2. Evacuation of excavated materials from construction sites. While all sites require the evacuation of materials during the first two years, only four sites will see relevant transport of excavated materials during another 6 to 8 years due to the deployment of tunnel boring machines.
3. Transport construction materials to the construction sites. All sites will see a moderate inflow of construction materials during the first two years, but only four sites will continue to have relevant construction materials inflow during the period when the tunnel boring machines are deployed. Construction materials also need to be brought in when the surface site buildings are constructed.
4. Transport of accelerator equipment during the six to eight-year installation phase that overlaps partially with the civil construction activities.
5. Transport of the experiment detector equipment during experiment installation that overlaps with accelerator installation and testing phases.
6. Commute of engineers and scientists during the installation and testing phases.
7. Commute of engineers and scientists during the operation phase.
8. Commute of engineers and scientists during regular maintenance periods and in the frame of repair activities.
9. Traffic induced by visitors to experiment sites during the operation and shutdown phases.

The main project-induced traffic is linked to the evacuation of the excavated materials. It will be confined to major transport routes. The inflow of construction materials represents a minor additional contribution to this traffic. Commute of workers is intended to be organised centrally, as is best practice for construction sites. The installation of equipment for the particle accelerator represents a minimal contribution to the traffic. The same is true for the transport of the experiment detector equipment. For this case, some isolated, exceptional loads may be required due to the size of pieces manufactured off-site. Once operational, only a few scientists and engineers commute daily to experiment sites. Technical sites are predominantly operated remotely and will see very little traffic for maintenance and repair. The traffic of an estimated total number of 25,000 visitors per year to an experiment site during the operation phase can be compared to the traffic induced by a typical museum or archaeological site such as the Grottes de Cerdon in the region (about 50,000 visitors per year[10]) or the Château Voltaire in Ferney-Voltare (about 50,000 visitors per year [89][11]). This traffic of individual visitors can be managed with appropriate directions to the site and through support by public transport. Visitors in groups arrive in buses, presenting a minimal amount of additional traffic.

More information about the quantities and the additional traffic induced can be found in sections Sect. 2.7.2 and Sect. 2.7.12. A first quantitative traffic analysis has been carried out to confirm that the traffic is manageable and that with respect to the nearby major transport routes, it represents only a minor addition.

3.3.9 Human activities

Human activities The analysis of the environmental state established the situation concerning human activities around the surface sites. The environment around site PA in Ferney-Voltaire is dominated by commercial activities (like the commercial centre shown in Fig. 3.42), the LHC Pt8 surface sites and the airport. The presence of a surface site does not add to these activities. The environment around PB in Presinge is rural and characterised by small hamlets. The Geneva Landscape and Architecture School (HEPIA) is an academic activity zone in the vicinity. Towards the west, the zone starts to be dominated by urban activities. The environment of site PD in Nangy is characterised by a mix of agricultural, commercial and industrial activities, residential zones and a major hospital (CHAL).)Due to this mixed environment and the major transport routes available, the location is advantageous for an experiment site with a permanent presence of scientists and engineers. PF in Éteaux is located on a main transport route with dispersed residential areas, small businesses and artisans and a major public works company opposite the site. PG in Groisy and Charvonnex does not have major human activities. The vicinity of Groisy, with schools and potential for local development, is an opportunity to develop a main experiment site with the presence of scientists and engineers. Site PH in Cercier is very rural, with agricultural activities (fruit production) and some small hamlets. No major human activities are carried out in this area. The environment around the PJ site in Dingy-en-Vuache and Vulbens is agricultural with commercial activities to the north-east in Valleiry. PL in Challex is in an agricultural zone with low-density residential areas. Commercial activities take place at a distance in La Plaine, Switzerland, which is not directly linked to the site.

Poplulation The population density around the eight surface sites varies significantly. Around PA, the area is moderately populated with about 34,000 inhabitants within a perimeter of 2 km. The major communes are Ferney-Voltaire, Prévessin-Moens in France, Meyrin and Grand-Saconnex in Switzerland. The population growth

[10] https://www.ain.cci.fr/sites/g/files/mwbcuj1466/files/2024-02/Chiffres%20cles%202024%20AIN_.pdf.

[11] https://www.lemanbleu.ch/fr/Actualite/Archives/Le-chateau-de-Voltaire-entierement-renove.html.

Fig. 3.42 Commercial district near the PA site photographed during the field investigations

Fig. 3.43 Residential district photographed during the field investigations

in this area is 2.4% per year but this is unrelated to CERN's activities. Around PB the environment is sparsely populated, at most 6000 inhabitants can be counted in a perimeter of 2 km. The main communes are Presinge, Pupling, Choulex, Meinier, Jussy in Switzerland and Ville-La-Grand in France. There is no annual population growth in Switzerland (between −0.3 and +0.3%). In neighbouring France, the annual growth is modest (+1.1%), comparable to the average in Haute-Savoie. Site PD is located in a moderately dense environment with about 4000 inhabitants in a perimeter of 2 km, the majority located in Nangy and Contamine-sur-Arve and Fillinges. The annual population growths in these communes are highly diverse, ranging from negative 0.5% in Nangy to +3% in Contamine-sur-Arve. The PF site is located in a moderately populated zone with about 4000 inhabitants in a 2 km radius with the majority of people in Éteaux and La Roche-sur-Foron. The population evolution is stable, ranging between −0.6% and +1.0% per year. PG is located in a sparsely populated area with around 4000 inhabitants in a perimeter of 2 km, mainly in Charvonnex and Groisy. However, the two communes see an annual population growth of between 2.2 and 3.2%. The environment around the PH site is very weakly populated. There are only 1500 inhabitants in a perimeter of 2 km in Cercier, Choisy and Marlioz. The population growth is around 1.5% per year. The area around PJ is also sparsely populated with about 6000 inhabitants in a perimeter of 2 km in Vulbens and Dingy-en-Vuache. Valleiry is a more densely populated commune nearby. The annual population growth is 2 to 3.5%, higher than the average in Haute-Savoie. PL in Challex is in a sparsely populated area with only about 3000 inhabitants in a perimeter of 2 km including Challex in France and Dardagny in Switzerland. Both communes experience an annual population growth of about 3% per year.

Housing As with the population, the housing situation also varies significantly amongst the surface site areas. In the immediate environment around PA, the housing sector is dominated by apartment buildings (like those shown in Fig. 3.43). Prévessin is dominated by individual houses. The housing sector around PB is mixed with individual houses in the closer vicinity and residential buildings further away. The communes in the vicinity of the site are not dominated by individual houses, but see a mix of houses and residential buildings. The area around PD is dominated by individual houses. Individual houses are also predominantly found around site PF. The entire area around PG is dominated by individual houses, as is the case with sites PH and PJ. Only Valleiry is an exception with a significant number of residential buildings and apartments. The surroundings of site PL have a highly contrasting housing sector. Mainly individual houses are found in the French communes of Challex, Péron, Saint-Jean-de-Gonville. Residential buildings are predominant in the Swiss communes of Avully and Dardagny.

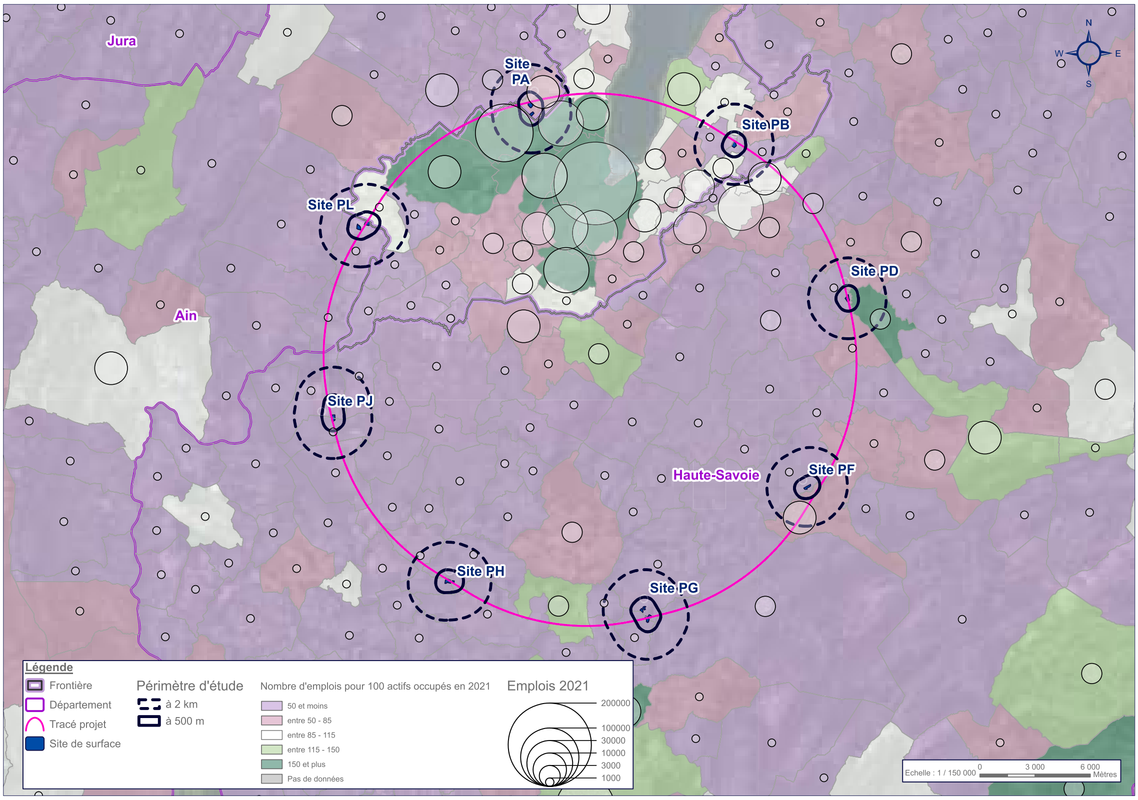


Fig. 3.44 Overview of the employment opportunities in the perimeter of the FCC reference scenario

Employment At a general level, the employment sector in the northern sectors of the FCC is dominated by Geneva and its surroundings on French territory (see also Fig. 3.44). The southern zone in Haute-Savoie is characterised by significantly fewer job opportunities and an overcapacity of available workforce. Depending on the region, the tertiary sector is only weakly developed. The secondary sector (industrial activities) offers opportunities in selected locations. Like Geneva, the Department of Ain in France has many more employment opportunities than the Haute-Savoie department.

Around PA, employment opportunities are mainly found in the tertiary sector. In the Swiss territory, the secondary (industrial) sector is also a major source of employment opportunities. Employment around PB is dominated by the primary sector (agriculture) and there is a slightly smaller number of job opportunities than people seeking work. PD has employment opportunities in the industrial sector and the health sector (CHAL hospital), although the job opportunities are limited. The area around PF offers few employment opportunities and those that exist are distributed between the secondary and tertiary sectors. The primary sector (agriculture) is rather weak in this area. There are fewer job offers than the available workforce. Also around PG there are fewer job opportunities than available workforce. In particular, the tertiary sector is only weakly developed. The same is true for site PH in which the primary sector (agriculture) is the main employer for almost one-third of the population. Also the area around PJ sees more job seekers than job offers. The main employment sector is agriculture. Around PL the situation is mixed: residents find their employment in France and in Switzerland.

Agriculture The area used for agriculture in the Pays de Gex (e.g., Fig. 3.45) between the site PL in Challex and PA in Ferney-Voltaire has been stable over the last 30 years. The evolution of plot ownership and agricultural exploitations in the 1990 s led to fewer but larger farms. The typical size of a single exploitation today is about 90 ha per farm, covering a total of about 3600 ha. The main product remains milk, although this sector is decreasing. Cereals represent a minor contribution. Free trade zones between France and Switzerland in this sector facilitate goods exchange, from which the sector for milk and milk-derived products profits mainly. Out of the 23 million litres produced in the Pays de Gex, 14 million are sold to cooperatives in Geneva. The volume of the milk production in the area is larger than the entire volume in Switzerland. The cereals produced by about 90 producers are almost entirely sold in Switzerland. The production of cereals saw a constant increase with a growth of more than 60% between 2000 and 2010.

Milk production is also an important agricultural sector in Haute-Savoie. Major, globally acting firms and groups (e.g., Société Laitière des Hauts de Savoie / Lactalis) are important economic players in the region who

Fig. 3.45 Agricultural land photographed during the field investigations

also produce milk derived products, in particular Reblochon and Abondance cheese. Green spaces for feeding the cattle are important for this industry. Growing urbanisation puts this branch of the economy under pressure, although the economic potential is high. Production and sales of hay as cattle food is a related main economic branch.

The agriculture sector around PB in Switzerland is dominated by the production of cereals. Recently, following the construction of glass houses, different types of agriculture are fostering the local production of various products. Local agriculture is one of the economic pillars of the canton, although the sizes of the individual operators are much smaller than in France (typically less than 50 ha). Vineyards are another relevant part of the cantonal agricultural sector. Land consumption creates pressure on the agricultural sector: about 20 ha of agricultural space is lost every year.

The sector around PD in Haute-Savoie experiences different climatic conditions than the northern sector. The countryside is more mountainous and the agricultural activities are more diversified, although the main product is hay and grass related to milk production. Almost 5000 ha are exploited in this area for milk and cheese production. 17 million litres of milk are processed by a firm in Fillinges alone.

Moving further south (sites PF and PG) shows that the importance of agricultural activities has decreased over recent decades and small farms dominate. The activities are diverse, including cereals, cattle farming, meat production, hay production, vegetables, poultry and some local wine production. Dairy production remains the dominant branch.

Towards the south-east (PH) the activities are still milk and cheese production with a total area of more than 12,000 ha devoted to it. Other important activities are fruit (apples and pears) and cereals (including maize) production. The entire zone processes per year about 45 million litres of milk. The eastern sector (PD) processes about 12 million litres of milk yearly and also sees dairy product industries (e.g., Baiko). Cattle farming for meat production is a related activity in the sector.

Forestry Forestry is mainly important in the French Haute-Savoie department. About 150,000 ha are utilised in the area. 70% of the forests are privately owned. Wood production comprises a variety of different tree types, both deciduous and conifer trees. Forestry in the French department of Ain is also well-developed, mainly supplying wood for carpentry and construction works.

The project scenario only affects forestry in a very limited way in PG (Groisy) and PH (Cercier and Marlioz) in the Haute-Savoie department in France. The economic loss has been quantified, and the potential effects on habitat and biodiversity have been analysed. Mitigation measures can be developed in a subsequent design phase based on this analysis.

Viticulture Vineyards (like the one shown in Fig. 3.46) are present in the Ain and Haute-Savoie departments in France, as well as in the canton of Geneva. However, the implementation scenario does not affect any of them. Wine production exists in the vicinity of the PL site in Challex, on both the French and Swiss sides. Wine production also exists at some distance from the surface site PB in Switzerland.

Tourism Tourism is already a major economic factor in Geneva and the immediate vicinity of CERN because of its Science Gateway visitor centre and the numerous exhibitions and guided tours that CERN offers. Every year more than 400,000 people visit CERN either individually or as part of groups. The economic impact due to local spending

Fig. 3.46 Vineyards photographed during the field investigations

that creates indirect, direct and induced jobs is significant, since people typically combine their visit with other activities in the region, on average for a stay of four days. For instance Ferney-Voltaire (PA site) is known for the Château Voltiare, its typical weekly market and numerous tourist attractions in the immediate vicinity (e.g., the Jura mountains in France and Coppet and Nyon in Switzerland). Geneva and its numerous tourist attractions are not exhaustively listed here. However, the United Nations, the International Red Cross Organisation, the old town, the Jet d'Eau, the watch museums, the cathedral are some examples. The economic benefits in this area today have been recorded and estimations for the effects to be expected with a future collider projects have been estimated and are reported in the section on socio-economic impact (see Section sustainability:results). With the increase of CERN's activities in the region, high-quality science tourism is expected to expand into the Haute-Savoie region, contributing to the tourism development there as well.

Concerning the new sites, PB in Presinge features a number of small, but relevant, tourist attractions that invite pedestrian and bicycle tourists, extending their excursions through the vineyards to the lake or towards France to the Arve valley.

The area around the PD site in Nangy in France is mostly known for its bicycle tracks that will be significantly extended by 2030. A track from the lake to Mont-Blanc is planned.

The surroundings of the PF site in Éteaux do not yet feature dedicated tourist attractions. However, several opportunities exist for discovering local cheese products between sites PD and PF. Together with a visitor centre at PG in Charvonnex and Groisy the entire zone could profit from a well-planned development of high-quality tourism that links the lake through the Arve valley with the Annecy area, which is highly developed in terms of tourism. Numerous mountain walking tours can be included in this programme.

The area around site PH in Cercier and Marlioz is not currently developed touristically and does not have noteworthy infrastructures.

The zone close to the Vuache next to site PD in Dingy-en-Vuache and Vulbens, on the contrary features, numerous bicycle paths (including ViaRhôna) that are inviting for tourists interested in nature.

The site PL in Challex is embedded in a regional nature and bicycle tourism area, linking the Jura mountains with the Rhône valley. It features hiking paths and trails through the vineyards. The area around the Swiss commune Dardagny is known as one of the most beautiful in Switzerland and is therefore particularly protected along with the landscape that surrounds it.

Economic development projects Development projects potentially relevant for the FCC scenario are included in the Geneva cantonal master plan (Plan Directeur Cantonal, PDCn) and concern the period to 2030. A project for new apartments on about 180 ha in the vicinity of the airport, involving major construction works and the employment of about 5700 workers, is potentially relevant for site PA in France. Also, about 1300 apartments are planned to be constructed in nearby Grand-Saconnex, involving up to 2400 workers. No development projects are registered in the vicinity of sites PL in Challex and PB in Presinge on the Swiss side.

In France, the potential main developments are in the vicinity of site PA in Ferney-Voltaire. A future commercial activity zone (ZAC) on about 65 ha and the creation of an additional 2500 apartments and educational facilities are planned for the period up to 2030.

In the vicinity of site PD in Nangy a new road widening project (RD903) and the intersection with the A40 autoroute are scheduled to be implemented before 2030.

Scientific activities The main scientific project in the region is the upgrade of the Large Hadron Collider, known as the High-Luminosity Large Hadron Collider (HL-LHC). It guarantees the continuation of the presence of scientists and engineers at today's level until the 2040 s. The FCC implementation scenario builds on this activity, leveraging the existing LHC Pt8 for the creation of surface site PA and hosting the injector on the CERN Prévessin site. Also site PL in Challex profits from being in the vicinity of CERN Meyrin.

Fig. 3.47 Architectural heritage photographed during the field investigations

For site at PB, the presence of the Geneva Architecture and Landscape School (HEPIA) in Lullier may be relevant. This facility is close to the site and potentially provides services that the surface site can leverage to reduce its own requirements. HEPIA could also potentially profit from common developments in different areas around the FCC, including agricultural studies and technical infrastructures. A collaboration already exists between the study, CERN and HEPIA to work on the re-use of excavated materials and agricultural aspects.

The national milk and meat industry school can be found in the vicinity of the PF site in Éteaux in La Roche-sur-Foron. The infrastructure also hosts a technical and scientific high-school. The school is active in scientific partnerships with INRAE, CNRS, universities and national research centres. Potential synergies can, for example, be found in the development of water and heat re-use.

3.3.10 Heritage

The analyses carried out in the frame of this study related to cultural, architectural and archaeological heritage first took into account all noteworthy elements that could be identified in a perimeter of 500 m around the surface sites. An example of architectural heritage is shown in Fig. 3.47. A subsequent, more detailed assessment focused on the elements in the immediate vicinity of the surface site candidate locations. This choice of perimeter was established in order to understand the richness of each surface site which, subsequently, would need to be considered in the designs and territorial integration of the sites.

Bibliographic analyses did not reveal any registered archaeological sites or interest in archaeological relevance at and in close proximity to the surface sites. There are no buildings or monuments of historical importance on the surface sites or directly affected by potential surface site constructions due to visibility or co-visibility. There are a few buildings of historical significance in the wider perimeters of some of the surface sites.

The sensitivity of the area of PA in Ferney-Voltaire, France with respect to heritage is low, particularly at the surface site itself. The site would be located on protected agricultural land. To the west of the study area, there is the protected woodland, Bois de la Mouille, also classified as wetland. To the northeast, in the vicinity of the site, there are a few isolated protected trees and a wetland with low functionality. Nevertheless, the implementation of a surface site avoids these classified and protected areas, despite the fact that some of them are on agricultural land.

The area around the site PB in Presinge, Switzerland has a strong heritage, architectural, cultural and landscape character. The surface site is relatively far from heritage sites but it remains partially visible from the hamlets to the north as well as those to the south. The existing wooded strips partially protect the views towards the villages of Choulex, Puplinge and Presinge, but remain open towards the communes of Jussy and Meinier. In order to preserve the rural character of the area, it is advisable to consider good landscape integration, such as a semi-buried surface site so that visibility from nearby hamlets is limited.

The heritage sensitivity within the study area of the PD site in Nangy, France, is considered medium to very high depending on the part of the site. The presence of the Château de Pierres and a classified wood located to the north and west, 180 to 300 m from the surface site induced this rating. In the area directly concerned by the site, the sensitivity is very low. The site is in the immediate vicinity of an autoroute and a departmental road which will be reorganised to improve traffic flow. No relevant visibility issues are recorded in an area that is dominated by high traffic, a hospital, or industrial and commercial facilities.

Sensitivity to heritage in the area of the PF surface site in Éteaux in France is low. Very high issues are noted in the wider vicinity of the site to the south and the southeast due to a woodland around a creek that is classified and protected. To the north-west, at a distance of about 400 m, there is a notable building, constructed in 1923, which formerly housed a cheese factory. There are also several groups of isolated trees that are witnesses to the history of agriculture. However, the implementation of the surface site avoids all sensitive spaces and stays close to the departmental road, directly opposite a public works construction company.

Fig. 3.48 Mountainous landscape with agricultural fields documented during field investigations, highlighting the interaction between natural and cultivated environments

The sensitivity related to heritage at site PG in Groisy and Charvonnex in France is considered to be low. Some areas in the south of the main site are remarkable due to the presence of areas with wetland characteristics and unclassified but high-quality woodlands. There are a few old buildings linked to the networks of old mills located in the surrounding larger study area. The surface site does not directly affect any heritage elements.

Heritage sensitivity in the immediate area of the PF surface site in Cercier and Marlioz, France is considered very low. This assessment is linked to the presence of the large forest (Grand Bois) and the Tabassé creek to the north of the surface site. Both present ecological interests, but are not considered heritage sites.

