need for a power quality system.
- **Waste-heat recovery and reuse** inside the facility, and for storage and provision to district services (heating and air conditioning).

The total electrical energy consumption over the 14 years of the research programme is estimated to be around 27 TWh, corresponding to an **average electricity consumption of 1.9 TWh/year over the entire operation programme, to be compared with the 1.2 TWh/year consumed by CERN today and the expected 1.4 TWh/year for HL-LHC**. For LEP2 the energy consumption ranged between 0.9 and 1.1 TWh/year. At the CERN electricity prices from 2014/15, the electricity cost for FCC-ee collider operation would have been about 85 Meuro per year.

For a total luminosity production of 5 ab^{-1} in the 3 years of the HZ running mode, about 1.1 GWh or ca. 50 keuro for electricity would need to be invested for producing 1 fb^{-1} of integrated luminosity. This translates into an **electricity cost of about 260 euro per Higgs boson**. Fig. 7 illustrates the efficiency of the FCC-ee with regard to electrical power consumption.

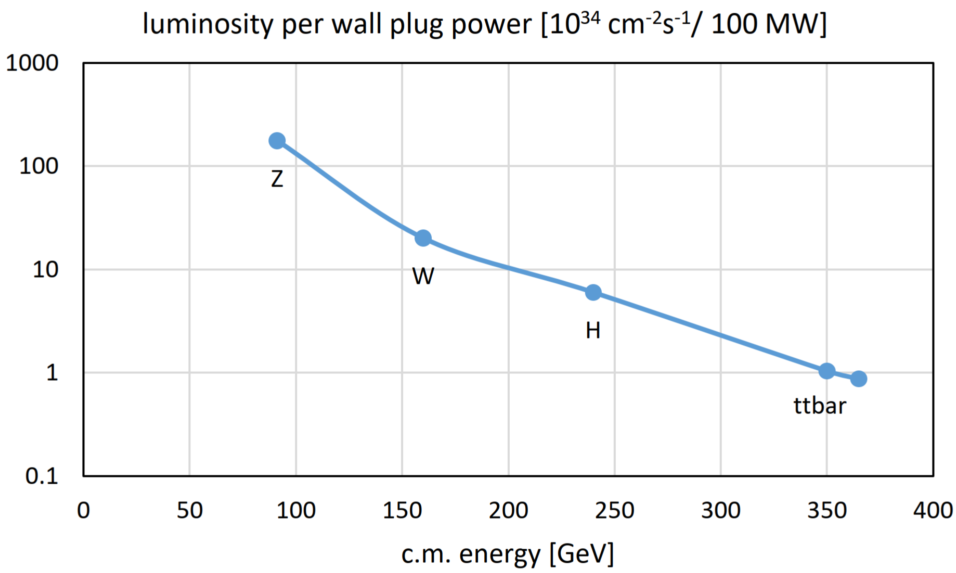

Figure 7: FCC-ee total luminosity divided by total electric power as a function of c.m. energy.

6.4 Computing requirements

The LHC operation era has shown that computing has evolved into a **service for a world-wide user community.** The existence of a large world-wide computing and data service infrastructure for the LHC programme today with a need for committed enlargement tomorrow will lead to a long-term sustainable, world-wide scientific computing and data management infrastructure for the physics community. Involving further **partners beyond the high-energy physics community** will facilitate this endeavour. Concrete examples include astronomy and astrophysics projects like SKA and ESO operated facilities, life-sciences via advanced medical imaging, microscopy and bio-molecular data processing as supplied by EMBL and ELIXIR, photon and neutron sciences such as crystallography, and a broad spectrum of scientific domains with more limited requirements, but with a need for affordable access to computing and data processing. Carrier neutrality, vendor and operator independence as well as the continued availability of **open standards, hardware and software technologies** are essential ingredients to guarantee independent and effective progress of science and education on a long time scale.

Specifically, for the FCC-ee, the **computing capacity requirements are in the range of those of the HL-LHC**. With a new project and tangible synergies, it should, however, be **possible to reduce the cost of the operation and the continued functional and performance enlargement over the decades to come**.