The heritage sensitivity of the PJ surface site in Dingy-en-Vuache and Vulbens in France is considered medium to high due to the location of the site in an area classified as a protected agricultural area and an ecological corridor protection zone. The entire zone is of agricultural character. In the south-west, in the immediate vicinity, some areas exhibit very high sensitivity due to the presence of classified woodlands along small creeks. The current shape of the surface site respects the integrity of the constraints. Still, particular attention will have to be paid for the specific design and integration of the surface site to maintain the registered ecological corridor, ensuring the free movement of fauna in the area.

The heritage sensitivity for the PL surface site in Challex, France is considered to be medium to high. The area around the site consists largely of protected agricultural and, further away, natural lands. There are several groups of isolated trees and alignments that bear witness to the history of agriculture. The site itself is located in a protected agricultural area and borders a protected ecological corridor registered in the municipal urban plan. The main issue is the visibility of the site from several locations in nearby villages. Therefore, care has to be taken for the specific design and landscape integration of the surface site.

In summary, the main heritage constraints are mostly related to the rural and agricultural character of the areas, with the presence of historical buildings at some distance from the sites. Particular attention related to heritage has be paid during site design and landscape integration at the site locations PB, PJ and PL.

3.3.11 Landscape

The initial state analysis included a detailed landscape analysis that was carried out with expert companies during field visits over an entire year. An example of the landscape considered is shown in Fig. 3.48. The landscape analysis extended up to 5 km around the surface sites, since the visibility of the sites depends significantly on the topography, urban and vegetation environment. Detailed landscape analysis and maps were developed that show the topography, the views from and to the sites and the visibility issues. They will serve as input for subsequent architectural design works and landscape integration concepts.

The site PA and its surroundings in Ferney-Voltaire (France) are dominated by agricultural areas, Geneva airport, highly urbanised commercial surroundings and an ecological corridor between the residual forests that occupy the buffer along the Franco-Swiss border. The area is in an open landscape with a view towards the Alps and Mont Blanc that has to be considered during the architectural design of the surface site. The nearby LHC site Pt8 (LHCb) and its planned extension provide an excellent opportunity to reduce the PA site footprint as much as possible to preserve the view and the ecological corridor that also stretches across the border.

The site PB in Presinge (Switzerland) is located in open countryside with valuable views towards the Alps and the Salève mountain. The landscape continuity is remarkable and the views from nearby hills over the landscape and its cultural and landscape heritage are highly valued. Much care must be taken in the architectural designs of the site, ideally integrating the site in the landscape as much as possible, taking care that the view from the nearby villages towards the mountains remains unobstructed.

The PD site in Nangy (France) is located in a mixed urban, agricultural and industrial environment that is dominated by major transport routes. Direct views to the sites are limited.

Table 3.14 Typical noise levels with practical examples

Noise	dB(A)	Level	Conversation
Jet plane takeoff	< **130**	Above pain threshold	**Impossible**
Jackhammer at 1 m	< **110**	Supportable for a short moment	
Motorcycle at 2 m	< **90**	Annoying	**Possible when shouting**
Heavy road traffic	< **80**	Very noisy	**Difficult without shouting**
Dwelling close to an autoroute	<**70**	Noisy	**Possible when speaking loud**
Working on a computer	< **60**	Moderate	**Possible with normal voice**
Noise level in a city during the day	< **50**	Rather quiet	
Construction noise at 100 to 200 m distance from a surface site	**40 - 45**	-	
Noise level in the countryside during the day	< **40**	Quiet	**Possible with quiet voice**
Noise level in the countryside during the night without wind	< **30**	Very quiet	
Snow falling in the mountains, recording studio	< **15**	Silent	

The PF site in Éteaux (France) is located in a natural environment, directly on highly frequented transport routes and commercial premises. No direct visibility from La-Roche-sur-Foron exists. However, the mountain views towards the Alps need to be considered when developing the architectural design of the site.

The site PG in Charvonnex and Groisy (France) is located in a highly natural environment, partially forested and with grass fields. The mountain views from the site are highly valued. A direct, but limited view of the site only exists from the Olières plateau.

The PH site in Cercier and Marlioz (France) is located in a rural environment with a forest. Some hamlets exist in the vicinity, but due to the forest and the topography, no direct view of the site exists.

The PJ site in Dingy-en-Vuache and in Vulbens (France) is located in a mixed natural and agricultural environment. The landscape is open and the view from Vulbens must be taken into consideration during the architectural design.

The site PL in Challex (France) is located in an agricultural/vineyard environment with views to the Jura mountain, the Rhône valley and the Alps. The open views require careful landscape integration, considering in particular the site's visibility from the nearby hamlets.

3.3.12 Noise

Noise, is considered to be unpleasant or annoying and is an environmental aspect that is relevant during the construction of the surface and subsurface structures and during the operation of the particle collider. The regulations concerning noise protection differ significantly between France and Switzerland. However, in all cases the impact due to noise depends on the presence of people and animals that would be affected by the noise. The relevant indicators are not only frequency and amplitude, but also the time during which an exposure to noise occurs and the duration of the exposure: during ordinary working hours, during the night, on non-working days, the typical presence of people in their homes, the age, health and other social conditions of the potentially affected people (e.g., noise in the vicinity of a hospital, a school or a retirement home). Typically, noise generated by machinery is considered to have noteworthy health effects from 40 dB(A) and higher. Noise up to 30 dB(A) is a level that is generally experienced by persons in a typical living environment (see Table 3.14).

Therefore, the first step required is to establish the existing background noise in the vicinity of the candidate surface sites using devices like those shown in Fig. 3.49 and Fig. 3.50. This activity is followed by estimations of noise generation without protection measures. This identifies sensitive areas. An eco-design is subsequently applied to reduce the noise where potential impacts on the environment are expected. The approach is to first work on low-noise designs. This also includes the relocation of noise-generating devices on the surface sites. Where this process turns out to be insufficient, noise protection measures to reduce the impacts are studied. Relocation of noise-generating equipment or adjustment of an entire surface site is an option that is considered if no adequate mitigation measures can be identified.

The background noise was established by first consulting national noise emission databases and then completing the data with field measurements. The measurements were carried out by expert companies on various days in 2024 at a selection of different locations and at different distances from the surface sites. Detailed analysis of the

Fig. 3.49 Field-based noise measurements conducted to assess ambient sound levels

Fig. 3.50 Noise measurements taken near a residential area to understand the current noise level

Table 3.15 Typical background noise measured in the vicinity of surface sites and the numbers of people potentially affected within the distances indicated from the site

Site	Background noise dB(A) 7 h-22 h	Background noise dB(A) 22 h-7 h	Potentially affected people	Distance to site
PA	55	45	0	100 - 200 m
PB	36	36	0† (< 10‡)	100 m
PD	48	44	0	100 - 200 m
PF	48	40	~10	100 - 200 m
PG	36 - 48	37 - 45	0	100 - 300 m
PH	35	29	< 10	100 m
PJ	39 - 47	35 - 44	0	300 m
PL	40	30	< 5	200 m

† People exposed according to Swiss limits, DS III

‡ People exposed according to permitted noise emissions in France

frequencies, amplitudes, and directions of origins have been made to permit mixing potential noise sources at the surface sites with the ambient noise at a later stage. The number of potential residents that could be affected by noise has been obtained using an analysis of the data collected with the geographical information system and statistical information (see Table 3.15).

The measurements indicate that the majority of sites are affected by significant background noise with no people present in a perimeter of 200 to 300 m. Therefore, neither the noise from construction nor operation, that will be kept as low as possible with noise protection measures, is expected to impact the population at sites PA (Ferney-Voltaire), PD (Nangy), PF (Éteaux), PG (Charvonnex and Groisy), PJ (Dingy-en-Vuache and Vulbens). At the PL site (Challex), construction activities during the night could lead to an excess of background noise, and therefore, the construction schedule would have to be adapted if a detailed technical design of the construction site in view of noise protection turns out to be insufficient. At sites PB (Presinge) and PH (Cercier and Marlioz) the background noise is particularly low with about 35 dB(A) compared to all other locations. In all cases, operation related noise can be kept below the threshold for residents potentially affected in the vicinity, but for the construction planning, care must be taken to respect the times during which noise exposure is more impactful (e.g., during the night, weekends and non-working days). For site PH, 3 to 4 houses at a distance of 100 m would be affected, and at site PB, two houses at a distance of 200 m would be affected. The construction-induced noise should, therefore, not significantly exceed the background noise during resting times in these locations.

3.3.13 Vibrations

Vibrations are rapid oscillating movements that propagate through solid paths and can be transmitted to the human body, especially through direct contact with the ground or the structure concerned. They are thus physical phenomena characterised by a wave with its amplitude and frequency.

The risks associated with vibrations are mainly damage to buildings and disturbance of people. Vibrations can occur due to seismic activities, ground movements, meteorological conditions and artificial sources such as construction activities and machinery. The environmental analysis revealed that in the entire perimeter of the project, seismic activities have a very weak to weak potential to create relevant vibrations, despite different occurrence probabilities for small-scale seismic events. Concerning vibrations caused by landslides surface site locations PA, PB, PD, PH, PJ and PL are at significant distances from risk zones and no subsurface cavities exist within a relevant distance of surface sites. A potential landslide risk zone exists only at a distance of 500 m from the PF site, but the likelihood of an event is very small. A cavity that is part of a defence infrastructure exists at a distance of 250 m. It is unlikely that this cavity would collapse. Weather phenomena such as violent winds and lightning may cause vibrations that affect trees and building structures. However, such events are infrequent in the perimeter of the scenario. Various human-induced vibration sources over the coming ten years were identified in the vicinity of surface sites PA, PD and PF. Road traffic is another source of ongoing vibration. It needs to be considered for sites PA, PD, PF, PG and PJ. No other noteworthy sources of vibrations could be identified in the vicinity of surface sites.

3.3.14 Light

Light pollution refers to the excess or poor management of artificial light in the nighttime environment. This phenomenon is increasingly concerning, both for its effects on biodiversity and human health. There are two types of light pollution. First, direct light pollution relates to the impact of light directly produced. Secondly, indirect light pollution results from an accumulation of light, creating a halo that obscures the stars and degrades the quality of the night sky. With respect to the surface sites, light pollution is a relevant environmental topic to be assessed during the detailed design phase concerning the construction activities and the subsequent operation phase. Therefore, at this stage, the existing light pollution in the vicinity of the candidate locations for surface sites has been analysed and documented to serve as a baseline for the development of the detailed design.

The main source of light pollution in the areas concerned by the project is public lightning along roads in residential areas. In addition, commercial zones are a source of artificial light, in particular when they use large-scale public screens. Frequently, lights are not controlled. Some outdoor lights of private houses contribute to light pollution. Finally, industrial installations for operation during nighttime and to ensure safety are a strong source of light pollution.

For the current state, data have been purchased from various sources, and maps have been developed using these data for the areas around the surface sites. The zone around site PA is strongly illuminated during the night. One source is the Geneva airport and another one is the commercial zone in the immediate vicinity. Road lighting and newly built residential houses also contribute. The Grand Genève plan foresees that the entire area is gradually restored to protect the ecological corridors and the fauna. However, no protection measures are currently planned at local French urban planning level. Site PB in Switzerland is located in the countryside and only few buildings are found in the vicinity. In the Grand Genève plan, the perimeter is classified in order to protect the 'night'. In particular, the zone close to the road is subject to refurbishment and the zone along the creek has a stake. However, no protection measures are mentioned at local urban levels. Site PD is in the immediate vicinity of major transport routes and industrial buildings on a field. No particular protection measures are planned at local urban planning level. Site PG is in a natural environment and in the forest with only little light pollution. Although no particular protection measures for the location exist, it can be assumed that preserving the current situation is a priority. Also, site PH in the forest is in an area with very low light pollution.

Although no particular protection levels are indicated it can be assumed that the current situation is to be preserved as much as possible. Site PJ in the countryside experiences small light sources in the vicinity from

Fig. 3.51 Types of radiation (Source: IAEA [90])

some distant urban constructions. The zone is classified to be preserved, and the ecological corridors constitute a stake. General protection measures apply to forbid artificial light along the water courses although at local urban planning level, no protection zones are indicated. Site PL is located in an agricultural zone and rather isolated next to fields, forests and vineyards. In Switzerland, nature protection zones forbid artificial light. At the local urban level, no protections apply in France.

Summing up, the site PD and its surroundings are located in an area where the night should be preserved with priority. However, no noteworthy species are affected and therefore the stake is average. The PA site is, however, in an area with high light pollution and there are ecological stakes in the surrounding area. Therefore, there is a will to restore the night environment, and the stake is high. The stake is also high for the PB site in Switzerland, since the night is intended to be preserved and light pollution should even be further reduced. Also, the stake for site PF is high since the site is located in an area with almost no light pollution today. Similar conditions with high stakes apply to sites PJ and PL. The wider surroundings of sites PG and PH are in a forest with low light pollution and nearby noteworthy biodiversity reservoirs. Therefore, the stakes with respect to light pollution are very high. These findings have to be considered and integrated in the design and planning of the construction sites and a plan to preserve the night has to be developed for all sites concerning the operation phase.

3.3.15 Radiation

Possible risks for the population and environment emerging from non-ionising and ionising radiation exposure at different locations on the surface were analysed based on available data in both Host States. Figure 3.51 shows the different types of radiation, non-ionising and ionising, that exist.

The Host States notified services in charge of carrying out measurements to establish national databases will require updated data before a particle accelerator is put into operation to establish a baseline for the ionising radiation.

Non-ionising radiation In France, exposure limits vary depending on the frequency range used, typically between 28 V/m and 87 V/m for the electric field. The Swiss regulations distinguish between public areas in which the persons stay only for brief intervals of time, such as roads or sports facilities, and sensitive areas, in which the persons may stay for a certain limited period of time including houses and apartments, schools, and hospitals. Switzerland imposes stricter installation limits for radio equipment than France, with maximum electric field values set at 4 V/m for 900 MHz, 6 V/m for 1800 MHz, and 5 V/m for installations operating across multiple frequencies. These Swiss regulations are designed to provide enhanced protection for sensitive locations compared to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. Swiss limits with respect to immission, which represent the cumulative exposure from all emitters, align with European recommendations and are identical to those in France. Figure 3.52 shows the values of the electric and magnetic fields measured under the line, as well as at 30 m and 100 m from the line, for very high voltage, high voltage and low voltage overhead lines.

No electricity lines are emitting low-frequency radiation in the vicinity of sites PB in Switzerland, PD, PG, PH, PJ and PL in France. A 63 kV line runs 250 m in the vicinity of the PF site in Éteaux in France, which emits a negligible electromagnetic field onto the candidate surface site. The 66 kV underground electricity line supplying LHC Point 8 in Ferney-Voltaire in France is just next to the PA site. It induces a very weak electromagnetic field onto the site.

Some radio stations that are sources of radio waves are present near the surface locations, but the recorded exposure measurements are well below the reference levels. The data collected from measurement stations near PA, PB, PD, PG, PJ show that all exposure measurements are significantly below the reference levels. No data was found for measurements within a 5 km radius of the PF, PH and PL locations in France. Detailed measurements will have to be carried out before the installation is put into operation, but the risk of exceeding the limits for ionising and non-ionising radiation specified in the regulations is considered to be very low.

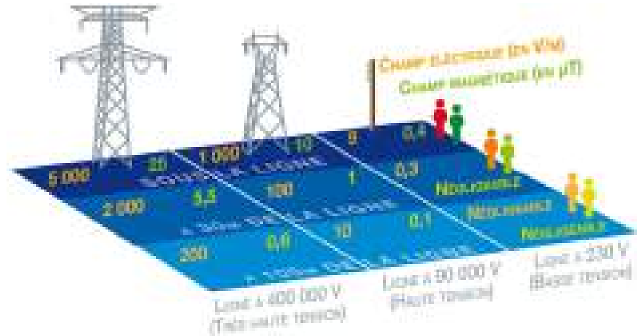


Fig. 3.52 Average values of the electric and magnetic fields around overhead power transmission lines at 50 Hz (Source: DGS [91])

Table 3.16 Level of exposure to ionising radiation at the surface site locations today

Nearest data entry	Annual exposure	Surface site
Ferney-Voltaire	5.2 mSv/year	PA (Ferney-Voltaire, France)
Ville-la-Grand	4.0 mSv/year	PB (Presinge, Switzerland)
Nangy	4.3 mSv/year	PD (Nangy, France)
Éteaux	4.4 mSv/year	PF (Éteaux, France)
Groisy	4.4 mSv/year	PG (Charvonnex and Groisy, France)
Charvonnex	4.9 mSv/year	PG (Charvonnex and Groisy, France)
Marlioz	4.9 mSv/year	PH (Cercier and Marlioz, France)
Cercier	5.0 mSv/year	PH (Cercier and Marlioz, France)
Dingy-en-Vuache	5.0 mSv/year	PJ (Dingy-en-Vuache and Vulbens, France)
Vulbens	5.8 mSv/year	PJ (Dingy-en-Vuache and Vulbens, France)
Challex	5.5 mSv/year	PL (Challex, France)

Source: Autorité de sûreté nucléaire et de radioprotection (ASNR)

Ionising radiation Ionising radiation carries sufficient energy to ionise atoms or molecules, leading to molecular changes. High doses can cause cellular damage and mortality, whereas controlled applications are pivotal in industries, scientific research, and medicine. The sources of exposure are of natural and artificial origins:

- Natural cosmic radiation: energetic particles from space contribute to exposure, influenced by altitude and geographic location. Terrestrial radiation: radioactive elements in the Earth's crust (e.g., uranium, thorium) emit radiation, varying regionally due to geological factors.
- Natural radon gas: a significant contributor, radon accumulates in poorly ventilated indoor spaces. It constitutes 33% of annual exposure in France. Incorporated radionuclides: naturally occurring radionuclides in food and water contribute 12% to annual exposure.
- Artificial sources, nuclear accidents and testing: fallout from historical nuclear tests and accidents like Chernobyl contributes marginally to current exposure.
- Nuclear facilities: emissions from civilian and military installations are tightly regulated, with negligible contributions (0.001–0.01 mSv/year near facilities).
- Artificial sources, medical applications: diagnostic and therapeutic uses dominate artificial exposure, contributing 34% of total exposure in France.
- Artificial sources, scientific research activities: the particle accelerators and colliders operated by CERN contributing less than 0.01 mSv/year.

Table 3.16 gives an overview of the current ionising-radiation background conditions at the surface site locations.

Exposure to cosmic radiation, originating from high-energy particles such as protons and heavy ions from space, poses hazards due to its ionising nature, which can damage living tissues. The intensity of exposure increases with altitude, being roughly twice as high at 1500 metres compared to sea level and further elevated during air travel. While the Earth's magnetic field reduces exposure near the equator, higher doses are received near the poles. In France, cosmic radiation accounts for about 7% of the average annual exposure to ionising radiation, with an effective dose at the surface sites between 0.32 and 0.70 mSv/year. In Switzerland, the dose associated to cosmic rays in the vicinity of the site is about 0.35 mSv/year.

Telluric radiation refers to ionising radiation emitted by naturally radioactive elements like uranium, thorium, and potassium-40 found in the Earth's crust. Exposure levels vary depending on regional geology, with areas rich in granitic or volcanic rock typically exhibiting higher radiation levels. In France, telluric radiation contributes approximately 14% of the average annual exposure to ionising radiation, with an effective dose of around 0.51 to 0.55 mSv/year in the areas of the surface sites in France and 0.33 mSv/year in the vicinity of the surface site in Switzerland.

Exposure to natural radionuclides occurs through the ingestion of radioactive elements, such as polonium-210, present in food, water, and air, which originate from terrestrial rocks, soils, or cosmic interactions. Foods like seafood are particularly rich in these radionuclides, and tobacco inhalation can also contribute significantly. In France, this accounts for approximately 12% of the average annual exposure to ionising radiation, with an effective dose of about 0.55 mSv/year in France, varying between 0.4 and 3.1 mSv/year depending on dietary habits. In Switzerland, the exposure is about 0.40 mSv/year. Tobacco consumption accounts for about 0.04 mSv/year.

Exposure to radon, a naturally radioactive gas, varies between France and Switzerland due to differences in geology and measurement methodologies. In France, radon contributes 33% of the average annual ionising radiation exposure, with a mean dose of 1.5 mSv/year, ranging between 0.54 and 3.2 mSv/year. Specific areas concerned by the surface sites in Ain and Haute-Savoie report slightly lower exposures, around 1.47 and 1.14 mSv/year, respectively. In Switzerland, radon is the largest natural contributor to radiation, with an average dose of 3.3 mSv/year, reflecting a higher impact. This discrepancy partly arises from different dose conversion factors used; France employs the UNSCEAR coefficient, while Switzerland uses the CIPR's updated factors, which approximately double the estimated risks. Consequently, radon exposure is relatively more significant in Switzerland.

Exposure to ionising radiation from artificial sources in France and Switzerland includes contributions from nuclear accidents, medical applications, nuclear installations and scientific research facilities.

Medical applications in both France and Switzerland, are the largest contributors to artificial ionising radiation exposure. In France, they account for approximately 1.5 mSv/year per capita, representing 34% of the total radiation exposure. Similarly, in Switzerland, medical applications contribute about 1.49 mSv/year per capita, highlighting the widespread use of diagnostic and therapeutic procedures involving ionising radiation in both countries.

Radiation exposure due to past nuclear accidents and fallout, such as Chernobyl, and atmospheric nuclear tests are now minimal in both countries. In France, the average annual dose is 0.012 mSv/year, with slightly higher doses in areas with significant fallout. In Switzerland, this exposure is even lower, contributing only a few hundredths of a mSv annually, reflecting the diminished impact of residual fallout over time.

Exposure from nuclear facilities is negligible in both France and Switzerland due to strict regulatory measures. In France, people living within 10 km of nuclear installations receive an annual dose of 0.001 to 0.01 mSv under normal operational conditions. In Switzerland, exposure near nuclear facilities and the scientific facilities of CERN, is similarly low, with annual doses generally below 0.004 mSv, demonstrating effective safety and monitoring measures.

Summing up, the ionising radiation context at the surface sites is significantly larger than the residual ionising radiation that is generated by CERN's scientific particle accelerators.

3.3.16 Technical risks

Natural Hazards As part of this study, several types of natural hazards that can potentially lead to interactions with the project have been identified. These will be analysed in further detail during a subsequent environmental impact assessment. The topics concern flooding, ground movement, seismic activities, avalanches, forest fires, cavities, radon, clay swelling and technological hazards. These natural hazards may also be caused by climate change effects. The evolution of the climate has been taken into consideration in the study of the current state of the environment, as well as the evolution of the environment in which the project would be embedded.

Flood and ground movement hazards that can be caused by numerous factors, such as rain, groundwater and rivers, are considered to have low probability for all the locations. Effects due to unstable ground, such as landslides, mudflows and erosion have also been taken into account. Overall, no significant hazards or potential effects leading to relevant risks were identified in the concerned locations. No surface site on French territory is subject to a ground movement. For the site PB in Presinge in Switzerland, the closest potentially unstable ground area is located 700 m east of the site, however the landslide risk is superficial. The candidate surface site location is not subject to the hazards linked to flooding or earth movement.

Seismic hazards vary depending on the location. France is divided into five seismic activity zones. The sites studied are located in zones of moderate or medium seismic activity. In particular, sites PA, PL and PJ are located in zones of moderate (level 3) activity, while sites PG, PF and PD are located in zones of medium (level 4) activity. This requires the application of earthquake-resistant construction principles during the surface site design development. In addition, some of the sites studied are located near active tectonic faults. For example, site PA in Ferney-Voltiare is located about 400 m from a fault. In Switzerland, the seismic hazard model classifies locations into five zones, of which site PB in Presinge is located in zone Z1b (level 2), characterised by low seismic activity. Further field studies are needed, and cooperation with scientific institutions to assess the local seismic risk in detail and develop specific engineering models will be undertaken.

Forest fires turn out to be a very low hazard in the zones concerned by the surface sites, although two locations are in forest zones. In France, the Forest Fire Risk Prevention Plan (PPRIF) established at the municipal or inter-municipal level, targets areas exposed to significant risk levels and strong land pressure. In addition, the PPRIF may also impose clearing of areas in order to isolate the buildings. It may also require that access roads be sized to allow fire trucks to pass and for people to evacuate in the event of a fire. No French municipality affected by the surface sites is subject to a forest fire risk prevention plan and none of the areas surrounding the surface sites in France are subject to the legal obligation of clearing. Although the site location PH in Cercier and Marlioz is not exposed to the natural forest fire hazard according to various regulatory and management tools, there always remains a residual and low hazard of forest fires in this area due to the presence of timber. In Switzerland and more specifically in the canton of Geneva, there is no law, prevention plan or specific forest fire risk management plan. The site PB in Presinge is not in the vicinity of a woodland that would generate a forest fire hazard to the site.

Avalanches are not considered a relevant hazard for the surface sites due to relatively flat terrain and low forest density in the vicinity of the locations analysed.

Cavities natural or man-made voids can be considered hazards for construction activities. The analysis addressed their presence and potential effects with respect to the implementation of the surface sites. No cavities are located within a radius of 500 m around the French surface sites, except for the PG Charvonnex site where several cavities linked to military works are located within a radius of more than 250 m around this site. Apart from their existence and location, no additional information is available. Thus, the potential hazard from underground cavities in this area requires additional data gathering.

Radon is a colourless, odourless radioactive gas that originates from the decay chains of uranium and thorium, both naturally present in the Earth's rocks. A key factor influencing radon concentration levels in buildings is the geology, in particular, the uranium content in the subsurface layers. In some areas, specific underground features (e.g., faults, mining works, hydrothermal sources) can exacerbate radon transfer to the surface, locally increasing its potential. For new constructions, radon transfer can be limited by enhancing the building's seal between the ground and the structure. In France, the mapping method estimates the radon potential of geological formations by considering factors that influence both radon production in the subsurface and its transport to the surface. Zones are classified as having low, moderate, or high potential. All French surface sites studied are located in low radon potential zones.

In Switzerland, the radon map shows the probability in % of exceeding 300 $\mathrm{Bq\,m^{-}}$ in buildings, divided into four categories: $\leq$1%, 2 and 10%, 11 and 20%, and >20%. Unlike France, there is no national campaign that estimates radon thresholds in buildings. The PB site in Presinge lies in a low-risk area, in the range of 2 to 10% probability of exceeding 300 $\mathrm{Bq\,m^{-}}$.

Shrinking and swelling of clays is a natural hazard that has been assessed for all surface site locations. Superficial clay soils have the ability to change consistency depending on their water content. When the water content of clay soil increases, its volume expands, a phenomenon referred to as the swelling of clays. Conversely, a reduction in water content causes the opposite effect, known as shrinkage of clays. Figure 3.53 explains the mechanism of the shrink-swell phenomenon. This shrinkage or swelling can cause structural damage to buildings.

From January 1, 2024, in France enforcement of the construction regulations has been tightened, and a new certificate for clay shrink-swell behaviour is now mandatory in zones subject to medium or high exposure. The surface sites located in France are subject to low to medium exposure to shrink-swell risks. Site PA in Ferney-Voltaire is mostly in a low hazard area, except for a small part of the site near the LHC site point 8 (LHCb) where the exposure level is medium. Sites PD, PF, PG and PF are rates as low exposure. PH and PJ sites are located in zone with medium exposure. The PL surface site in Challex is mainly located in the zone with low exposure, except for a small fragment in the southern part of the site with medium exposure, which is not foreseen to host constructions, but a green buffer. In Switzerland, a lithological map that provides an overview of the subsoil classified according to lithological and petrographic criteria indicates that the site PB in Presinge is located in soils containing clays. However, the concentration and depth of this clay element in the soil are not precisely described. Detailed soil investigations are required during a subsequent environmental impact and surface site design phase to clarify the conditions and, if needed, to take them into account during the design of the surface site.

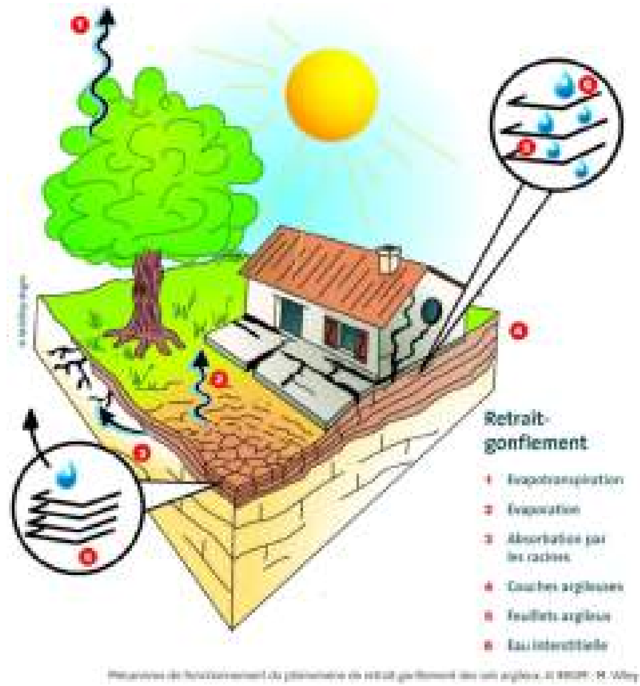


Fig. 3.53 Expansion and shrinkage of clays. Damage to the building is caused by the rain induced expansion on one side and shrinkage caused by removal of water by the tree on the other

Technological hazards Technological hazards linked to industrial, environmental, and infrastructural activities could potentially have effects on human health, safety and the surrounding environment. Risks emerging from these hazards and effects arise from industrial installations, the transport of hazardous materials and other activities involving dangerous substances. Therefore, their presence near candidate surface site locations has been analysed.

In France, two categories of industrial facilities are considered to generate risk. The first group concerns establishments reporting emissions and transfers of pollutants into the air, water or soil and the production of hazardous waste. This covers establishments such as large industrial installations, large municipal sewage treatment plants and certain livestock farms. Second, installations classified for environmental protection (called ICPE) that are industrial or agricultural facilities subject to regulations for the prevention of environmental risks and are classified according to regimes ranging from simple declarations to authorisations, depending on the risk. In addition, the SEVESO regulations (EU Directive 2012/18/EU) impose strict controls on facilities processing hazardous chemicals in order to prevent serious accidents.

In Switzerland, the Ordinance on Major Accident Prevention (so called OPAM) seeks to protect people and the environment from severe damage caused by extraordinary events in installations or during the transport of hazardous materials. OPAM applies to businesses exceeding specific hazardous material thresholds, genetic organisms under strict confinement, and transport infrastructures like pipelines, railways, and highways used for dangerous goods. The planning authorities (cantons and municipalities) are responsible for integrating aspects of major accident prevention into their plan for land use. Although Switzerland does not apply the SEVESO directive, OPAM adopts even stricter thresholds for hazardous substances and includes transport routes, pipelines, and dangerous microorganisms within its scope.

A gas pipeline passes through the PA annex surface site near the LHCb, extending from Switzerland and running along the edge of the main PA surface site towards the north. This installation must be taken into account when designing the surface infrastructure; however, there are no hazardous industrial installations located near the PA site, and the main threats might come from the proximity of major communication arteries (airport and departmental routes) that can transport dangerous goods.

There is a gas pipeline approximately 200 m south-west of the PB surface site which poses a potential risk of an accident involving hazardous materials. The Route de Jussy, classified as a major transit route, runs alongside the eastern boundary of the site. This road is subject to regulations concerning the transport of dangerous goods under the Swiss OPAM ordinance. Apart from these, there are no other industrial installations, facilities declaring pollutant emissions, or safety perimeters within the vicinity of Site PB.

The PD, PF and PG surface sites are located near major transport routes (highways and departmental roads) that are used for regional and national goods transport, including hazardous materials, creating potential risks of accidents or spillages. A railway line currently used for passenger transport passes near the PG site. Neither the PD or PG sites have other classified industrial facilities or pollutant-emitting sources within a 500 m radius, ensuring a relatively low environmental risk. The classified installation for environmental protection SARL Luc

Maulet, which handles inert waste, is located 150 m from the PF surface site near the A410 but poses no risk as its activities are related to the storage of non-recoverable inert waste.

There are no major roads or highways within a 500 m radius of PH surface site, there are just local roads and paths, which significantly reduces transport-related risks involving hazardous materials. There are also no classified installations, pollutant-emitting facilities, or other industrial sites in proximity. However, there is a gas pipeline near the PH site and special attention should be paid to heavy transport that would cross the gas pipeline route.

Apart from the presence of the A40 autoroute located 50 m to the south of the PJ surface site and the associated potential exposure to risks associated with the transport of dangerous goods, there are no classified installations or establishments reporting releases and transfers of pollutants in the vicinity.

Also, for the PL surface site, apart from the proximity of the departmental road, no classified installations or establishments reporting releases and transfers of pollutants were identified within a radius of 500 m, including the Swiss territory.

The risk of the dam bursting has also been analysed. Such an event could cause water to leak from the reservoir and flood the surrounding areas to a greater or lesser extent. None of the communes in France where the surface sites are located are at risk of dam failure. In the canton of Geneva, there are two dams, each downstream of the PB surface site thus, the site is not subject to the risk of dam failure.

There is no nuclear installation present near the surface sites, in France and Switzerland. Furthermore, there is no facility subject to the ICPE nomenclature for activities related to pyrotechnic risk, within a radius of 500 m around the sites, on French territory. In Lake Geneva, the entire geographical area of the Petit Lac is polluted by the presence of munitions dumped between 1948 and 1979. These are munitions such as shells, rifle cartridges, aircraft bombs and other explosive residues. The PA and PB sites are located 4 km from the shores of the lake. Thus, these surface sites are not subject to the pyrotechnic risk associated with un-decommissioned munitions in the lake.

In summary, some sites are located near transport routes such as autoroutes, departmental roads and railways that carry or may carry dangerous goods. There is only a gas pipeline in close proximity to the PA, PB and PH sites, which needs to be considered when designing the surface site to minimise the risk of an environmental accident. However, there are no nearby nuclear facilities, polluting facilities or classified industrial facilities within 500 m of any surface site, and the risk of a dam failure or pyrotechnic hazards from munitions in Lake Geneva is minimal. Overall, these sites pose a relatively low environmental and safety risk, with special consideration being given to infrastructure near transport routes.

Polluted sites In France, polluted sites and soils are described as locations that, due to past waste disposal or pollution infiltration, pose ongoing risks to people or the environment. These issues often stem from outdated waste disposal practices, chemical leaks, or accidents. Some areas also experience pollution from atmospheric fallout, which has accumulated over many years. It is different from diffuse pollution, like that from agricultural practices or car emissions near major roads. Industrial or agricultural activities that could cause pollution or risks to the local population are considered classified installations and are subject to regulations. The national policy aims to prevent future pollution while managing existing sites and ensuring they are safe for their intended use. Three complementary databases (BASIAS, BASOL, SIS) provide comprehensive pollution diagnostics, with detailed inventories of polluted sites and their risk levels.

In Switzerland, polluted sites refer to locations where waste has been permanently stored, such as landfills, as well as areas where waste has been stored or infiltrated. Contaminated sites are those that cause harmful or disruptive effects on the environment or have the potential to do so in the future. Thanks to waste regulations established in the 1990 s, Switzerland has prevented the creation of new contaminated sites, by prohibiting hazardous waste landfills and untreated urban waste. It has put the infrastructure for proper waste treatment in place, ensuring that any waste is handled responsibly.

For surface sites, PA, PD, PG, PH and PB there are sites listed in BASIAS, BASOL, SIS or Swiss database located within a radius of 500 m, however, none of the areas of PA, PB, PD, PF, PG, PH, PJ and PL have contaminated sites in immediate proximity.

3.3.17 Other projects

Introduction In an environment that is subject to continuous development, urbanisation and demographic development in a cross-border context, the constraints and opportunities that can emerge from other projects must be considered when conceiving a new research infrastructure with significant territorial development needs. Therefore, the analysis of the initial state of the environment included the establishment of an inventory of projects that were planned and constructed and that were potentially relevant to the FCC. Continuous monitoring needs to be implemented to keep this inventory up to date and to act rapidly in case a new project concept is developed, in order to understand if synergies are possible and to avoid potential conflicts emerging.

Today, the most relevant other projects to be considered are:

- Geothermal exploitation
- Lake crossing
- Grand Genève development project
- Grand Annecy development project
- Enlargement of the departmental road D903 and integration with the A40 autoroute in France
- District heat network in Switzerland
- Heat networks in France
- Water networks in Switzerland
- Water networks in France
- Railway network development Nord Genève
- Railway network developments in France
- Territorial development in the Dingy-en-Vuache, Vulbens, Valleiry sector
- Development of Groisy
- Development of Ferney-Voltaire and Geneva international sector

Geothermal exploitation The energy provisioning strategy of the canton of Geneva foresees extensive further development of heat recovery from geothermal sources that range from about 100 m depth to several hundred metres. The investigations carried out in the frame of the feasibility study reveal no incompatibilities between the FCC and existing geothermal installations today. Given the depth of the FCC subsurface structures, it cannot be excluded that further geothermal probes lead to potential conflicts. It is, therefore, of utmost importance to implement an early warning system based on the current reference trace that permits CERN, as the project owner, to engage with the persons who plan to create such installations. A minor displacement of the probe can frequently resolve any incompatibility. Should a probe be built without knowledge or until the subsurface volumes are properly protected from other projects, the conflicting geothermal probe would have to be removed, and the loss would need to be replaced. In France, no geothermal probes are known in the vicinity of the current reference scenario and no knowledge of a department or region-wide geothermal campaign exists. However, the need for reserving the subsurface volumes is equally important on French territory.

Lake crossing Various subsurface lake-crossing projects have been conceived on Swiss territory during recent decades in the sector of the FCC, but they are not in its immediate vicinity. Most recently, a metro railway tunnel project has been proposed. Such a project can lead to potential synergies as well as to potential conflicts. Synergies would exist around subsurface investigations, tunnelling technologies, and excavated materials management. Conflicts could arise from overlapping construction schedules that could lead to increased nuisances, increased difficulties for the management of excavated materials, availability issues for engineering companies and workers, and organisation of construction sites and activities. The convolution of the authorisation processes of two almost concurrent projects could eventually generate societal acceptance issues for both projects. Care must also be taken to ensure appropriate designs for both projects in case the two tunnelling projects overlap, although the depths differ.

Grand Genève development project Territorial planning documents in both host countries integrate the continuous development of a 'Grand Genève' in their planning documents. In addition, it is a cross-border project that involves substantial coordination. The project involves numerous improvements, such as road and railway mobility, urbanism, economic development, environmental sustainability, housing, social cohesion and cross-border governance. The project facilitates the extension of CERN's scientific activities in a larger zone. It also creates constraints, since the urban development implies stricter preservation of natural and agricultural zones. This rapid evolution needs to be considered in the further developments and authorisation processes of the research infrastructure. The existing planning documents span a time horizon until 2030. Updates that are imminent need to include a future particle collider project in the region. Therefore, the timeliness of deciding for an intent to advance with a construction project or not is important. As the example of the departmental road enlargement in the Nangy sector has shown, the improvement of mobility can be an opportunity. However, it can also rapidly jeopardise the feasibility of the current scenario when surface site candidate locations are concerned.

Grand Annecy development project The regional development around Annecy is captured in numerous planning documents in France with a long-term horizon of 2050. It concerns mobility, management of natural resources, common use of infrastructures and services, preservation of nature and agricultural spaces, support for innovation and energy transition, development of eco-responsible tourism, development of education and training offers, social cohesion and solidarity, and the development of improved joint governance among municipalities, public and private actors, associations, and the public. This development permits the development of synergies with the FCC that for instance is also aiming at the development of innovation, education and training as well as high-quality tourism in the region, in particular in the sectors Groisy and Charvonnex that would host an experiment site. Conflicts could potentially emerge from the increased protection measures.

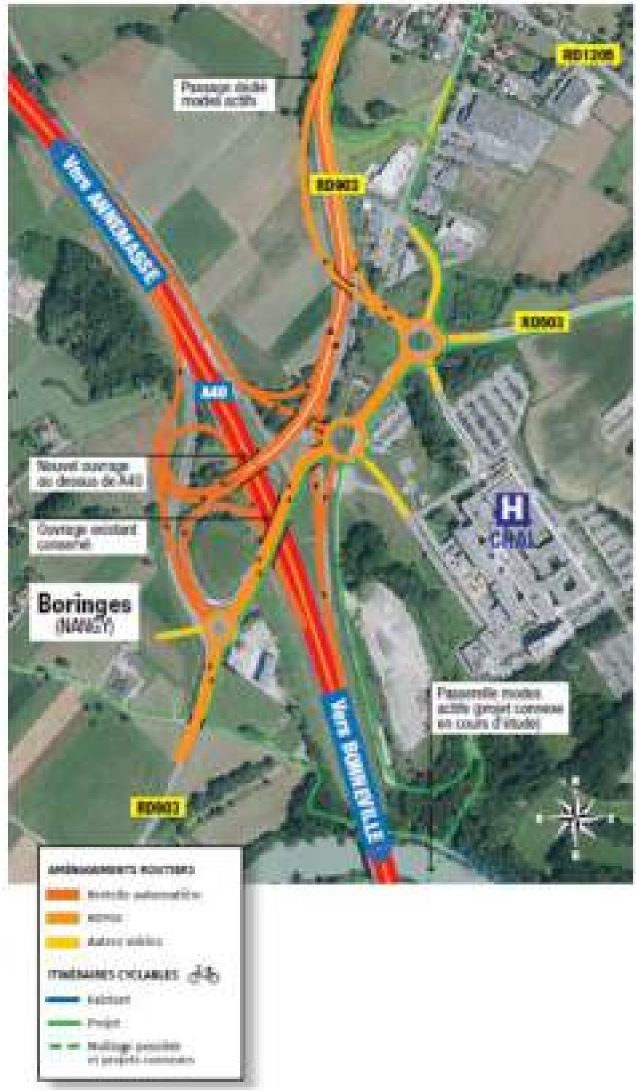


Fig. 3.54 Overview of the RD903 redevelopment project between the A40 Findrol interchange and the Chasseurs crossroads

RD903 enlargement and A40 integration The project to link the A40 autoroute with the 903 departmental road (see Fig. 3.54) and to enlarge this road significantly in the immediate vicinity of the experiment site PD in Nangy was a potential risk for the feasibility. Timely interaction with the Host State administration permitted the development of a suitable solution to adapt the surface site to the road project. Depending on the start date and duration of the road construction works, very good coordination between the two projects is required.

District heat network in Switzerland The canton of Geneva has committed[12] to substantially enlarge its heat distribution networks, in particular with major heat transport axes. The integration of geothermal heat, the GeniLac and the GeniTerre systems ensure heating and cooling capabilities in view of supporting the achievement of climate protection goals. This project leads to concrete synergies with the future research infrastructure that will be able to supply significant amounts of waste heat that can be injected into this network. No conflicts are identified.

Heat networks in France Several district heat networks are starting to be conceived and developed in the perimeters of various candidate surface site locations in France. This concerns, but is not limited to, the PA site in Ferney-Voltaire, for example. This development does not generate conflicts, but as the case of Ferney-Voltaire shows, it creates concrete synergy potentials. The network in Ferney-Voltaire today profits from the heat supplied by the Large Hadron Collider. A future particle collider would not only ensure continuity, but would permit a significant

[12] https://www.ge.ch/installer-remplacer-chauffage/reseaux-thermiques-structurants-rts-0.

increase in the heat supplied. Specific studies of the demand have been carried out in the frame of the feasibility study and these have confirmed this potential synergy.

Water networks in Switzerland The regional plans for water treatment in the Geneva region are currently under revision, but details are not available. Although conflicts with the FCC project are unlikely, it is prudent to monitor the evolution of the regional water management plan developments. The raw water for cooling the particle collider may have a high fraction of undissolved residuals after multiple recirculation. It is important to ensure that the residual materials, including the total dissolved solids (TDS) in the cooling water, can and will be accepted by the regional water treatment stations.

Water networks in France Similar to the situation in Switzerland, the knowledge of the planning and evolution of the local water networks and water treatment facilities is not centrally available. Although conflicts with the FCC project are unlikely, it is prudent to monitor the evolution of the regional water management plan developments. As mentioned above, it is important to ensure that the cooling water can and will be accepted by the regional water treatment stations.

The water treatment facility in the vicinity of site PD represents an opportunity for the project. The study included the verification of the feasibility of extending the water treatment facility with infrastructures to accept the residual cooling water from the particle collider. In addition, the study revealed that it is, in principle, technically and economically feasible to treat the waste water from the treatment plant and to use it for water cooling systems. This generates a potential to reduce raw water consumption and creates a socio-economic benefit potential for using treated waste water when the particle collider does not need it.

Railway network development Nord Genève The existing Léman Express is already reaching its maximum capacity and road traffic saturation calls for further development of the railway infrastructure. The development of a north-south railway transport axis is a priority of the Geneva canton. A conflict with the FCC is unlikely and the additional transport may, on the other hand, lead to potential synergies for the operation period of the new particle collider infrastructure.

Railway network developments in France The continuous increase of road traffic, accompanied by traffic saturation and air quality impacts also calls for a development of the railway infrastructure in France in the region concerned by the FCC. This mainly involves the Léman Express lines that pass in the vicinity of some of the FCC surface sites. Therefore, the development of the railway system presents opportunities for the project and potentially for the territory.