One of the highlights of the FCC-ee physics programme is a comprehensive campaign of measurements of Standard Model (SM) precision observables, spanning the Z pole, the WW threshold, the maximum rate of Higgs boson production, the $t\bar{t}$ threshold, and above. Through this campaign, the FCC-ee will provide a set of ground-breaking measurements of a large number of new-physics sensitive observables, with improvement by one to two orders of magnitude in precision with respect to today. The possibility **to fully exploit the particle collider's capabilities depends much on the capability to perform theoretical computations that provide precise and accurate predictions of Standard Model phenomena** at levels where quantum field theory can be checked at the next order(s) of perturbation theory. **Today, predictions with the required precision and accuracy are unavailable.** A leap that leads to theoretical computations which precisely and accurately predict Standard Model phenomena needs to be induced. This includes the **development of new event generation techniques** and a campaign to advance the theoretical physics calculation methods. The latter will in turn become an input for the conception of highly efficient software tools that are capable of performing the computations. Furthermore, **tools need to be developed to compare the experimental results and the theoretical predictions** to a level of precision that is better than the anticipated experimental uncertainties. Such an activity is expected to **strengthen the cooperation between theoretical and experimental physicists**, leading to a more coherent world-wide community by developing common goals and a sense of shared responsibility. This work will be the **result of a global collaborative effort by theoretical and experimental physicists and contributors from relevant information technology** disciplines. An initial estimate of the effort required points to about 500 person years, corresponding to about 25 full-time-equivalent experts throughout the design, construction and operation phases of the FCC-ee programme.

For **experiment data acquisition and on-site on-line processing, the technical solutions of the current era will be adequate.** However, the new FCC-ee project offers **opportunities to pioneer new data processing paradigms** that can come to fruition when data rates and volumes make a quantum leap at projects which may eventually supersede this project. As demonstrated in domains such as detector controls and readout electronics of the LHC project, the **development of common services will further improve the cost-efficiency** of such a project, **during the cost-intense operation phase**. As the separation between off-line and on-line computing gradually vanishes, common services, which were traditionally purpose-built by each collaboration, become attractive.

Embedded and real-time computing are of interest **for an infrastructure that is characterised by its longevity** and thus dominated by maintenance costs. Given the significant increase in the number of devices for a future collider, **standardisation**, **coordinated testing, certification**, **procurement** and **maintenance/repair** services, available to all users, will improve sustainability. These activities can create impact far beyond the particle accelerator community, if properly set up and coordinated with ICT communities.

Cyber-security plays an increasingly important role and scientific computing is no exception to this. Intensified support to ensure adequate coverage of this domain is an important requirement for a future project. The use of COTS operating systems and embedded Web servers in all kind of equipment ranging from simple I/O devices, over measurement instruments to autonomous robots require an effective but lean infrastructure.

Cooperation on ICT standards, technology developments and relations with other research facilities with similar requirements (e.g. DESY, ESRF, ESS, FNAL) needs to be strengthened. Synergies with other scientific domains (e.g. astronomy and radio astronomy facilities, light sources and FELs, neutrino and gravitational wave observatories, particle accelerators for medical applications and nuclear fusion experiments) can be developed to lead to more effective operation of **various IT services for research**. Activities spawned by DESY on front-end computing hardware and CERN's openlab are examples for such initiatives.

Considering the fast pace of information technology evolution, the long-term cost impact of in-house developments and their potentially limited industrial reach, it is prudent to base designs for a future project on widely accessible hardware, software and service infrastructures. The particular needs of an FCC-scale facility may also represent attractive test-beds for emerging technologies. Co-innovation projects with industrial partners during the early construction phase will facilitate pre-commercial procurement initiatives that can lead to high-performance infrastructure services at competitive costs.

Finally, **long-term data availability** has become an important feature to ensure the lasting impact of a facility. The accessibility of several decades of LHC data, metadata and analysis results has turned out to be a major topic for the community. With a future particle collider, the time span will extend to the end of the 21st century, calling for **evolving data storage and management systems that serve the core community** for long periods of time. Considering the continuous evolution of data formats, the ever-evolving particle detectors and a user community with significant turnover, **data quality management is a chief topic to be addressed. The value of a particle collider research facility depends directly on its data quality and long-term, world-wide open accessibility for as large a community of scientists as possible.**