Territorial development in the Dingy-en-Vuache, Vulbens, Valleiry sector The modernisation of the A40 autoroute in the Dingy-en-Vuache, Vulbens and Valleiry sectors is planned by the operating company ATMB for between 2023 and 2028. It is important that the construction of the FCC starts after the tunnel through the Vuache has been refurbished to avoid limitations. If this is the case, the planned autoroute works do not lead to a conflict with the FCC. However, timely design work must be foreseen concerning the autoroute access for site PD for the FCC construction period. It would take about 10 years to put such access in place.

The territorial developments around local mobility (e.g., bike paths), education (e.g., high school) and emergency services (e.g., fire brigade) represent attractive opportunities to develop synergies with the FCC. Timely engagement with the local, departmental and regional stakeholders is required to leverage the FCC project, support these territorial development projects and integrate them into the surface site activities at PJ.

Development of Groisy A school development project was validated by the department of Haute Savoie in 2023. There is no conflict with the FCC project. However, this and related further development projects in Groisy and Charvonnex represent attractive opportunities to generate synergies such as the supply of waste heat, high-quality tourism and the creation of apprenticeship programmes and other cooperation in the education domain.

Development of Ferney-Voltaire and Geneva international sector The commune of Ferney-Voltaire has recently launched a large-scale redevelopment and modernisation programme around a new commercial activity zone (ZAC) in the vicinity of the PA surface site (see Fig. 3.55). The supply of waste heat from the existing CERN LHC point 8 (LHCb) site is also integrated in the development of a local district heating network. Developments that create synergies with the Geneva airport are also envisaged in this sector. The plan also foresees the creation of high-tech and innovative facilities and a significant increase in housing capacity. At the same time, on the Swiss side of the border, significant development activities have started in Grand Saconnex. The development of the local tramway system connecting the Geneva international sector (United Nations) with Ferney-Voltaire has been planned.

Fig. 3.55 The future Ferney Genève ZAC project with an extension of the tram line and terminus located less than a kilometre from the PA site

All these local economic development activities can potentially create conflicts with the FCC construction activities due to a local concentration of construction sites and construction-related traffic. A timely coordination with the local actors on the planning of an FCC construction is therefore needed.

On the other hand, these developments can lead to significant cross-fertilisation in terms of waste heat supply, mobility, education and economic developments.

3.4 Conclusion

The feasibility study phase anticipated studies and field investigations that are part of the environmental authorisation process in both countries. Those include, for example, the establishment of an initial state of the environment, the identification and prioritisation of noteworthy environmental aspects, the identification of indirect and induced connected enabling projects (road accesses, electricity, water and water treatment) as well as informal engagements with the public and their representatives. The scenario development process has been documented together with variants, and evolution of versions, the reference scenario and project invariants.

The studies permitted the identification of relevant issues and points requiring attention. The critical subsurface zones were located and the need for a continuation of subsurface investigations in order to establish a comprehensive and detailed 3D model was identified. The latter will serve as input to the construction process. The results of the preliminary subsurface investigations will provide information about an improved depth and inclination of the tunnel alignment. The initial state analysis revealed that different surface sites are subject to very different environmental constraints and present different opportunities for the creation of synergies. The work on the description of the project elements and the environmental aspects showed that an iterative approach is required due to the long and iterative development of the technical designs. A detailed description of the subsurface construction works is needed as a first step to assess the environmental impacts of the construction phase. A plan for the adequate management of the excavated materials according to industrial best practices and suitable for presentation to notified bodies in both Host States needs to be established as soon as the preliminary subsurface investigation results are available. The particle accelerator requirements need to be formally documented to permit a sufficiently detailed development of the technical infrastructure designs that are needed to assess the environmental impacts.

An eco-design strategy and guidelines have been developed that need to be integrated in subsequent project development by putting a project-wide, transverse systems engineering approach in place.

Although challenges and environmental sensitivities were revealed and documented, no fundamental showstopper with respect to technical, engineering and environmental feasibility could be identified.

The reference locations of the surface sites will require very different optimisation, reduction and integration approaches. Where residual impacts cannot be mitigated with these approaches, compensatory measures may be required. Such measures can differ substantially in terms of type, size and approach among the site locations. For the loss of protected agricultural spaces, a 1-to-1 compensation by re-creating the lost area by transplanting the topsoil to wastelands or areas with poorer quality is envisaged. Rewilding is another way of compensating for the loss of habitats and biodiversity.

Reforestation around surface sites where forests have been removed is an option, along with new forest establishment in previously non-forested areas. Landscape integration and preservation of visibility can be achieved by half-buried site elements, the separation of sites into different segments and by terracing.

The use of decarbonised, including renewable energies, aims at keeping Scope 2 emissions low. Incremental socio-economic benefits can, for example, be generated by entering energy supply contracts and agreements that include the creation of new renewable energy sources and by integrating waste heat recovery and supply from the onset. Location-specific innovation projects can lead to further reductions of the environmental footprint and incremental socio-economic benefits such as the use of treated waste water, the creation of soft mobility infrastructures, the development of high-quality tourism and local services around some of the surface sites and the creation of training and education opportunities in the project as a whole and at individual surface sites.

Chapter 4

Sustainability

4.1 Context

CERN's longstanding commitment to sustainability, integrating scientific, environmental, and societal goals, is a guiding principle in the development of a future particle collider infrastructure. The results presented in this chapter show the integration of strategies in the scenario development process that align with the Organisation's guiding principles and policies, ensuring that the FCC is conceived as a model of responsible large-scale scientific infrastructure development.

From the outset, the studies and developments for the FCC integrated CERN's existing guiding principles for the protection of the environment. It includes topics that extend beyond the biosphere, covering several aspects of the three sustainability dimensions. Examples include optimising resource use, limiting greenhouse gas emissions, and prioritising sustainable excavation and material reuse. The feasibility study also considered CERN's ongoing biodiversity and land-use management efforts, ensuring that construction and operational activities respect local ecosystems. It builds on the results and experience of CERN's past and present energy efficiency and waste heat recovery initiatives, aiming to reduce overall energy consumption, make responsible use of energy and contribute to regional energy networks. Water conservation, noise management, and emissions mitigation are further key elements of the study, reinforcing CERN's goal of balancing cutting-edge scientific progress with responsible environmental stewardship.

Achieving these objectives requires close cooperation with the authorities in both Host States, as well as meaningful engagement with the public. The feasibility study provides the foundation for the dialogue with national and regional regulatory bodies, ensuring that the FCC project aligns with environmental legislation and sustainability goals in both France and Switzerland. Furthermore, open and continued discussions with local communities will be essential to address concerns, share best practices, and build a collaborative approach to come to an environmental, social, and governance (ESG) framework that can ensure the long-term sustainability of such a new research infrastructure.

By incorporating lessons from past and existing projects at CERN and by leveraging the innovations adopted by other large-scale infrastructure projects in science and beyond, the FCC feasibility study seeks to set new standards for sustainability in large-scale scientific projects. It builds on the principles laid out in international and national laws and regulations, best practices and CERN's published policies and strategies, integrating best practices in impact avoidance, reduction and mitigation, circular economy principles, and stakeholder engagement. As such, this chapter lays the groundwork for a potential FCC implementation project that not only advances knowledge creation through fundamental physics research but does so with a firm commitment to long-term sustainability that embraces scientific excellence, the environment and society.

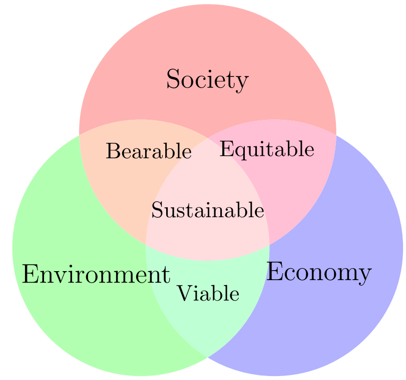


Fig. 4.1 Sustainability dimensions

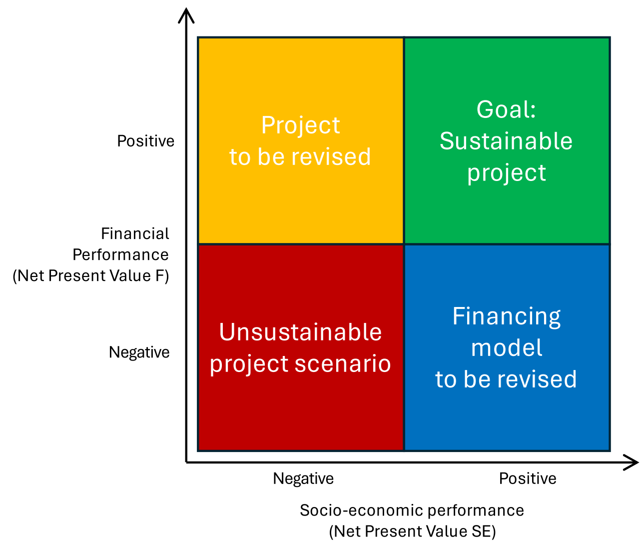


Fig. 4.2 Guidance for the sustainability of public investment projects. From Ref. [97]

4.2 Introduction

4.2.1 Sustainable research infrastructures

Research infrastructures (RI) are facilities that provide resources and services for research communities to conduct research and foster innovation [92]. An RI can be a single facility, such as, for example, the European Spallation Source (ESS) or the European XFEL, or it can be a facility that is part of an organisation that hosts multiple facilities, such as the Large Hadron Collider (LHC) and other particle accelerators at CERN (e.g., Antiproton Decelerator, ELENA, PS, SPS) that offer dedicated scientific research opportunities. The Future Circular Collider will be a research infrastructure that is hosted by CERN, conceived and constructed by an international collaboration, providing open access to a worldwide community of scientists.

Sustainability refers to the ability to maintain an activity at a certain rate or level. It integrates three stakes: Society, Economy and Environment (Fig. 4.1). A science programme or project can be considered sustainable if it is able to successfully address and complete its scientific core mission satisfying the requirements of three stakes: it obtains a 'social license' to operate [93], it maintains an ecological balance applying an avoid-reduce-compensate sequence [94], and it is affordable in the long term with well-understood and managed risks.

An appraisal process helps understanding if a programme or project is sustainable and provides means to identify pathways to make them more sustainable. This process integrates financial and socio-economic aspects. The latter comprise social and environmental benefits as well as negative effects including environmental costs. The ISO standard for monetisation of environmental impacts (ISO 14008 [95]) and the guidelines for determining environmental costs and benefits (ISO 14007 [96]) are evidence for the importance of applying such environmental unit costs in environmental and sustainability reporting at the organisation and project levels. Science projects can achieve a positive socio-economic net present value. If their financial performance is too low, the funding model needs to be revised. Projects that are financially viable but have no or little socio-economic benefits need to be revised. Projects that are financially and socio-economically positive can be sustainable (Fig. 4.2).

Early and accompanying socio-economic analysis that integrates all sustainability dimensions helps benchmark variants and versions of project scenarios, permitting planning for long-term sustainability. An RI needs to periodically monitor and track the social, environmental, and economic performance against the initial estimations in order to implement a continuous improvement process.

In line with the 'Ecodesign' EU Directive 2009/125/EC [17], sustainable development requires proper consideration of all three sustainability elements, including the identification and accounting of positive and negative impacts throughout the entire lifecycle of a programme or project. For RIs carrying out science missions, at least the following stakes should be considered:

- Economy
  - Scientific excellence
  - Total costs (capital and operation expenditures)
  - Risks and residual risks after mitigation
  - Direct, indirect and induced 'value added' and employment
  - Quantified incremental economic benefit potentials
- Society
  - Quantified incremental social benefit potentials
  - Common good value (the value of the science mission as perceived by people)
  - Territorial compatibility
  - Social license
- Environment
  - Quantified negative externalities
  - Quantified incremental environmental benefit potentials

Sustainability also encompasses an *equitable* aspect (see Fig. 4.1). Equity and inclusion are increasingly recognised as essential components for the long-term viability of research infrastructures. They contribute to strengthening the talent pipeline, enriching the diversity of perspectives, and fostering public trust in science. In line with European Commission priorities, the FCC study has integrated equity and inclusion considerations into its sustainability approach. Key elements include:

- **Support for under-represented regions and groups:** Facilitating participation from less-represented states and disadvantaged communities through training opportunities, mobility schemes, and targeted collaborations.
- **Engagement with communities as partners:** Moving beyond a one-way transfer of 'cultural goods' by fostering dialogue with local populations, cultural institutions, and schools, and by recognising the perspectives and strengths that these communities bring.
- **Broadening participation in physics:** Embedding diversity, equity, and inclusion (DEI) principles into outreach, recruitment, and cultural engagement strategies to address the exclusionary image of physics and to support the long-term sustainability of the field.
- **Enhancing societal value:** Ensuring that the benefits of large-scale science projects are broadly shared, thereby reinforcing public legitimacy and demonstrating relevance to society at large.

4.2.2 Approach

A new particle collider and its enabling technical infrastructure represent significant long-term investments for participating countries and funding partners. An appraisal process is necessary to gain an understanding of the cost drivers and benefit levers. Reducing the former and developing the latter, along with conceiving a long-term financing model that relies on international collaboration, are required to ensure long-term sustainability from the conceptual phase onwards. Funding agencies, science strategy bodies (e.g., ESFRI), national notified bodies in charge of issuing authorisations and investment banks that potentially grant long-term loans for publicly funded projects (e.g., EIB), request evidence for the project's viability. The structured process of assessing the case for proceeding with an implementation preparation project and validating the project's viability is called 'project appraisal'.

This chapter also compiles a set of regulatory frameworks and appraisal guidelines that exist at the European level, in France and in Switzerland to provide a landscape of the sustainability requirements that govern the planning and implementation of new research infrastructure projects with strategic importance and territorial development needs at CERN. In the countries that are part of the European Research Area (ERA), legal frameworks govern compliance with sustainability aspects. Other countries such as Australia, the UK, and the USA are largely applying panel-based project decision-taking, although the UK does carry out ex-post evaluations on a case-by-case basis, and Australia evaluates the sustainability of research infrastructures periodically. Sustainability and environmental criteria, such as climate considerations, are increasingly being incorporated into proposal design and assessment. Switzerland has recently made sustainability aspects explicit for CERN's strategically important projects with territorial development in the update of the law [98, 99] for the encouragement of research and innovation that introduces an authorisation process at the federal level. The 'Ordonnance concernant l'approbation des plans des constructions et installations du CERN (OCIC)' [100], the prescription on how this plan for the authorisation process is to be implemented, has been issued for public review in February 2025. In addition to the commonly known environmental topics (e.g., air, water and soil) it includes the need for the assessment of the impacts on the climate and specific measures to comply with climate protection laws.

Consideration of quantitative environmental externalities,[13] both positive and negative, is still an emerging approach in the domain of research infrastructures unless it is explicitly required by national legislations and governed by national guidelines. Such a 'wider' socio-economic analysis (as shown in Fig. 4.2) is, however, already common practice in the general infrastructure project appraisal in numerous European countries such as France [101], Germany [102, 103], Italy and Switzerland and at EU level through EC funding conditions for numerous sectors, e.g., Connecting Europe [104], transport [105], energy [106], regional investment projects [107] as well as nature preservation and restoration [108].

Methodologies for assessing public investment and ensuring that a project contributes to the increase of public welfare[14] exist across different policy sectors and institutions [109, 110] including environmental impacts [111] are already used for research infrastructure projects including particle accelerators like the ALBA light source [112], the SOLEIL light source [113], the DESY/PETRA III synchrotron [114], the CNAO hadron therapy facility [115], the LHC [116], High Luminosity LHC (HL-LHC) [117–119] and the Compact Linear Collider (CLIC) study [120]. The Future Circular Collider (FCC) [121] study has, in particular, devoted significant resources to this topic over a time frame of almost ten years and has contributed to the advancement of the research infrastructure appraisal process at an international scale through scientific contributions to the field and participation in collaborative impact assessment projects at EU level. The approach is also used for other science facilities such as the Einstein Telescope [122], the Paris Saclay heat supply facility [123], the Nantes University hospital [124], and by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [125] to evaluate a number of different science programmes. Increasingly, research infrastructures, such as the Square Kilometre Array (SKA), are considering this approach with a view to planning for sustainability [126]. Environmental factors are increasingly being integrated into these assessments [97, 127–129]. As indicated in the 2026 roadmap guide (see page 25 of Ref. [130], a comprehensive socio-economic impact assessment is needed when a new research infrastructure project proposal requests being entered into the European Strategy Forum for Research Infrastructures (ESFRI) roadmap [131].

4.2.3 The context in Europe

Research infrastructure long-term sustainability at European Research Area (ERA [132]) level is primarily guided by the European Strategy Forum for Research Infrastructures (ESFRI) [133, 134] [15]

EU regulation 2021/695 [135] defining the Horizon Europe Framework Programme for Research and Innovation explicitly includes requirements to address global challenges, including climate change and the United Nations Sustainable Development Goals (SDGs).

EU member states typically translate and integrate the strategies, policies, and guidelines into their national roadmaps and plans in addition to their existing national policies.

A robust long-term vision is a prerequisite to successfully and sustainably operating a research infrastructure. Therefore, ESFRI issued a number of recommendations and actions [136].

Scientific excellence is the condition sine qua non. However, sufficient funding and sustainable funding models, required across the entire life cycle, are indispensable for a successful strategy for a new research infrastructure. Together with adequate human resources, it is crucial for the operational phase. Effective governance is another key element for ensuring long-term sustainability. Moreover, research infrastructures should contribute to their sustainability by contributing to their carbon neutrality in order to support the carbon neutrality goals at the national level. It must be noted that carbon neutrality accounting is being implemented at the national level and that therefore the application of this concept to international, transnational and distributed research infrastructures is highly challenging.

While the current recommendations place an explicit focus on scientific excellence, financial sustainability and societal acceptance, the call for comprehensive sustainability and impact assessment implicitly includes all

[13] An environmental externality is a cost or benefit that affects a third party who didn't choose to incur that cost or benefit, specifically in relation to the environment.

[14] Public welfare refers to the collective well-being of society that is promoted through public services and institutions, aiming to ensure equity, social cohesion, and access to essential goods and services for all. Paraphrased summary from Florio, M. (2019). Public Enterprises: Resurgence and the Future of the Public Sector. Springer.

[15] ESFRI (https://www.esfri.eu) was established in 2002 with the purpose of developing a European approach to Research Infrastructure policy as a key element of the emerging European Research Area (ERA). Further Research Infrastructures contribute to this effort in the frame of the EIROforum and the European Research Infrastructure Consortium (ERIC).

environmental aspects. The recommendations also state that RIs should allocate sufficient resources to periodically evaluate and communicate their socio-economic performance to various stakeholders. CERN's pioneering activities in this domain are explicitly mentioned by the ESFRI guide [137], encouraging national authorities to support the approach in cooperation with experts in the field.

The ESFRI policy brief [138] details the need to tailor the impact assessment to the specific project and requests the inclusion in the roadmap of project proposals that aim for implementation on a ten-year time frame, for which the wider socio-economic impact assessment is provided. Following the OECD definition [139] these impacts comprise *"the extent to which the intervention has generated or is expected to generate positive or negative, intended or unintended, higher-level effects"*. The European Commission [140] states that "*The term impact describes all the changes which are expected to happen due to the implementation and application of a given policy option/intervention [such as investment in a Research Infrastructure and its activities]. Such impacts may occur over different timescales, affect different actors and be relevant at different scales (local, regional, national and EU)"*. An ex-post assessment is needed to determine whether the intended objectives and the ex-ante estimations have actually been achieved.

EU Regulation 2021/1060 of the European Parliament and of the Council of 24 June 2021 lay down common provisions on the European Regional Development Fund, the European Social Fund Plus, the Cohesion Fund, the Just Transition Fund and the European Maritime, Fisheries and Aquaculture Fund and financial rules for those and for the Asylum, Migration and Integration Fund, the Internal Security Fund and the Instrument for Financial Support for Border Management and Visa Policy. According to Article 100 of Regulation (EU) No 1303/2013 [141], a major project is an investment operation comprising "a series of works, activities or services intended in itself to accomplish an indivisible task of a precise economic or technical nature which has clearly identified goals and for which the total eligible cost exceeds EUR 50,000,000 [...]". A socio-economic impact assessment of such major projects is recommended. The European Commission Economic Appraisal Vademecum 2021-2027 [142] captures the general principles and provides sector application examples for impact assessment, including research and innovation in Annex I. It extends and complements the common provisions regulation that recommends cost-benefit analysis in line with EU regulation (EU) No 207/2015 [143]. The methodology is explained in detail in the 'European Commission Guide to Cost-Benefit Analysis of Investment Projects' [107].

Climate change adaptation, mitigation, and disaster resilience are covered by this regulation. For instance, the volume of greenhouse gas (GHG) externality.[16]

An analysis of sustainable development (environmental protection, resource efficiency, climate change mitigation and adaptation, biodiversity and risk prevention) should be covered. An analysis of the options, considering technical, operational, economic, environmental, and social criteria for the location of the infrastructure, is requested for a feasibility study. This also describes the project's consistency with the applicable environmental policy. Considerations should include resource efficiency, preservation of biodiversity and ecosystems, reduction of GHG emissions, and resilience to climate change impacts. The process must comply with Directive 2011/92/EU, which defines the environmental impact assessment (EIA) process, ensuring that projects likely to have a significant environmental impact are subject to an assessment prior to their authorisation. Therefore, the total costs of the negative environmental impacts and their compensation have to be included. Environmental benefits can also be assessed and added. They include, for instance, contributions to improve water supply and sanitation, waste management, energy capacity and stability, transport, ports (airports, seaports, inter-modal), research and innovation, and broadband communication.

The appraisal process aims to assess if a project will contribute to overall social welfare and economic growth, taking into account benefits and costs to society. The EC [107] and UNIDO [144] handbooks focus on economic and societal topics, although aspects such as assessment of the environmental externalities are typically part of project appraisal as required by EU regulation. For instance, the shadow cost of carbon and the GHG emissions are shown in project appraisal examples. Eventually, the requirements for appraisal are defined for each project, specifically by the notified body for that project. For instance, to obtain funds from the European Investment Bank (EIB), a comprehensive appraisal study is required that includes both the positive and negative environmental externalities. The EIB published a guide [145] dedicated to this topic that includes references for the shadow cost of carbon as well as comprehensive calculation examples and guidelines for capturing environmental externalities.

Other requirements emerge, for instance, from applying to the Connecting Europe Facility (CEF). The InvestEU regulation introduces climate, environmental and social sustainability as elements in the decision-making process

[16] An externality is a cost or benefit that is caused by one party but financially incurred or received by another. Externalities can be negative or positive. A negative externality is the indirect imposition of a cost by one party onto another. A positive externality, on the other hand, is when one party receives an indirect benefit as a result of actions taken by another. The external cost of carbon is explicitly included, and alignment with the EU 2050 decarbonisation objectives is required. Regarding climate adaptation, the costs of measures aimed at enhancing the project's resilience to climate change impacts, as justified in feasibility studies, should be included in the economic analysis. The benefits of these measures, e.g., measures taken to limit the emissions of GHG or enhance the resilience to climate change, weather extremes and other natural disasters, should also be assessed and included in the economic analysis, if possible quantified; otherwise, they should be properly described.

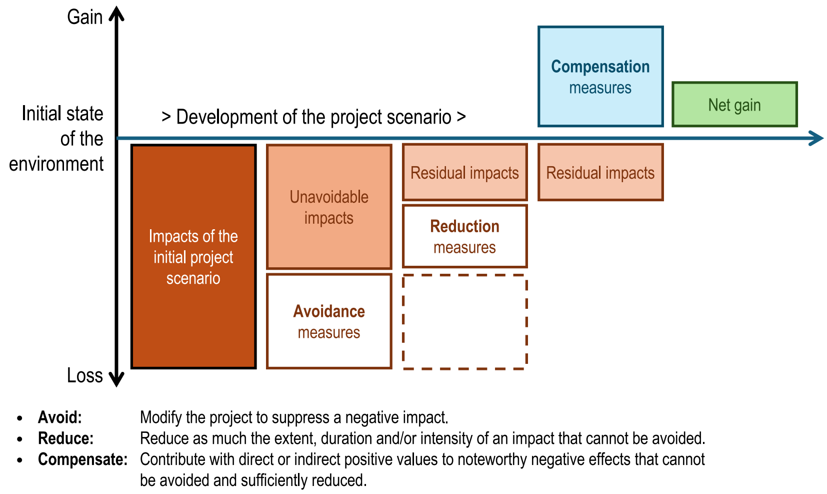


Fig. 4.3 'Avoid-Reduce-Compensate' approach for iterative development of a sustainable project scenario to achieve an ecological balance and, as far as possible, a net gain [13]

when applying for the InvestEU Fund. The process is also a requirement in the framework of the preparatory phase of ESFRI projects. The European Bank for Reconstruction and Development (EBRD) requires project assessment with potentially relevant greenhouse gas (GHG) emissions of more than 25,000 tonnes of CO_2(eq) per year with respect to a baseline of 100,000 tonnes of CO_2(eq) emissions per year. National requirements differ substantially from each other, requiring assessments for investment projects with public funding as low as, for instance, 300,000 euros in Lithuania.

4.2.4 The context in France

In France, the 'Code de l'environnement' [146] guides the approach to develop a sustainable project scenario in the frame of an environmental evaluation process that is part of the authorisation of the project. The term 'environment' is to be understood in its original meaning and in a wide sense: the surroundings and conditions in which the project will be placed.

The goal of the process is to develop a feasible and sustainable project scenario following the 'avoid-reduce-compensate' method (French: éviter-réduire-compenser, ERC), which is anchored in European regulations and which is implemented in French law [147]. As a consequence, the project scenario to be authorised aims at a net positive value (see Fig. 4.3).

This approach of iterative development of variants and versions that are continuously improved is also documented in the international standard ISO 14001 concerning environmental management. It describes the Plan-Do-Check-Act (PDCA) model as an iterative process to ensure continuous improvement (ISO 14001, Step by Step, Chap. 1).

Considering that programme and project evaluation in France is compulsory for public investments that exceed 20 million euros and a second assessment is required for investments that exceed 100 million euros, the national assembly tracks and reports on such projects every year using a standard information sheet approach that includes the net present value as an overall sustainability indicator and the greenhouse gas emissions avoided. Such information is published as an annex of the annual budget law [148]. In 2023, 13 research investments underwent comprehensive socio-economic evaluations.

The evaluation concerns the entire project throughout all life cycle phases. It is understood that the level of detail in descriptions for individual phases and project segments can initially differ. The process accompanies the project throughout its entire lifetime. Consequently, the documentation needs to be regularly updated. The process records the initial state of the environment, including nature and a variety of other topics such as urbanism, public health, population safety and economic impacts.

The process actively identifies and assesses the relevant effects on the project environment (environmental impact analysis) and provides input to the design process, following the steps of avoid, reduce, and compensate. The process includes the involvement of the population via, for instance, an informal dialogue and participation phase and a formal public consultation process ('débat public') and public inquiry ('enquête publique'). The latter process is carried out with nationally notified bodies.

To capture sustainability performance properly, the French government requires a socio-economic evaluation for each project funded via public investments of more than 20 million euros. The evaluation must be carried out according to the guidelines of the 'Secrétariat général pour l'investissement' (SGPI) [149]. Projects with a total public investment of more than 100 million euros are subject to a second expert assessment, on which the SGPI provides an assessment to the French parliament and the Prime Minister as well as to the minister under whose responsibility the project falls.

The socio-economic evaluation comprises a detailed description of the project, its variants and alternatives, the key characteristics, the implementation schedule, a list of relevant socio-economic indicators, a list of indicator values showing how the project performs with respect to public policies (e.g., climate impact reduction objectives), the financial plan, compliance with laws and regulations and a risk registry.

Until 2020, socio-economic evaluations of programmes and projects included only limited environmental aspects such as habitats and green spaces. The ever-growing importance of more global topics led to a broadening of the positive impacts and negative externalities covered. The 2023 impact assessment guide in France [149] explicitly includes all environmental aspects relevant to the project, such as CO_2 equivalent emissions, noise, air pollution, water use and pollution, and soil use and pollution, and requires them to be associated with monetary values and to quantify the positive contributions in monetary terms. For instance, the legal value of one tonne of CO_2 for the socio-economic evaluation has been set to €32 (base year 2010) in the 2023 guideline, which corresponds to about €40 in 2024. Despite this value, the annex that indicates the guidelines of converting non-tradeable goods and externalities into monetary terms indicates a progression of the shadow cost of carbon €250 per CO_2(eq) to 2030 and €775 per tCO_2(eq) in the year 2050. This progression is in line with the EIB recommendations on the shadow cost of carbon.

The socio-economic evaluation of the FCC is based on a standard cost-benefit analysis, which reports a net present value and a benefit-to-cost ratio based on the comparison of discounted total costs and benefits over a defined observation period. Costs and benefits were quantified with respect to a ‘counterfactual scenario’ in which CERN operates the LHC until its expected end of life and continues to act as a scientific research platform with the existing particle accelerator complex. Noteworthy positive and negative direct effects and externalities, including environmental effects, were taken into consideration for the entire life cycle of the project.

For the social discount rate (SDR), the 2023 guidelines for socio-economic impact assessment in France [150] recommend using a value of 3.2% for projects with a lifetime up to 2070. However, for very long-term and low-risk projects such as research infrastructures, a lower social discount rate in the range of 2.5% can be justified. For the FCC CBA, economists selected an SDR of 2.8%, based on the weighting of the SDRs in each individual CERN Member State considering its annual financial contribution to CERN.

If there is a ‘déclaration d’utilité publique’ (DUP), which governs the authorisation process for public investment projects, the socio-economic evaluation is part of the legally required ‘enquête publique’ files to obtain project authorisation.

The socio-economic evaluation has to be updated regularly, following the iterative approach of refining the project scenario and comparing expected effects to the actual effects once the project is implemented (‘ex-post’ analysis).

A project can be considered sustainable if both the socio-economic and the financial net present value are positive. In addition, the social discount rate applied should be larger than the average weighted cost of the capital needed to finance the project. This can be verified by determining the so-called Internal Return Rate (IRR), which is closely linked to the calculation of the net present value. It expresses at which value of the social discount rate the net present value of the project would become zero. For instance, if the loans for the project are granted at 3% but the net present value becomes zero at only 5%, the condition would be satisfied.

If the project does not generate revenues, i.e., in the case of a research infrastructure for fundamental scientific research, no financial net present value can be provided, a positive socio-economic net present value and an internal return rate higher than the cost of the capital support the sustainability condition. If the socio-economic net present value is negative and the financial net present value is positive, the investment may be financially viable, but it is not recommended from a societal point of view.

4.2.5 The context in Switzerland

The authorisation process in Switzerland is based on guiding principles that require the demonstration of compliance of the scenario with all applicable, individual laws and regulations. All laws and regulations that would apply to the project need to be identified and explicitly listed. It is considered best practice to follow the Avoid-Reduce-Compensate approach as required in France and Europe with continuous involvement of notified bodies, public administration services, and the population. It is to be accompanied by monitoring and continuous improvement measures.

With the recent update of the law for the encouragement of research and innovation (LERI) [151] and the development of a dedicated plan for new constructions and installations of CERN [152], guidelines with respect to the sustainability of research infrastructures become more specific.

The consumption of land, in particular, high-quality crop-rotation arable land that is regarded as a precious resource, needs to be avoided. Where this cannot be achieved, the residual consumption of such land that is registered in a national inventory needs, in principle, to be compensated. Therefore, alternatives and variants of the project need to be documented and assessed. Compensation can, for instance, be achieved by stripping the topsoil of the original land affected and using that soil for creating high-quality arable land within an agreed geographical perimeter, for instance on wastelands or degraded soil. The authorities facilitate the process of identifying suitable compensation areas and administrative processes.

The sector plan for CERN's constructions and installations with territorial needs (PS CERN) [153] highlights a number of topics that need to be considered when developing new projects:

- Water-bearing layers need to be protected and should not be used to provide raw water for cooling purposes. Care must be taken not to pollute water-bearing layers or to mix the water of superimposed water-bearing layers.
- Exclusion buffers next to watercourses protect the habitats.
- Forest clearings are generally forbidden in Switzerland. An exemption can only be granted in exceptional cases for installations that are in the public interest.
- Measures need to be taken to manage rainwater and used water to avoid flooding and polluting the environment. The same holds for the management of water used to extinguish fires.
- Limitations for dust and particle emissions need to be respected.
- Limitations for noise emissions need to be respected. Noise emission limits in Switzerland are absolute and defined for different sensitivity zones as opposed to France, which considers noise limitations in excess of existing background noise.
- Measures need to be taken to manage waste of any kind during all phases of the project.
- The national and cantonal energy and climate protection goals are to be taken into consideration during the planning, construction and operation of future research installations. Energy consumption is to be reduced to a minimum compatible with the capacity to fulfil the scientific research goals.
- The emission of greenhouse gases is to be minimised within the boundaries needed to meet the scientific goals and requirements of the project.
- The design and implementation of technical systems have to integrate the optimisation of energy efficiency and the recovery and use of waste heat. The capacities and characteristics available for internal and external use need to be identified and documented.
- Buildings must comply with the national energy efficiency regulations.
- In general, any optimisation and minimisation effort is understood to be conditioned by the technical feasibility and economic viability. These efforts must always be compatible with the feasibility of achieving the specified scientific research goals.
- A mobility plan that supports the national and cantonal climate plans is to be developed. Parking spaces are to be optimised, in line with the applicable regulations.

4.3 Methodology

The study adopted the approach and methodology to carry out a comprehensive, wider quantitative sustainability assessment based on the well-established cost-benefit analysis methodology [154] defined by the European Commission, the European Investment Bank and as described by national guidelines such as the one in France [149]. Such an assessment includes the identification and quantification of costs, benefits, and positive and negative externalities.

The goal is to present an implementation scenario that is likely to be long-term sustainable and for which the sustainability level can be continuously improved with respect to an initial forecast that serves as a baseline. The approach permits the analysis of variants and sustainability boundary conditions to be established.

Following a lifecycle approach, it is a best practice to develop an initial cost-benefit assessment as early as possible at the pre-feasibility stage and to update it regularly as long as the key project features continue to be adjusted during the design phase and even during the implementation. This approach helps address the challenge of exhaustive coverage of costs and benefits, and focuses on gaining a good understanding of the key sustainability enablers and risks.

Sustainability analysis is an ingredient of informed decision-making. The project and sustainability appraisal of the scientific research project do not, however, capture the opportunity and value of the underlying scientific mission. The indicators must therefore not be used to compare research projects or to make an investment choice between several projects.

To be useful during project authorisation, implementation and operation, the project must plan periodic sustainability monitoring and tracking throughout its entire lifetime and implement an iterative improvement process following the standard 'Plan-Do-Check-Act' principle either at the infrastructure level or for new programmes and projects.

Life Cycle Assessment (or analysis) (LCA) [155, 156] is a methodology that is suitable for individual project segments. It enables the assessment of a set of environmental aspects relevant to achieving sustainability. Its

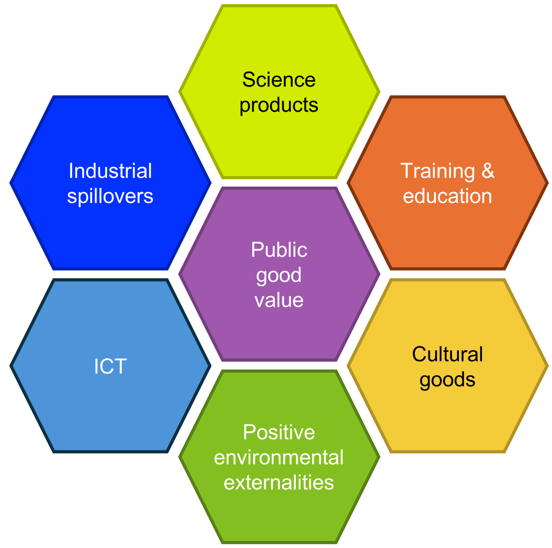


Fig. 4.4 Main socio-economic impact pathways that are sustainability enablers of particle accelerator and particle physics research infrastructures

goal and scope must be well-defined, and its results must be integrated in the overall project and sustainability appraisal. When conducting an LCA, care must be taken to be as specific as possible and to thoroughly document the scenario variant and version assessed, including the assumptions, input parameters, data quality, and allocation procedure (algorithms and tools) to ensure that the results have a meaningful value for appraisal. LCA is unable to capture all relevant environmental aspects and therefore does not replace an environmental impact evaluation. It cannot, therefore, be used to report on the overall environmental performance of a project.

For a comprehensive sustainability assessment, a quantitative Cost-Benefit Analysis (CBA) method based on state-of-the-art economic knowledge that integrates total costs, negative externalities (including environmental ones), industrial, social, and environmental benefits is the preferred and adopted approach. A more complete description of the approach is provided in Sect. 4.5.

Project developers must stay up to date with national and international regulations and legal frameworks during the subsequent design and preparatory phases. They must continuously improve their knowledge of state-of-the-art project appraisal methods and the development of approaches to convert positive and negative impacts and externalities into quantitative terms suitable for reporting an overall sustainability indicator, such as a project's net present value and benefit-cost ratio. For this reason, as long as additional knowledge and assumptions about the project scenario and its key features are developed, the benefit-cost ratio (BCR) and the internal rate of return (IRR) evolve throughout the lifecycle phases.

4.4 Socio-economic sustainability enablers

4.4.1 Impact pathways

Socio-economic impact pathways represent a valuable inventory of sustainability enablers. Building on the concept of the 'Theory of Change' [157], the EU-funded RI-PATHS project has developed a toolkit [158], linking and coordinating research infrastructures from different scientific domains into a shared network, so that resources and expertise can be pooled and accessed more efficiently. This includes particle accelerator facilities such as ALBA, CERN, and DESY.

The main pathways typical for particle accelerator-based facilities are shown in Fig. 4.4. This section outlines briefly some drivers influencing the pathways that in turn lead directly to benefits and positive externalities.

Future projects are highly encouraged to conduct a comprehensive charting of the impact pathway potentials and develop sustainability-enabling measures in conjunction with such a systematic exploration and design activity.

The following paragraphs outline selected aspects that should be carefully considered during the design, planning, and implementation of a future particle-accelerator-based research infrastructure. They influence directly the generation of benefits in the impact pathway model.

Sustainability through the creation of fundamental physics knowledge Science is formalised knowledge that is rationally explicable and tested against reality, logic and the scrutiny of peers, and is a global public good [159]. Ultimately, it is the main output of research infrastructures. In our transforming society, knowledge is poised to become the primary economic resource, gradually replacing capital, land and labour. There is evidence that the public sector has and continues to fund much of the innovative science that stimulates private sector responses [160]. But what is the value of that knowledge that fundamental science projects generate? Are continued investments in new particle accelerator projects for scientific research sustainable in the perception of those people who do not directly use those instruments and who do not directly profit from the generated knowledge? Which means exist to capture the value of such investments?

Particle accelerators for fundamental science may or may not generate knowledge that can be directly used by society. Other particle accelerators, such as synchrotron light sources, typically serve the needs of applied research. This means that a lower bound for the value of the knowledge generated can be quantified in terms of the cost of publications, the fees charged for facility use, and the resources that users invest in this research. The approach is based on the assumption that research results ultimately lead to products and services that society uses. An example is the characterisation of the COVID-19 virus structure at the BESSY-II synchrotron [161]. Particle accelerators and colliders that serve curiosity-driven research, such as the LHC or the Electron-Ion Collider, cannot use this model since it is not obvious how the knowledge gain leads to direct societal applications. There exists, however, no doubt that the scientific outcomes advance society. This view is shared by the majority of people, even if the asset is not directly used.[17]

Evidence for the validity of the approach is available through the award of several Nobel Prizes in economics for advances in this domain. It is proof that this value generation process is of fundamental importance for society and welfare economics [162–167].

To capture the value that science missions and research infrastructures represent to laypeople who cannot directly use them, methods that originally have been developed to elucidate the public good value of outdoor recreational spaces [168], to identify suitable value levels for environmental protection measures [169], to determine adequate levels of environmental incident mitigation measures [170] and to determine investment levels to protect natural and cultural heritage can be used. This approach has first been taken to estimate the value of the LHC project [171], then for the HL-LHC project [172] and now for the FCC [173]. The approach has recently also been adopted by an atmospheric research infrastructure [174]. Briefly, the value that people associate with a science project can be captured by estimating their willingness to participate financially using well-established approaches in economics, such as contingent valuation, also referred to as ‘stated preference’.

The valuation of non-market impacts is challenging but could be undertaken wherever possible, and the ‘EU better regulation toolkit’ indicates the instruments for it [175]. This will enable a better understanding of the public perception towards the science vision and test the validity of the public funding sustainability hypothesis, i.e., what level of periodic investment is justified in the public perception. To design, plan and carry out a public good value estimation, experts in the domain and qualified companies need to be employed. It is important to ensure that such a willingness to participate in analysis, typically based on surveys, is carried out independently, without the influence of the project owner and according to the internationally established guidelines on ethics and the quality standards required of survey-based analytics. Examples of this approach can be found in Refs. [173, 176].

Depending on the number of countries or funding agencies that would carry out the project, such a survey can require substantial resources. Economists, therefore, use techniques based on the ‘Benefit Transfer Method’ [177] to estimate the perceived value of a large population based on the identification of only a few significant parameters that can be derived from a limited number of samples. These parameters may be different for different projects. Therefore, such a study requires a pilot phase to determine the significant parameters, followed by a mass survey to determine the value that the public associates with the investment.

If the estimated willingness to financially participate (WTP) is larger than the actual or expected contribution to the planned new project, the public good value of the funded infrastructure can be considered consistent with the financial participation and, therefore, can also be considered justified. If the WTP is less than the actual or planned contribution, a discrepancy exists between the value perceived and the contribution supplied. In this case, the project should be revised.

Sustainability through education and training Particle accelerators and experimental physics research infrastructures offer the possibility to engage people at all education and training levels, from apprentices to post-doctoral researchers. If people have the opportunity to actively participate in the design, construction and operation of such projects and programmes, they enjoy benefits that translate directly into a 2 to 10% lifetime salary premium [121, 178] compared to their peers who were enrolled in conventional training programmes at schools and universities. A dedicated programme to integrate people after their active time in a research facility into the labour market in their country or region of origin can significantly improve the return on investment for the participating country or region [179].

[17] The notion for this concept is the ‘public good’ as opposed to the ‘common good’ that is jointly used. Examples of common goods are fish stocks in the ocean and public roads. Examples of public goods include knowledge, natural and cultural heritage, open-source software and datasets, as well as tangible assets such as street lighting.

Sustainability through participation of international science communities Involving a significantly large and continuously growing community of scientists and engineers through collaborative research projects over long periods ensures the long-term sustainability of a science project or programme. The reasons are

- The personnel costs are distributed over many contributing organisations and countries.
- A stable generation of scientific products [180, 181] (i.e., books, peer-reviewed articles, pre-prints and technical reports, proceedings and presentations) can be guaranteed.
- The knowledge can be effectively transferred into lasting education curricula through publications and direct training over generations.
- Impact can be generated through the training of early career professionals (see previous section).

High value is mainly achieved by ensuring that the science products generated directly by the research project or programme are taken up effectively and cited by an even larger second-tier community. Open Access publication of trusted (peer-reviewed) publications is a pre-requisite to generating research infrastructure sustainability through scientific product generation. Finally, the concept of Open Innovation that involves a large number of knowledge domains around a scientific core mission will ensure that the probability of knowledge generation that is stimulated through the challenges of the science mission will eventually spill over to society in domains that are immediately relevant to them [182].

Sustainability through industrial spillovers Industrial spillovers from science projects generate benefits directly for industry and society [183–185].[18] This impact pathway is most effective if science projects construct their instruments and infrastructures in collaboration with industrial partners [186–188]. It works best when companies work closely with the research project to develop technologically intensive solutions and deliver non-standard services [189]. This approach is more laborious than a conventional client-supplier relationship, as it requires exchanges of ideas and knowledge, the development of integrated processes, the mutual adaptation of working methodologies, and risk sharing. This process, however, leads to the creation of lasting products, services, and processes that industrial partners can leverage in other markets, yielding earnings multipliers exceeding 3 and effects that can last between 5 and 8 years. Lasting territorial effects have also been reliably documented [190, 191].

Sustainability also depends on the design of the science mission: short-lived and non-upgradable programmes will lead to lower and shorter-lasting industrial spillovers than long-lasting programmes that are characterised by periodic upgrades and operational efficiency improvement measures involving industrial partners in continuous challenge-based activities.

Industrial spillovers can also lead to lasting positive environmental externalities. The challenge of reducing the carbon footprint and environmental impact of the construction of a new particle accelerator facility creates an opportunity for industrial innovations in numerous construction-related domains. For instance, it creates a potential of developing or putting in place low-carbon concrete and other construction materials production facilities. It serves as a pilot platform for improved construction techniques, like using natural resources, such as wood and compressed earth. Showcasing the application creates market interest. Developing processes and products for the use of excavated materials can generate benefits significantly beyond the needs of the research infrastructure project, since the management of construction waste is a challenge facing society, and for which conventional construction projects typically have insufficient time and budget. Eco-design-based industrial architecture is another emerging discipline for which particle accelerator facilities are suitable early adopters. Environmental benefits can also be generated in the area of technical infrastructures that are developed with industrial partners. They include:

- More efficient refrigeration systems, which find their application, for example, in gas liquefaction and transport.
- More efficient water cooling systems (adaptive water intake, use of waste water).
- Improved electrical systems (loss reduction via DC-based systems.
- High-speed power control management.
- Short and medium-term energy storage.
- Adaptive and machine learning infrastructure operations.
- Waste heat buffering and supply.

Sustainability through open information and computing technologies The development of Information and Communication Technology (ICT) and the generation of widely available data not limited to scientific results (e.g., engineering test data, operation monitoring, system tests, etc.) are essential outputs of particle accelerator-based research infrastructures [192]. Implementing a global data sharing and processing infrastructure has already led to

[18] Industrial spillover (also known as spinoff) refers to the phenomenon whereby innovations, technologies, or organisational practices developed within a given firm or industry diffuse beyond their original context, generating positive externalities that enhance productivity, competitiveness, or innovation capacity in other firms or sectors, typically without direct market transactions or compensation.

the creation of numerous openly accessible software packages, platforms, and online services, which are also utilised in environments outside high-energy physics. They range from scalable data storage and distribution middleware to data analysis and visualisation, as well as data management and workflow systems. Also, openly accessible software has been developed with a value that extends beyond scientific collaborations. Examples include innovative Cloud computing services (e.g., Helix Nebula Science Cloud serving five scientific research domains), meeting and event management software (e.g., Indico), particle/matter interaction modelling and analysis (e.g., Geant4, FLUKA and ActiWiz) and electronic library and information access software (e.g., Invenio and Zenodo). Long-term data preservation is another technological domain of high societal relevance that is gaining importance, primarily driven by fundamental science research infrastructures.

Particle accelerators and high-energy physics research projects are strongly encouraged to create an inventory of potential ICT tools that can be made available openly and free of charge for societal use. The feasibility of quantifying the societal impact of these solutions relies heavily on accounting for software uptake and uses (e.g., the number of installations and the number of times it has been integrated into commercial and other open software packages) over sustained periods of time. Today, there is a lack of such accounting, which makes quantitative estimation of the societal impact challenging and labour intensive. However, it is important to establish systematic monitoring and evaluation since ICT tools developed in the science environment have a major impact factor with significant and tangible value potentials [193, 194].

Open and freely available software developed and maintained by science projects and programmes are sustainability enablers for research infrastructures. Their investment and continuous development and maintenance costs are marginal with respect to the societal benefits they can generate over decades. Future particle accelerator projects and programmes should focus on properly managing and promoting ICT developments and make sure they are taken up by society through a technological competence leveraging process and sustained online presence in potential user domains.

Sustainability through cultural goods Creating an interest in science among all citizens is part of the mission of any research infrastructure. Projects and organisations can develop a broad variety of activities to attract lay people, for instance, through permanent and travelling exhibitions, open days, guided tours, engagement with schools and teachers in joint workshops, citizen science projects, websites, social media, engagement with video bloggers, online and TV documentaries, art internships, common art projects, feature movies, books, science fairs, presence in radio and TV shows and much more. The limit of cultural good creation is the limit of the imagination of an ever-changing and diverse group of creative people that are best employed over sustained periods of time. Each of these cultural goods has the potential to generate value for society. Creating a sustained interest in the science project breaks down barriers and fear of people who are outside the science community.

It is important for particle accelerator and physics projects to engage laypeople in playful and entertaining ways rather than aiming at education and teaching, which is a different socio-economic impact pathway. The two should be kept separate, although effective cultural good creation and engagement raise the possibilities for explaining the underlying science in a second step.

The identification of value for cultural goods can be very different for each good. Therefore, future projects and programmes will need to focus initially on a few cultural pathways. If the estimated value of a pathway turns out to have sufficient potential, it should be further developed with a view to sustainable engagement. Continuous monitoring of the value should be carried out.

The value of on-site visits represents a cultural good of science infrastructures that can generate substantial tangible economic value in a sustainable way [195, 196]. Such visits include the discovery of the environment and nature [197, 198]. It should, therefore, be the first to be considered for development.

Social media presence has the most impact on online cultural goods today and should therefore also be considered with priority [117]. It is particularly important to create a sustained interest in science and to explain in which ways science impacts the environment and people's everyday lives. Different means of communication are needed for different generations and socio-economic groups [199].

Finally, citizen science projects on the periphery of the physics science mission are effective tools to engage lay people and to reinforce the environmental and territorial compatibility of the research infrastructure. An example is the initiatives to create biodiversity inventories of the surface sites, to improve the quality of habitats on and around sites.

Sustainability through positive environmental externalities Any future particle-accelerator-based project has the potential to create positive environmental externalities that can compensate for the residual, unavoidable negative environmental effects that cannot be reduced further. Before developing compensation and accompanying measures, negative effects on the environment have to be avoided. If they cannot be avoided, they should be reduced as far as is compatible with achieving the goals and objectives of the infrastructure within accepted cost and schedule constraints.

National and international legal and regulatory frameworks define boundary conditions for the avoidance, reduction, and compensation approach. The recently adopted update of the law for research and innovation in Switzerland, for instance, explicitly requires the consideration of the national and regional climate protection plans and energy-related aspects [200]. Other countries, such as France, have already encoded the fight against climate change, resource and biodiversity protection, circular economy, and sustainable territorial development in the environmental protection laws (L110-1 of [146] and [201]) that govern the authorisation of new projects [201]. Hence, 'environmental' is always to be interpreted in a wide sense. The greenhouse gas emission reduction goals defined by the Paris Agreement are to be integrated in new projects at EU level and following its translation into the national laws [202].

If properly planned, evaluated and monitored, collective compensation can even lead to a net positive effect [203]. Switzerland does not foresee such an approach and requires compensation based on equivalent surface and quality in principle within the affected canton [204–206]. Despite this constraint, the overall environmental performance may still be neutral or positive from a socio-economic assessment point of view if the positive environmental externalities are properly evaluated and integrated in the net present value of the project.

Some typical examples of positive environmental externalities that particle-accelerator facilities can integrate in their designs from the onset are:

- Re-creation of agricultural spaces by transferring top soil to low quality land plots and wasteland.
- Creation of green spaces with covered roads, fertilising wastelands and backfilled quarries, creation of parks, greening of roofs, reforestation around sites, creation and quality improvement of natural habitats and wetlands.
- Increase of biodiversity by the creation of new habitats on the research infrastructure's domain.
- Improvement or creation of new ecological corridors, green and blue continuities.
- Creation of forests with trees and plants adapted to climate change.
- Introduction of forest management in view of protection from wildfires.
- Improved water management of existing, but low-quality water courses.
- Creation of water reservoirs.
- Creation of raised hedges to fight soil erosion and create new habitats.
- Creation of soft or multimodal mobility concepts for use beyond the research facility.
- Creation and improvement of natural habitats and nature protection zones on the research infrastructure sites.
- Carbon footprint reduction by helping to avoid fossil fuel use through waste heat supply.
- Supply of raw water for non-drinking purposes by supplying purified wastewater when not used by the research facility.
- Increase of renewable energy resource capacities through long-term power purchase agreements and energy purchase communities.
- Development of products and processes that leverage circular economy principles and low environmental impact technologies that spill over into the industrial domain (e.g., in the areas of electrical substations, construction materials, architecture solutions, power transmission and buffering, industrial cooling).
- Dismantling of infrastructures which are no longer used to create environmental and societal value.

4.4.2 Innovation and R&D

Particle accelerators and experiment detectors at the collision points of particle colliders are projects which use cutting-edge technologies over periods spanning several decades. As a consequence, they tend to develop and use technologies that do not exist at the time of design. This process continues throughout the operation as detectors are upgraded. The required technical advances may be designed in-house and/or in partner institutions (such as universities) in conjunction with external companies. The development can take the form of joint design or procurement of technologies to be developed by the company. In both cases, industries profit from a technological knowledge transfer which may lead to technological breakthroughs, patents, or new business opportunities [207, 208]. Such processes are encouraged and accompanied by dedicated knowledge transfer (KT) centres at the participating organisations [209–212]. As enabler of the science mission, such technological advancement is a valuable output, which significantly affects the social sustainability of a project.

Other sustainability potentials International science projects such as the FCC also provide possibilities to develop soft skills and international cooperation. Such projects bring nations closer together as they aim to pursue a common, peaceful goal. As recently seen with the ceremonies of CERN's 70th anniversary, heads of state and ministers come to visit the site and have bilateral discussions that may or may not be related to the scientific mission of the project or even to science. National news outlets have reported on the event, focusing on the common project and these side aspects. Often, who discusses with whom is seen as more important than the event itself. Collaboration leading to more collaboration, there is a societal interest to bring decision makers together to discuss issues of the world in an informal setting. Spinning off from particle accelerator scientific research, the

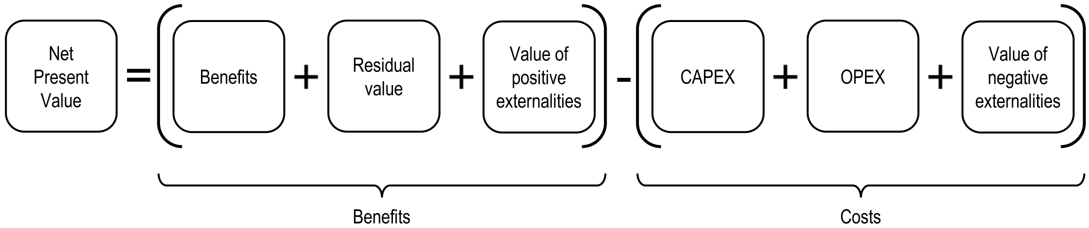


Fig. 4.5 Expression to determine the net present value (NPV) of an investment project considering economic, societal and environmental aspects

SESAME project in Jordan [213] was set up with international collaboration in mind, as much or even more than the proposed scientific project. The Heidelberg, CNAO and MedAustron light-ion cancer therapy facilities are concrete examples of the direct transfer of knowledge, expertise, skills, and technology from fundamental particle physics and particle accelerator research to meaningful societal application. A future circular collider can achieve all this for Europe and beyond.

4.5 Comprehensive sustainability performance assessment based on Cost-Benefit Analysis

The approach (Fig. 4.2 is to create an inventory of negative cost and positive benefit items including externalities and convert them into monetary terms that are combined to determine a net present value (NPV) of the investment at the end of a chosen observation period (see Fig. 4.5). The ratio of the benefits of a project relative to its costs (BCR) including externalities and the so-called internal return rate (IRR) are two measures that can be derived from this analysis to provide valuable insight in the sustainability of the undertaking. The IRR is the discount rate that would bring the NPV of the entire project over the observation period to zero. An investment can be considered sustainable if it is financially feasible (net cash flow is non-zero) and profitable from a socio-econonomic perspective. A positive BCR has been determined through a comprehensive socio-economic impact assessment under the most conservative assumptions, including total costs, externalities, and benefits, and an IRR that is greater than the cost of obtaining the required capital. These results support the overall sustainability of the project.

In line with the guidelines on cost estimation of research infrastructures [214], the following items need to be established:

1. Unit of analysis with clear scope and boundary descriptions.
2. Reference period with a start and an end date of the observation based on the expected useful life (note that this period may be different from the physical life of the infrastructure and may lead to residual asset values).
3. Base year, i.e., the point in time when the quantitative estimation is made that does not necessarily coincide with the start date of the investment or the project operation. Past values are capitalised and future values are discounted with respect to the base year using the same mathematical formula. Conversion rates of the unit of measure with respect to other relevant currencies are to be recorded for the base year.
4. Unit of measure for costs and benefits in a specific monetary currency.
5. Approach for converting in-kind contributions into monetary terms.
6. Definition and description of the counterfactual scenario.
7. Project-specific Social Discount Rate that is justified by an economist expert advisory committee.
8. Structure of capital and operation expenditures.
9. Structure of negative externalities considered.
10. Structure of positive impacts (benefits) considered.

In addition to full financial costs, negative externalities must be integrated in the assessment, as far as they can be reasonably identified, accounted and converted in monetary terms.

Concerning potential impacts on the climate, the methodology includes the accounting of project-relevant emission factors, the estimation of the net greenhouse gas (GHG) emissions (a negative externality) and emissions avoided (positive impact or benefit) compared with a counterfactual baseline scenario. The resulting amount of generated and avoided GHG emissions, in tonnes of carbon dioxide equivalent (tCO_2(eq)), must be converted into monetary terms using a shadow price of carbon. In line with the EC technical guidance on the climate proofing of infrastructure, [215], for the shadow cost of carbon, it is recommended to use the values established by the

European Investment Bank (EIB) as the best available evidence on the cost of meeting the goals of the Paris Agreement [216].[19]

Input-Output analysis [217] is a methodology that only captures economic linkages and determines the value-added of an investment and can be used to estimate the effect on the job market and in which domains and geographical regions the economic activations take place. This tool is regularly used by governments and at the international level (e.g., EU, OECD) for empirical economic research and structural analysis and is therefore widely known. However, it is purely an economic instrument that should only be used as follows:

- As a complementary tool to document economic linkages, permitting the development of international in-cash and in-kind contributions.
- To identify project-relevant industrial sectors.
- To develop targeted common activities and synergies.
- To understand the job market implications.
- To develop regional specialisation policies.
- To develop focused training and skilled labour mobility plans.

Recently, the FCC study implemented the economists' recommendation to carry out a complementary analysis of the public perception [176] using a stated preference and Willingness-To-Financially-Participate (WTP) approach [218]. Such a survey can help to reveal if the full costs and cumulative impacts of a research infrastructure or scientific investment are at least justified with respect to the perception of the public.

The establishment of a risk registry, risk assessment, and evaluation of residual risks is crucial for new science missions and research infrastructure projects and programmes. It should include economic, social, and environmental domains in addition to standard topics such as financial and project management-related matters. Selected chapters are to be analysed using a simplified appraisal process with a limited and self-contained CBA or a multi-criteria analysis (MCA). Presenting several variants and versions of the project and individual segments together with their full financial costs, economic, social, and environmental performance levels is considered good practice in project appraisal and has been implemented by this study.

The results of the integrating and wider sustainability analysis are reported in a condensed summary form using the following key performance indicators:

Net Present Value (NPV) is the discounted sum of all future benefits less the discounted sum of all future costs over the appraisal period as a whole. To properly estimate the NPV, realistic estimates are required of the streams of benefits and costs over the appraisal period that can reasonably comprise around 30 years. Beyond this time frame, quantitative socio-economic estimates become challenging. The key to determining both these streams is knowledge of the times at which the various elements would come into play. Investment costs will typically be incurred prior to the date of opening, whilst operating costs (for example, personnel and resources for operation and maintenance) and user benefits would arise after the year of opening. User benefits, operating costs and revenues can be estimated from model runs for two or more years and the stream of benefits can be derived by interpolation and extrapolation between the benefits for the modelled years.

Benefit/Cost Ratio (BCR) is given by the ratio of the discounted sum of all future costs and benefits. The BCR is, therefore, a value-for-money measure, which indicates how much net social benefit could be obtained in return for each unit of investment. Although the values are monetised, i.e., converted into monetary units in this approach, they do not necessarily represent financial investments (e.g., the monetary shadow cost of carbon is not a paid amount of money. It represents a monetary cost to restore the effects linked to the quantified, potentially emitted carbon dioxide equivalent). Formulae for the NPV and BCR will be found in CBA textbooks, a good example of which is Pearce and Nash (1981).

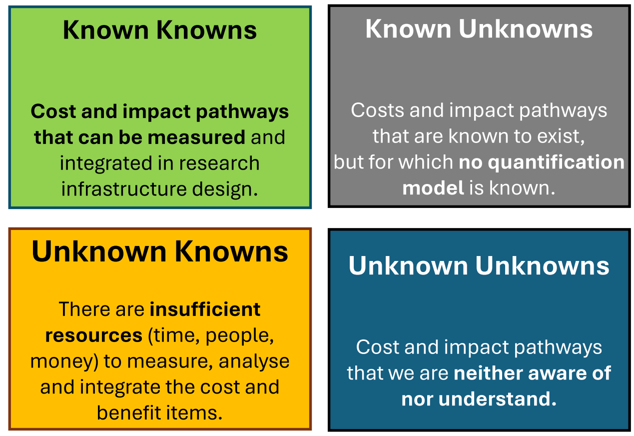
Internal Rate of Return (IRR). Whereas the NPV and BCR measures require a test discount rate to be specified, the IRR reports the average rate of return on investment costs over the appraisal period. This can be compared with the test discount rate to see whether the project yields a higher or lower return than is required to break even in social terms. Calculation of the IRR and issues surrounding it is discussed in Pearce and Nash, Chap. 4 and in other cost-benefit textbooks.

4.6 Limitations

While Sect. 4.5 outlined the comprehensive sustainability performance assessment based on cost-benefit analysis (CBA), it is equally important to acknowledge the methodological limitations of this approach in the context of research infrastructures.

[19] The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015. It entered into force on 4 November 2016.

Fig. 4.6 The Rumsfeld matrix [224] applied to the identification of costs and benefits of research infrastructures



Particle accelerator facilities are characterised by a diverse set of investment and operation cost items, negative externalities, benefits and positive externalities. Research infrastructures dedicated to fundamental science generally do not generate direct financial revenue. Unlike commercial ventures, they do not sell a product or service that generates income and therefore cannot be evaluated in terms of profit generation.[20] This makes it challenging to evaluate their performance using standard business metrics, such as return on investment or earnings.

This situation presents challenges for conducting project appraisals and assessing long-term sustainability through traditional financial methods. In the absence of direct financial returns, the value of such projects must be reflected in their broader socio-economic impact. Thus, the assessment relies on identifying and, where possible, quantifying societal benefits relative to costs and externalities.

One way to address this limitation is through the evaluation of the *public good value*, i.e., the benefit of providing a science infrastructure as a non-rival, non-excludable good to society at large. In the FCC study, the public good value in the countries likely to participate financially was estimated and found to exceed the sum of all known and quantified costs. This supports, from a societal perspective, the justification for such an investment. As with the LHC, it is also expected that participation would extend beyond CERN Member States, as international collaboration has historically underpinned such large-scale science projects.

As recommended by the OECD [219, 220], the French government [221], the UK government [222], and the European Commission [142, 223], a comprehensive sustainability assessment should consider all relevant elements: total costs, total benefits, negative externalities, positive impacts, and environmental benefit potentials. In practice, not all elements are equally relevant for every investment project, not all can be reliably quantified or monetised, and some remain unknown (Fig. 4.6). Both costs and benefits are affected by uncertainties (Fig. 4.7). The results presented in this chapter must be interpreted in this light. Although the EC CBA Guide [107] recommends a Monte Carlo–based uncertainty analysis, this approach requires probability distributions for each cost and benefit component, which are themselves difficult to obtain with confidence.

The comprehensive socio-economic study therefore describes as precisely as possible the scope, assumptions, and methods used to quantify and monetise costs and benefits, together with the results obtained. This includes acknowledging that not all externalities can be fully captured, and that ex-ante analyses always project future conditions into today's socio-economic environment with associated uncertainty ranges.

Rationalising comprehensive sustainability assessment using standard cost-benefit analysis [225] helps to identify limiting and enabling aspects and can guide the iterative design of research infrastructures. Time is explicitly accounted for, which is essential when considering environmental effects. While methods to quantify costs and negative externalities are well developed, approaches to capture and monetise benefits and positive externalities are less standardised and often project-specific, requiring tailored methods and models.

Sustainability should not be seen narrowly as the internal viability of the project alone, but more broadly in terms of its interactions with external economic, social, and environmental factors. The 17 high-level development objectives (with more than 160 sub-objectives) of the 2015 UN Sustainable Development Goals (SDGs), shown in Fig. 4.8, illustrate the breadth of these factors. The FCC study has not yet conducted a full mapping to the SDGs, but such an analysis should be developed in the next design phase, including the project authorisation stage. Meanwhile, the SDGs can serve as a reference catalogue of potential impacts to be considered, both positive and negative, alongside quantitative CBA results. CERN has already implemented such approaches in its periodic environment report, which relies on the GRI framework [226].

[20] Financial profit is the net income earned after deducting all explicit costs from the total revenue.

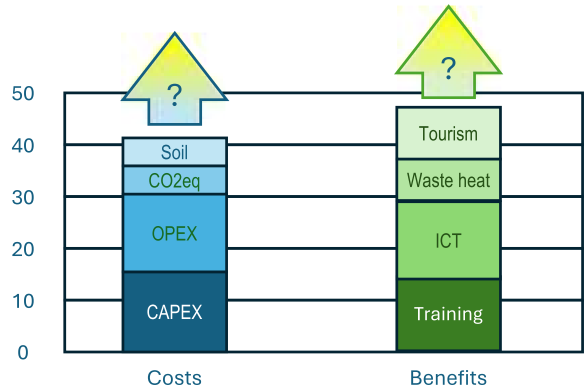


Fig. 4.7 Examples for the accounting of full costs and benefits for an integrated sustainability analysis. Only the identified cost and benefit items that can be converted into monetary terms were considered in this specific assessment. Exhaustive coverage of all negative and positive externalities is challenging and must be accepted in all socio-economic impact assessments

Fig. 4.8 The UN Sustainable Development Goals (SDGs)

Finally, the choice of the Social Discount Rate (SDR) influences the integration of costs and benefits. Different SDR values can be used to perform sensitivity analyses and to test the robustness of the overall net present value. For this study, only a single SDR value has been applied.

4.7 Lifecycle analysis

4.7.1 Context

As the global focus on combating climate change intensifies, reducing greenhouse gas (GHG) emissions has become a top priority. Infrastructures spanning transport, construction, and scientific instruments play a critical role in this transition. A lifecycle analysis is an essential tool to analyse the sources of emissions that affect the climate, to understand the drivers, and to optimise the project in view of improved environmental compatibility.

The topic is comprehensive and complex, determined by many uncertainties and by the fact that the different segments of the project are only gradually known as the concept development and design advance. A long-term project like the future circular collider does not deliver detailed designs of the technical infrastructures and particle accelerator components until shortly before procurement. Detectors that constitute the scientific experiments will only be built and procured as a collaborative effort at a much later stage. To be able to leverage the technical advances, detailed designs are only developed when the particle collider equipment is well known, procured, and potentially already being installed.

In addition to this time dependency, LCA and the associated carbon budget assessment strongly depend on the procurement scenario and the scenario of specific technologies. Therefore, the FCC study has taken the approach of focusing first on the best-known project segment, the environmental footprint of civil construction based on the current concept.

The study also included the estimate of the Scope 2 footprint for operation, i.e., the carbon emissions that would be associated with the consumption of energy. Also, a specific procurement hypothesis had to be assumed for this analysis.

It must be understood that the results presented herein are subject to further evolution throughout the lifecycle phases of the project, should a decision to pursue it be taken. In particular, they do not consider certain negative externalities related to the construction of the particle accelerators and experiments, optimisations, which are possible with the use of further advanced technologies, materials, products, local production, responsible sourcing and procurement and the outcomes of commercial negotiations during the procurement processes. Consequently, continuous socio-economic performance monitoring, incorporating eco-design based on an iterative Plan-Do-Check-Act cycle, is important and should be established before entering a preparatory project phase.

The analysis carried out using the European LCA Norms ISO/EN 14040 and ISO/EN 14044 aimed to estimate the carbon budget of the infrastructure construction that would serve two subsequently installed particle colliders. It aims to establish a credible benchmark, leveraging the use of European norm EN 15804+A2 and French FDES norm standardised Environmental Product Declarations (EPDs) of materials and products available today. This approach ensures a comprehensive assessment in line with the European standard and norm EN 17472, which provides requirements and guidelines for calculating and reporting GHG emissions associated with infrastructure projects. The work also included the recommendations of Cerema for the evaluation of greenhouse gas emissions for road projects, the Swiss 'Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren' (KBOB) and French 'Les données environnementales et sanitaires de référence pour le bâtiment' (INIES) databases for ecological product footprints, and the ecoinvent (ecoinvent is an internationally active, mission-driven organisation devoted to supporting high-quality, science-based environmental assessments) database for products and materials where no EPDs were available. The work revealed some realistic pathways to further reduce the consequences of the construction and gave some recommendations on future aspects that need to be considered during the subsequent design phase.

The results are integrated in the integrating, wider socio-economic impact assessment by converting the results of the LCA into monetary terms using the recommended approach of the EIB and the European Norms EN 14007 and EN 14008.

4.7.2 Methodology

The work for the estimation of the construction-related greenhouse warming potential included the following steps:

1. Component identification: Compilation of the detailed inventory of materials based on the bill of quantities for the subsurface construction, the 4 experiment sites and the technical sites. The current conceptual design was considered for this step. The products chosen are used throughout the infrastructure's lifecycle.
2. EPDs acquisition: Sourcing of EPDs for each material identified, ensuring compliance with EN 15804+A2, the foundational basis for EN 17472. The materials are selected based on expert knowledge of the local environment and product availability and hence, represent state-of-the-art solutions.
3. Software tool: Selection of a certified tool compatible with French and Swiss Environmental Product Declaration - One Click LCA®, ensuring robust and accurate calculations.
4. Data entry: Imported data into the tool and entered project-specific data, including material quantities and lifecycle phases, transport for excavated and construction material.
5. Calculations: The tool was used to estimate the carbon budget, drawing on EPDs data to evaluate GHG emissions for each lifecycle phase.
6. Result analysis: Analysed the results to pinpoint major emission sources, comparing them against benchmarks and reduction targets.
7. Formulation of recommendations: Based on the results and the identification of the key impact drivers, a set of recommendations was formulated that is to be taken into consideration in the subsequent design phase to further reduce the environmental footprint of the construction.

For the estimation of the Scope 2 emissions, the following steps were taken:

1. Consumption identification: estimation of the electricity consumption for the baseload and for each operational phase and establishment of an operational schedule.
2. Procurement hypothesis: Establish a credible scenario for procuring the energy based on an external expert consultancy with a focus on sourcing energy from renewable energy sources.
3. Quantification: Quantification of the associated climate effect by using the accredited French ADEME [21] database.

[21] ADEME stands for Agence de la Transition Écologique, which translates to Agency for Ecological Transition. It is a French public agency under the supervision of the Ministry for the Ecological Transition and the Ministry for Higher Education and Research.

Table 4.1 Summary of the LCA-based carbon budget of the construction process

Item	Footprint
Subsurface	477,390 tCO_2(eq)
4 technical sites	17,546 tCO_2(eq)
4 experiment sites	31,735 tCO_2(eq)
Total	**526,671 tCO_2(eq)**

Table 4.2 Summary of the LCA-based carbon budget of the construction process

Indicator	Value
Potential contribution to ozone layer depletion	19.3 kg CFC 11 eq
Potential acidification	929 t SO_2 eq
Potential eutrophication - fresh water	96 t $(PO_4)^{3-}$
Potential eutrophication - marine	12 t N
Potential eutrophication - land	2.1 x 10^6 mol N

4. Formulation of recommendations: Based on the results and the identification of the key impact drivers, a set of recommendations was formulated that are to be taken into consideration in the subsequent design phase to further reduce the environmental footprint of the operation.

In both cases, the results were converted into monetary terms using the EIB-established shadow price for carbon. The results were integrated over time and discounted using the 2.8% Social Discount Rate established for the assessment project.

4.7.3 Results

Construction phase The LCA [59] provided a breakdown of GHG emissions across various lifecycle phases and materials. It is essential to note that the results were achieved using the most advanced, state-of-the-art products and materials currently available on the market. The results are, therefore, credible, and the carbon-related climate footprint can be further reduced as more advanced technology can be included in the project. The key emission sources are reinforced steel (14%), precast concrete (49%) and concrete (23%). The climate effects due to the use of electricity have been included in this analysis. It is assumed that the electricity required for the entire construction process can be obtained from renewable energy sources via local suppliers in France and in Switzerland. The official carbon footprints of today's renewable energy mix in the two host countries have been used in the study (see Table 3.5). The results obtained highlight opportunities for emission reduction by establishing technical requirements for the infrastructure with carbon reduction in mind, careful selection of materials which meet the requirements, construction process optimisation, and energy efficiency improvements. The GHG impacts of the initial and benchmark scenarios are given in Table 4.1.

The value obtained corresponds roughly to 3 years of CERN's annual carbon budget [78] or to one-third of the carbon budget of the Olympic Games in Paris, 2024 [79].

Further environmental performance indicators obtained with the LCA are shown in Table 4.2. Compared to classical, non low-carbon construction processes, the most relevant indicator is marine eutrophication, which can be linked to the use of recycled steel.

The results also enable a comparison to be made between the construction of subsurface structures and conventional structures, such as road and metro tunnels, and tram lines. The latter is characterised by significantly higher carbon footprints as a result of the much stricter requirements that public use imposes. For comparison, the construction of the U5 underground line in Berlin (Germany), a typical small-scale metro line, has a carbon footprint of 80,000 tCO_2(eq) per km. The footprint of a typical tramway line has between 7600 and 10,850 tCO_2(eq) per km. The linear part of a future circular collider subsurface structures has a carbon footprint of about 5300 tCO_2(eq) per km (see Fig. 4.9).

Based on the findings, the following levers were identified to reduce GHG emissions:

- Document technical requirements for the structural surface and subsurface elements that capture the strict minimum needs to fulfil the scientific research programme.
- Develop an eco-design that meets the established requirements with carbon reduction in mind.
- Make structural modifications by reducing the inner line thickness of subsurface structures by 5 cm, leading to a reduction in the quantity of precast concrete and rebar steel of 16%.

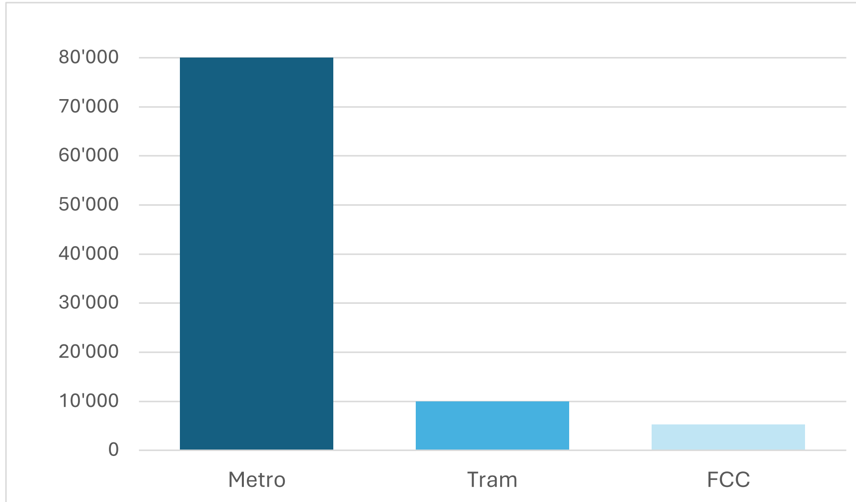


Fig. 4.9 Comparison of carbon footprint between a small-scale underground metro line, a tramway line and the FCC. [59]

- Substitute materials, using low-impact materials wherever possible, leading to a further reduction of GHG emissions.
- Optimise the construction process to minimise emissions, including local sourcing of raw and recycled materials and production of construction materials.
- Fully electrified construction processes and transport.
- Reuse excavated materials, for instance, in concrete production.

Climate effects due to energy use during operation To estimate the climate effects related to the use of energy (Scope 2) during the operation phase, the electricity requirements have been estimated for the baseload and for each individual operation phase (Z, WW, ZH, $t\bar{t}$). During the operation phase, the energy needed to power the infrastructures, particle accelerators, and experiments will be sourced entirely from the French electricity grid, managed by the national grid operator RTE. A portfolio of multiple electricity contracts and power purchasing agreements (PPA) facilitates the diversification of the electricity mix and sourcing it from different operators who can provide certificates of origin, leading to market-based carbon footprint reporting. A preparatory study with two independent external consultants identified that on a short timescale, before 2030 60% of the required energy could already be obtained from renewable energy sources and in a time frame of 15 years (around 2040) a portfolio to cover 80% of the needs with renewable energies can be established. For 2050, when the FCC is envisaged to operate, a coverage of 90% is assumed with a residual supply of 10% nuclear energy. For the purpose of the socio-economic performance assessment, a conservative maximum use of 80% energy from renewable energy sources has been used, thus over-reporting the carbon equivalent footprint. To estimate the carbon intensity of the project scenario, the official values of the French National Environment and Energy Management Organisation (ADEME) were used, leading to a mix with a carbon intensity of about 15 tCO_2(eq) per GWh. For the calculations in the socio-economic performance assessment, a more conservative degressive carbon intensity starting with 26 tCO_2(eq) per GWh in 2024, 19.10 in 2046 and 18.41 in 2050 assuming a constant decrease in the emission factor of 4% have been used. Again, this approach leads to an over-reporting of the carbon equivalent footprint. Table 4.3 provides the Scope 2 indication of the carbon budget for each particle collider operation phase with beam for scientific research and the total footprint for all operation and shutdown phases for two different carbon footprint assumptions leading to a range for the expected carbon footprint: 15 tCO_2(eq) per GWh and 25 tCO_2(eq) per GWh.

Integrating the energy consumption requirements over the years of operation leads to an integral carbon budget that corresponds to about 2.5 years of CERN's annual carbon footprint today. For comparison, the Meta company known for its products Facebook, Instagram and WhatsApp operates currently at least three data centres in the United States with electricity consumptions between 1.2 and 1.4 TWh per year [227]. Their individual, location-based Scope 2 emissions are significantly above, 350,000 tCO_2(eq) per year.

Shadow cost of carbon The conversion of the carbon budget aligns with the overall goals for climate protection and temperature limits established by a community of nations in the Paris Agreement. The European Investment Bank (EIB) has calculated a so-called 'shadow price for carbon' that represents the costs that humankind needs to associate with climate protection measures to achieve the agreed goal. The shadow price of carbon increases over the years, making one tonne of CO_2(eq) more expensive for society each year. The discounted value of the monetary conversion of the construction and operation-related carbon footprint is about 342 million euros. This amount is added to the integrated socio-economic assessment on the cost side of the balance and is used to estimate the

Table 4.3 Summary of the operation-related Scope 2 carbon emission footprint using two different market-based carbon intensity assumptions for the electricity purchased. Note that the integral carbon footprint also covers Scope 2 emissions during shutdown periods

Phase	Duration	GWh/year	Footprint all years at 15 $tCO_2(eq)/GWh$	Footprint all years at 25 $tCO_2(eq)/GWh$
Z	4 years	1100	66,000 $tCO_2(eq)$	110,000 $tCO_2(eq)$
WW	2 years	1300	39,000 $tCO_2(eq)$	65,000 $tCO_2(eq)$
HZ	3 years	1500	67,500 $tCO_2(eq)$	112,500 $tCO_2(eq)$
$t\bar{t}$	5 years	1770	132,750 $tCO_2(eq)$	221,250 $tCO_2(eq)$
Total		20,350	**305,250 $tCO_2(eq)$**	**508,750 $tCO_2(eq)$**

Table 4.4 Shadow cost of carbon under in currency unit per tonne $CO_2(eq)$ for various jurisdictions. Rates in the first row are also published as European Union law 2021/C 280/01. Note that the 1.5% near-term Ramsey Discount Rate is applied to the US indicated rates

Organisation	Unit	2020	2025	2030	2035	2040	2045	2050	2060	Source
EIB and EU	Euro 2016	€80	€165	€250	€390	€525	€660	€800	n/a	[228]
EIB and EU	Euro 2024†	n/a	€208	€316	€492	€663	€833	€1010	n/a	
SGPI France	Euro 2018	€87	n/a	€250	n/a	€500	n/a	€775	€1203	[149]
UBA Germany	Euro 2023	€240	n/a	€254	€253	n/a	n/a	€301	n/a	[229]
UK (high)	GBP 2020	£361	£390	£420	£453	£489	£527	£568	n/a	[230]
EPA USA	USD 2020	$340	n/a	$380	n/a	$430	n/a	$480	$530	[231]

† Adjusted based on EU-27 GDP deflator 100.0 in 2016 and 126.3 in 2023. It measures the amount to which the real value of an economy's total output is reduced by inflation.

net present value of the future research infrastructure at the end of its scientific operation programme. Table 4.4 shows the shadow cost of carbon currently recommended for project appraisal by the European Investment Bank (EIB) and its time-adjusted value to be used in 2025.

4.8 Socio-economic performance

4.8.1 Context

The goal of the comprehensive socio-economic impact analysis including a wider set of components such as environmental externalities is to get a better understanding of the cost drivers and potential benefits (as indicated in Fig. 4.2). This approach has been adopted to plan for a sustainable scenario. The analysis can also reveal under which conditions the overall socio-economic performance can be positive, i.e., represent a long-term sustainable investment for the society. Carrying out such analysis from the onset enables the project to incorporate the findings in the subsequent design phase, where it is easier to plan for sustainability enablers than during construction or when the infrastructure is already in operation.

The socio-economic analysis relies on a working hypothesis of the investments and resources engaged for the project by an international collaboration. Therefore, the work is based on a total project cost estimate including all investment costs, operation costs, and relevant negative and positive externalities for the entire observation period carried out in 2024. This estimate may differ from project cost estimates carried out later or presented elsewhere, since it represents a snapshot of the estimates taken in June 2024 and it includes global personnel engagements such as those of the international collaborations and monetised negative environmental externalities. The total costs required for the socio-economic analysis include the investment costs (capital and operation expenditures) as well as monetised externalities such as environmental costs and the shadow cost of carbon. Therefore, those costs figures must not be used to determine the financial needs to implement the project. They represent the total cost of the science missions for society for the entire observation period. The same holds for the reported benefits: they represent a collection of identified, quantified and monetised positive effects for society and are not limited to direct economic effects. Neither costs nor benefits can be exhaustively covered due to uncertainties, available resources, and time limitations. However, the herein reported results are sufficiently comprehensive and detailed

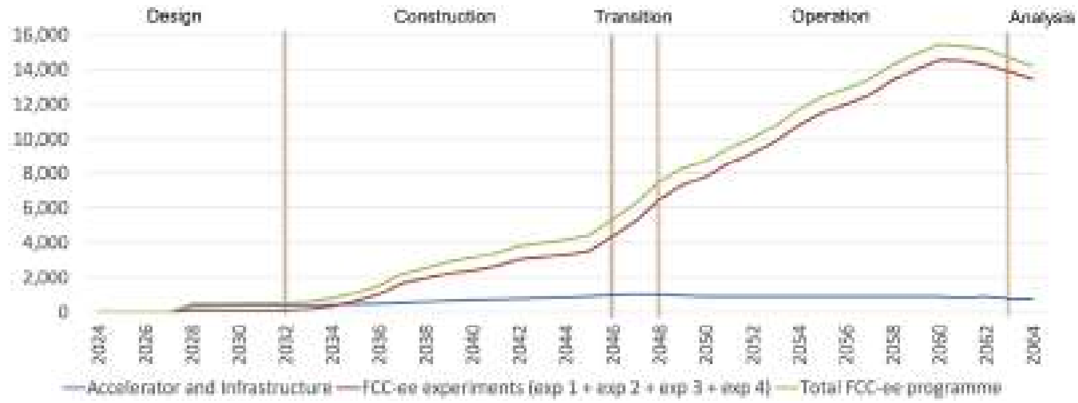


Fig. 4.10 Number of persons engaged in the project over the years throughout all project phases

to establish a stable Benefit-Cost Ratio that is unlikely to decrease further with the introduction of additional, minor cost and negative externalities. The socio-economic performance requires periodic updates as the project is defined better and in more detail and as models and resources to estimate additional benefits become available.

A comprehensive report on the socio-economic performance analysis [121] details the data, assumptions, methodologies and outcomes of the first socio-economic impact analysis for the first phase of the integrated FCC research programme: the FCC-ee lepton collider based on only two interaction points. The analysis spans the entire lifecycle of FCC-ee, encompassing its design, the construction of the surface and subsurface structures, the creation of the technical infrastructures, the particle accelerator and experiment detector construction, the operation and the gradual beam energy upgrade phases. The entire analysis spans a duration of 41 years (2024 to 2064), starting with pre-investment study expenses, the financial investment decision and lasting until the end of the operation phase. The methodological approach is based on the regulatory guidelines issued by the European Commission (EC) [232], the European Investment Bank (EIB) [228], the European Strategy for Research Infrastructures (ESFRI) guidelines [214] and the French Secrétariat général pour l'Investissement (SGPI) [149]. The guidelines adopted are compatible with those in other countries of the European Research Area, for instance, in the UK [222]. The study also considers the latest literature, works, and results of empirical research on the economic quantification of impacts associated with research infrastructures.

In evaluating the FCC-ee project, costs and benefits are expressed in comparison to a scenario where the project is not implemented. In this counterfactual scenario, the LHC would continue its operation until its anticipated end of life around 2040, and no new particle-collider would be constructed. CERN would continue its operation of the existing particle accelerators (e.g., AD, ELENA, LINAC4, PS) and the experimental infrastructures linked to them. It is based on the methods of standard cost-benefit analysis (CBA). All costs and benefits are incremental, i.e., expressed as a difference between the costs and benefits of the operation of the existing infrastructure after the shutdown of the LHC and the costs and benefits that the FCC-ee would induce Consequently, the approach captures the net change, focusing on causally related effects that can be reliably attributed to the FCC-ee project.

This social cost-benefit assessment carried out assumes an FCC-ee project with four experiments, collectively involving approximately 260,000 person-years over the project's lifespan. The engagement of people is expected to reach its peak of about 15,500 people during the operation phase (Fig. 4.10). This diverse group comprises scientists, engineers, technicians, administrative staff, doctoral and post-doctoral researchers, undergraduate students, master degree level students and apprentices. Of the total participants, approximately 11% is assumed to be active on the particle accelerators and technical infrastructures, while the remaining 89% will be engaged in the detectors and experimental physics.

4.8.2 Results

The initial socio-economic impact assessment based on 2 experiment collaborations, limited to the investment costs, operation costs, and core benefit pathways, yielded a positive net present value at the end of the FCC-ee operation phase [121]. The subsequent complementary assessment carried out in 2024 [233] used an even more conservative calculation based on an update of the project configuration, considered only a reduced set of well-justifiable benefit pathways, and extended the analysis to wider effects and negative environmental externalities:

- Revised investment and operation costs, reflecting the price evolution of goods and services between 2018 and 2024.
- Four experiment collaborations (instead of two as assumed in the initial assessment).

Table 4.5 Social cost-benefit assessment of the FCC-ee project expressed as an incremental benefit with respect to a counterfactual scenario in which no collider project is implemented after the end of the HL-LHC operation. The results of the 'wider' socio-economic analysis include noteworthy negative externalities and environmental benefits

Cost/Benefit	Undiscounted	Discounted
(A) Costs		**19,666 MCHF**
Investment costs (for 4 experiments, injector and $t\bar{t}$ stage)	16,215 MCHF	10,171 MCHF
Personnel costs	16,802 MCHF	7544 MCHF
Operation costs (materials, consumables, services)	4410 MCHF	1879 MCHF
Dismantling costs	228 MCHF	72 MCHF
(B) Negative externalities		**354 MCHF**
Shadow cost of carbon	634 MCHF	342 MCHF
Loss of agricultural income, biodiversity & habitat	7.6 MCHF	4.1 MCHF
Social cost of project-related, induced noise	0.02 MCHF	0.02 MCHF
Social cost of project-related, traffic-induced air pollution	0.9 MCHF	0.6 MCHF
Social cost of project-related, traffic-induced GHG externalities	9.8 MCHF	7 MCHF
Social cost of ionising radiation	1.3 MCHF	0.6 MCHF
(C) Core benefits		**23,974 MCHF**
Scientific production	6507 MCHF	2813 MCHF
Early career researcher training	20,687 MCHF	4986 MCHF
Industrial benefits for suppliers	17,577 MCHF	9569 MCHF
Onsite visitors	4538 MCHF	2129 MCHF
Online and social media	229 MCHF	102 MCHF
Open software (experiments and detectors)	7428 MCHF	4375 MCHF
Total costs including negative externalities	**(A + B)**	**20,020 MCHF**
Total core benefits	**(C)**	**23,974 MCHF**
Reference net present value (NPV)	**(C) − (A + B)**	**3954 MCHF**
Reference Benefit Cost Ratio (BCR)		**1.20**

- Revised social discount rate (2.8%).
- Introduction of noteworthy environmental negative externalities.
- Revision of the major benefit pathway monetisation, including additionally gathered data.
- Strict limitation of benefits to core benefit pathways.

Table 4.5 presents the most certain and stable results of this additional social cost-benefit assessment, showing the core cost and benefit pathways. A set of wider benefit pathways may occur, provided that dedicated planning and implementation are incorporated into the project designs and appropriate contextual conditions are in place (see Table 4.6). To aggregate the value of measured benefits and compare them with costs and negative externalities, a social discount rate (SDR) was established specifically for the project. Instead of relying on existing SDRs suggested by international organisations, this project-specific rate accounts for the level of development and preferences for consumption and investments in countries contributing to the CERN budget and the very long duration of the project. The SDR value assumed is 2.8%. The result, strictly limited to costs, noteworthy negative externalities, and core benefits, indicates a positive net present value of approximately 4 billion Swiss francs for the project, resulting in a benefit-cost ratio (BCR) of approximately 1.20. This value must not be interpreted as a fixed and certain number. A positive BCR under highly conservative assumptions provides confidence that the project scenario can achieve an overall beneficial contribution to society. Depending on the project design and implementation measures to support benefit generation and control costs and externalities, the BCR may be lower or higher. Continuous tracking of the impact generation throughout subsequent project phases and monitoring during the project implementation and operation are required to assure an overall positive performance.

Table 4.6 Additional benefit potentials not considered in the calculation of the reference net present value and benefit cost ratio

Cost/Benefit	Undiscounted	Discounted
(D) Residual asset value for a subsequent collider project	−7911 MCHF	−2480 MCHF
(E) Wider benefit potentials		**6916 MCHF**
Open information platform	5053 MCHF	2681 MCHF
Open collaborative software	7516 MCHF	3487 MCHF
ICT spin-offs	832 MCHF	409 MCHF
Creation of renewable energy sources through contracts	227 MCHF	117 MCHF
Supply of waste heat	313 MCHF	132 MCHF
Avoided greenhouse gas emissions (GHG) by supply of waste heat	170 MCHF	74 MCHF
Rewilding (habitats and biodiversity)	0.4 MCHF	0.2 MCHF
Contributions to regional emergency services	31 MCHF	16 MCHF
Net present value including residual asset value	**(C) − (A + B + D)**	**6446 MCHF**
Total core and wider benefit potentials	**(C + E)**	**30,890 MCHF**

The findings of the studies carried out over a time frame of about seven years suggest a positive socio-economic net performance of the FCC-ee project. This result serves to demonstrate the long-term social sustainability of the proposed new scientific research infrastructure. The analysis so far has helped identify the main impact pathways with the goal of supporting the design of the research infrastructure for sustained socio-economic impact generation. The findings reported here are, however, not exhaustive. Concerning costs, the estimates are likely to evolve further during the design phase until an investment decision is made provisional and will be subject to updates. The approach taken to integrate the analysis of impacts on the environment, economy, and society at large is in line with EU practice in policy and infrastructure impact assessment. Further complementary socio-economic analysis, given additional time and resources, would permit additional positive impacts to be uncovered and quantified, strengthening the robustness of the benefits already estimated. Studies by Flyvbjerg et al. [234–236] highlight a common trend of underestimating costs, overestimating revenues, and misjudging environmental and economic impacts and the unintentional introduction of bias. Literature, therefore, supports carrying out an uncertainty analysis, especially in large-scale infrastructure projects. To achieve this, the existing deterministic framework of the CBA can be expanded with a probabilistic model, covering costs and benefits. This approach will provide a more comprehensive view of the project's expected outcomes.

4.8.3 Cost and benefit coverage

Good coverage of the main cost and benefit pathways has been achieved with the presented socio-economic assessment, although exhaustive coverage of a large research infrastructure is limited by the knowledge about impact pathways, models to quantify them, time, personnel and budget. The assessment carried out includes the full investment costs for the civil structures, the injectors, the booster, and the collider up to $t\bar{t}$ stage and 4 experiment detectors. Full personnel costs comprising CERN paid and personnel supplied by the international collaborations to the programme were accounted for. Full materials, maintenance, consumables, and service costs for the operation phase were included in the costs. Finally, the dismantling costs of the main ring booster and collider were also included. This part does not include the disposal of equipment that would be classified as radioactive waste. Such an estimate can be done only once the technical designs have been completed. It does also not consider the residual market value of the metals that would lead to a gain after dismantling.

The establishment of a proper residual value for a proposed investment is a key element for input to the financial sustainability analysis of such a project. According to the guide to the European Commission Cost-Benefit Analysis of investment projects, the discounted value of any net future revenue after the time horizon of the project has to be included in the residual value. The guide indicates that it is "the present value at year n of the revenues, net of operation, costs, the project will be able to generate because of the remaining service potential of fixed assets whose economic life is not yet completely exhausted". In line with this EC guideline (p. 45, [223]) which economist practitioners use, the residual value is highlighted as a value with a negative sign in the cost account. If there is a 'use value' for the assets, then the residual value is greater zero. If not, the residual value is considered zero.

Both scenarios were considered in the analysis. Since the proposed infrastructure can serve two particle colliders in sequence, the residual asset value is considered in this assessment. Due to the very long timespan associated with the integrated programme, this social benefit-cost assessment, however, only concerns the first phase, the lepton collider FCC-ee. A residual asset value at the end of the FCC-ee operation phase is calculated that can be made available as a 'gift' to a potential subsequent hadron collider project (FCC-hh). The residual asset value becomes zero if no subsequent particle collider is installed that can profit from the built-up assets. This approach has also been taken for the social cost-benefit assessment of the Large Hadron Collider [192]. The calculation of the reference net present value (NPV) for the lepton collider FCC-ee project is carried out in a very conservative way: it does not include the residual asset value at the end of the observation period. For the purpose of showing that further societal impacts are possible and that an integrated programme consisting of a lepton collider (FCC-ee) followed by a hadron collider (FCC-hh) is preferable, this benefit can be included in a wider NPV.

The materialisation of negative externalities and benefits depends largely on the design of an impact-creation framework and external conditions.

Negative externalities such as the carbon footprint and the associated shadow cost of carbon depend on the procurement actions taken for the construction, the power purchasing agreements concluded for construction and operation, and the national carbon pricing at the time of generating the carbon footprint. The shadow cost of carbon indicated considered the construction and operation of the research infrastructure. The costs for the accelerators and detectors could not be included at this time since they rely on the availability of a technical design and a procurement scenario.

The effects of potential disturbances such as noise and induced traffic linked to the construction depend significantly on the actual number of people that would be affected. Additionally, certain impacts are challenging to predict at this early stage because of a lack of forecast models for certain benefit pathways, because they could not be identified, because of a lack of time and resources, or simply because of large uncertainties. Examples include the wider positive externalities that can emerge from developing novel products and processes for re-using excavated materials, advancing technologies for low-carbon construction materials, generating local synergies with the municipalities hosting surface sites, the unanticipated creation of high-value technology spinoffs, and the invention of entirely novel technologies.

This analysis focused on the direct benefits currently known and foreseeable based on past factual evidence, for instance, from the LHC and the European XFEL projects. It was concluded as soon as a high level of confidence was achieved in demonstrating a break-even point between benefits and total costs, including noteworthy negative externalities. Conservative assumptions were made for all estimates. Where a causal relationship between positive or negative effects and the project could not be reliably established, the item was entirely left out. For cost and benefit items for which commitments remain to be formulated (e.g., the development of dedicated open software platforms to support knowledge dissemination and international collaboration, the conclusion of renewable energy contracts or PPAs, the supply of waste-heat, projects to re-create and strengthen the lost habitats, contributions to the operation of regional emergency services), the elements were labelled to be considered as a 'wider' societal impact. They were included in the calculation of a wider net present value only.

The economic benefits of visitors rely on the existence of a visit programme, dedicated visit points, infrastructures and guides. The reported benefits of onsite visitors are incremental with respect to the counterfactual scenario in which no future particle collider project is implemented. This means, it captures the likely benefits on top of the effects generated by visitors that come to CERN after the end of the HL-LHC programme. This counterfactual case is envisaged to be less impactful, since CERN without a new flagship project at a global scale is assumed to be less attractive for visitors, as recent surveys of CERN visitors carried out in the first quarter of 2025 reveal. Some benefits are intangible in nature, such as advances in scientific knowledge, impacts related to science diplomacy, ethical considerations, and trust in science. Although benefits created by open software and collaborative platforms have significant value potential, it is challenging to estimate which, when and in which ways such benefits reach society without a dedicated innovation creation and transfer programme in place for such technologies.

Several further wider benefits have been envisaged, but were not pursued further at this stage due to resource and time constraints associated with unambiguously clarifying the demand. They include, for instance, the strengthening of the local and regional electricity and communication networks, the creation of soft mobility, the contribution to the improvement of public transport, the creation of housing and schooling facilities, and the development of local businesses and services. However, the study included the development of a framework to start elucidating the demands for such wider benefit potentials with the municipalities in the perimeter of the project. Ongoing and future socio-economic analysis will shed more light on those opportunities once the demands are better understood.

4.8.4 Cost and negative externalities

For the cost-benefit calculations, the FCC has been considered as a design-to-cost project, with a total investment including 4 experiments and the $t\bar{t}$ stage, projected at approximately 16.2 billion Swiss francs (undiscounted) with an uncertainty range of −5% to +20%. This figure encompasses studies, preparatory activities, design work, civil construction works, creation of technical infrastructures, all particle accelerators (injectors, booster and collider) and all investment costs related to the four experiment detectors.

Personnel costs include all human resources involved in the project throughout all lifecycle phases, irrespective of the organisation employing them. The total personnel costs are composed of wages, indirect costs and employer-related costs without overheads. They are averages for different personnel categories in the different countries participating in the project. In total, personnel costs make up about 16.8 billion Swiss francs (undiscounted) and 7.5 billion Swiss francs (discounted).

Operation costs refer to all expenses (both in-kind and outflows) that are needed for running, maintaining, and repairing the research infrastructure throughout the entire scientific exploitation (e.g., electricity, water, spares, and human resources for maintenance and repair). The likely scenario for the operational costs amounts to a total of 4.4 billion Swiss francs undiscounted with a range due to uncertain costs of resources (e.g., electricity and water), supplies and service contracts. The discounted costs are around 1.9 billion Swiss francs. This corresponds to an average annual undiscounted cost of about 250 million Swiss francs and about 105 million Swiss francs discounted over the operational time that spans from commissioning to the end of operation.

The cost figures used for this analysis, along with the projected number of project users must be regarded as a working hypothesis that serves for estimating the socio-economic performance, that helps to identify key impact pathways. It also helps in understanding which benefit potentials may still have potential for further development. They are formulated based on the understanding of the project at the time of the analysis and are expected to undergo further revisions and refinements as the design progresses.

Estimates of the following cost items covering the period from the investment decision to the end of the FCC-ee operation phase have been included in the analysis presented:

- Capital expenditures for civil construction, technical infrastructures, all particle accelerators (injector, booster, collider) including the upgrade to $\mathrm{t\bar{t}}$ operation and four experiments.
- Cost of acquisition of all land for the surface sites, accesses and nature enhancement around the sites.
- Cost of access road creation or refurbishing.
- Creation of off-site infrastructures required for construction and operation (e.g., accesses, water supply, water treatment, local electricity connections).
- Full personnel cost estimates (CERN and the international collaboration) required for the design, construction and operation phases covering the particle accelerators, technical infrastructures and experiments.
- Typical operation costs (consumables, water and energy, maintenance, repair).
- Dismantling cost of the lepton collider and its specific technical infrastructures that cannot be reused for a subsequent hadron collider.
- Negative residual value of the infrastructures for a subsequent particle collider project.

In addition to the items mentioned so far, a portion of the investments in reusable and durable assets, such as superconducting radiofrequency systems, electricity infrastructure, civil structures, and basic technical infrastructure, will be used in a subsequent particle collider project. According to the EC guidelines on Cost-Benefit Analysis (p. 45, [223]), this residual value is reported as a discounted value with a negative sign in the cost part. The residual value of the initial phase assets is significant and contributes to the sustainability of the integrated FCC programme. The estimated discounted value stands at approximately 2.5 billion Swiss francs, equivalent to 24% of the total investment.

Estimates of the following negative externalities have been included in the analysis presented:

- Cost of managing excavated materials as part of the investment cost.
- Shadow cost of carbon for civil construction and the energy used for operation.
- Cost of rewilding measures in the vicinity of the surface sites (e.g., preservation and improvement of wetlands, creation of trees to compensate for forest clearance and the creation of meadows and grasslands) as part of the investment cost.
- Economic loss (direct, indirect, upstream and induced downstream) caused by the consumption of agricultural land for a period of 30 years.
- Economic value of the cleared forest.
- Economic value of loss of habitat and biodiversity.
- Societal cost of construction and operation-related noise.
- Societal cost of added traffic and air pollution induced by the transport of excavated materials.
- Societal cost of additional ionising radiation.
- Societal cost of radioactive waste as part of the operation cost.

4.8.5 Impact pathways

The following impact pathways have been included in the analysis either as core elements or as potential wider benefits:

Fig. 4.11 Expected distribution of FCC-ee scientific products over time

- Value of scientific content production.
- Increased market value of early-stage scientists and engineers.
- Value of on-site tourism.
- Value of online presence and social media activities.
- Value of industrial spillovers involved in the construction of infrastructures, accelerators and experiments.
- Market value of ICT spin-offs based on the frequency of past and current spin-off company creation at CERN.
- Societal value of open software products.
- Market value of waste heat supplied and the societal value of carbon emissions avoided.
- Market value of additional renewable energy sources created as a result of long-term power purchasing agreements.
- Market value of treated waste water.
- Societal value of improved and recreated wetlands, meadows, grassland and forests.
- Economic value of compensated agricultural spaces.
- Societal value of regional emergency and fire-fighting services required for the new research infrastructure.

The following impact pathways are considered highly reliable and form, therefore, a set of core benefits on which the conservative net present value is based:

1. Value of produced and cited scientific publications.
2. Lifetime salary premium of early-career researchers and engineers aged under thirty.
3. Incremental value for suppliers due to follow-up contracts that result from their activity in the project.
4. Value of on-site visitors based on the travel cost method and local spending.
5. Leisure time value of people consuming project-related online and social media content.
6. Estimated value of open software developed in the area of particle detectors and experiments, used by other scientific institutes and industries.

The first impact pathway assessed is the value derived from scientific content production. It stems from the knowledge flow generated by scientists and engineers engaged in the collider and its experiments, resulting in a diverse range of scientific products, including journal articles, working papers, conference proceedings, and presentations. These products can have a lasting impact, extending beyond the high-energy and particle physics community, and potentially influencing other knowledge domains to address broader societal challenges. Scientometric techniques were employed to estimate scientific production and its propagation from the FCC-ee project. The methodology involved analysing historical patterns observed in comparable physics research programmes like Tevatron, LEP, and LHC. The economic concepts of opportunity cost and value of time were employed to determine the social value of scientific products. This approach considered the time spent by individuals, depending on their involvement and responsibilities, in an experiment collaboration for producing these outputs and valued it based on their average hourly salaries. This method was applied to estimate the social value of scientific products produced by researchers directly involved in the research programme (so-called 'tier 0' products), those citing the initial tier 0 knowledge (so-called 'tier 1' products), and products citing tier 1 outputs (so-called 'tier 2' products). Between 34,000 and 38,000 scientific products are expected to be directly produced in the course of the FCC-ee project (tier 0 publications), with an additional 538,000 to 618,000 tier 1 and 2 products likely to be generated based on that corpus until the year 2083 (see Fig. 4.11).

Considering that about 55% of the time spent by researchers is dedicated to scientific research activities and the production of the production of scientific outputs, but only about 22% can be attributed to FCC-ee specific scientific products, the estimated benefit from scientific production is around 6.51 billion Swiss francs undiscounted and about 2.8 billion Swiss francs discounted. This valuation accounts for the diminishing value of tier 1 and tier

Fig. 4.12 Lifetime salary of early-career researchers by sector of employment

2 products compared to tier 0 products, as knowledge propagates through subsequent waves of production and the initial input from FCC-ee progressively diminishes.

The second impact pathway studied is the value of early career research and engineer training, which reflects the project's role in imparting knowledge, fostering skills development and building capacities for individuals actively engaged in the research programme throughout its lifecycle. The value stems from the fact that persons who were engaged in large-scale, multi-sectoral high-tech and science projects at CERN represent a higher value to their eventual employers than persons who do not have such training experience. This is reflected by higher starting wages and faster-growing salaries. The effect remains until the person retires, and it leads to an overall incremental added value with respect to peers without such an experience. The analysis specifically evaluated the benefits accrued by technical students, doctoral students, post-doctoral researchers, and associated scientific and engineering personnel up to a cut-off age of 30. The analysis did not include the training value for apprentices and other highly qualified personnel with limited-term contracts, temporary labour and contracted workers. The benefit has been quantified by estimating the lifelong career development improvements for participants upon entering the labour market after gaining work experience within the research programme. Previous studies, further validated through a survey involving approximately 2600 individuals, indicate that the lifetime salary benefit for an early-stage researcher working at FCC-ee ranges from a minimum of 2% to 10% for the average period of stay in the research infrastructure (3.78 years) (see Fig. 4.12). The total undiscounted socio-economic benefit is assessed at around 20.7 billion Swiss francs, and the discounted value is around 5.0 billion Swiss francs.

The third impact pathway explores the benefits generated by the project for industrial suppliers engaged in the construction of the infrastructure, the particle accelerators, and detectors. The benefit stems from increased financial performance of the suppliers a few years after they have received contracts in the frame of the project. The effect of being a supplier in a large-scale project, in particular in domains that are characterised by project-specific designs, developments, and adaptations of off-the-shelf products and services, is linked to the gain of experience, increase in efficiency, and a broadened market access. In essence, the impact stems from a knowledge gain acquired through close collaboration with the research infrastructure. This knowledge, in turn, contributes to the creation and improvement of new processes, products, and services that suppliers can leverage in other markets and domains. It leads to additional contracts that the supplier is able to conclude because of that knowledge gained. This cause-effect-impact chain has been exhaustively analysed over some decades, and it has been found to be robust and stable. A profit multiplier has been determined, standing at 1.96 for procurement of items with low or moderate level of technology intensity and 3.06 for procurement with high level technology intensity. Applying this multiplier to the investments that are likely to generate further industrial spillovers, the undiscounted benefits are estimated at 17.6 billion Swiss francs. The discounted benefits are estimated at 9.6 billion Swiss francs (see Fig. 4.13).

The fourth impact pathway concerns the benefits generated by on-site visitors. Before 2020, 150,000 visitors per year came to CERN. In 2024, after the opening of the new Science Gateway visitor centre, the number increased to about 350,000 external visitors (not counting visits of persons participating in CERN projects, company visits and visits of employee families, accounting to about 40,000 additional persons). While in the period before the Science Gateway the participation was equally distributed among group visits and individuals, the significantly increased capacity to welcome unguided visits led to a change in the distribution. Today about 76% of people visit CERN individually and 24% come as part of groups that enjoy the possibility to also visit experiment facilities, in particular the ones linked to the LHC. 55% are classified as 'CERN motivated' visitors, whose primary purpose

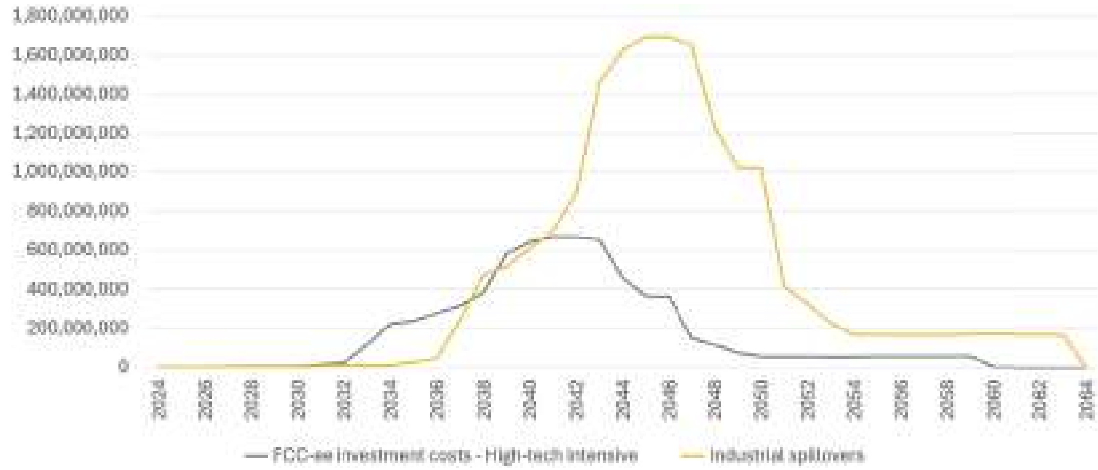


Fig. 4.13 Time profile of FCC-ee industry benefits for suppliers, compared with the high-tech investments costs (Swiss francs, undiscounted - baseline scenario)

of the trip was to visit CERN, while 45% are "region motivated" visitors, who travelled to the area for other reasons and took the chance to also visit CERN. The absolute number of persons that are part of visit groups remained relatively stable. Two campaigns of guided systematic interviews with on-site visitors before and after the opening of the Science Gateway permitted a robust multi-year spending behaviour of the visitors to be established (see Fig. 4.14). In total, more than 4000 individuals were interviewed, and only about 3550 responses with self-consistent and credible answers were retained for the analysis. The average stay of persons in the region is 3.75 days, indicating that once they have visited CERN they extend their visit to further destinations in the vicinity.

The local spending associated with the visit ranged between 625 Swiss francs for group visitors and 713 Swiss francs for individual visitors, with a mean of 691 Swiss francs for all visitors. Based on the survey, sampling from the obtained visitor spending distribution, the sum of the local spending due to 350,000 annual on-site visitors translates to a tangible economic benefit for the region of about 250 to 350 million Swiss francs per year. This figure does not, however, capture the socio-economic benefit related to the FCC-ee. Based on this current survey, only a certain fraction of future visitors can be attributed to an FCC. As outlined initially, the analysis limits benefit potentials to the incremental effects, i.e., the difference between the effects of on-site visitors that can be attributed to the existence of the FCC and the evolution of CERN without the FCC. For this reason, the following assumptions were applied to estimate the incremental socio-economic benefit for the FCC-ee:

- Conventional CERN visits: an increasing share of these visitors is attributed to FCC-ee, starting at 0% in 2024 and gradually rising to 50% by 2064.
- Visitors to the FCC-ee construction sites and the four experimental sites: these visitors are fully attributed to FCC-ee, as they would not have been accounted for in a scenario without FCC-ee.
- Visits to the decommissioned LHC tunnel: adhering to a conservative approach, these are not attributed to FCC-ee since they would be justified even in the absence of the FCC-ee.
- Visits to FCC experiment visitors centres.
- About 10% of all visitors are coming to the CERN main site.
- Open-day visitors: these are attributed to FCC-ee only for the additional capacity created by the new accelerator; all other visitors are excluded from the count.

Based on these assumptions, it is estimated that out of almost 19 million visitors throughout the entire observation period, only about 5.5 million are assumed to be attracted by FCC-ee (see Fig. 4.15), while the remaining will be motivated more by the overall CERN activity and longstanding worldwide reputation of scientific excellence.

Considering that only the incremental benefit is reported here, the difference between the number of visitors that CERN would welcome without and with an FCC-ee is about 13.5 million over the observation period.

The benefit for on-site visitors was monetised using the travel cost method, which incorporates the costs borne by visitors to travel to CERN and FCC, the economic value of time spent travelling, along with local expenditures connected to their visit based on two actual surveys carried out at CERN over two years (pre- and post COVID). The discounted benefit generated by about 5.5 million onsite visitors attributable to FCC-ee is estimated to be approximately 2.1 billion Swiss francs.

The fifth impact pathway analysed concerns virtual visitors who consume webpages and social media. Due to the limited availability of data, the analyses concerned only websites and social media channels that are di-

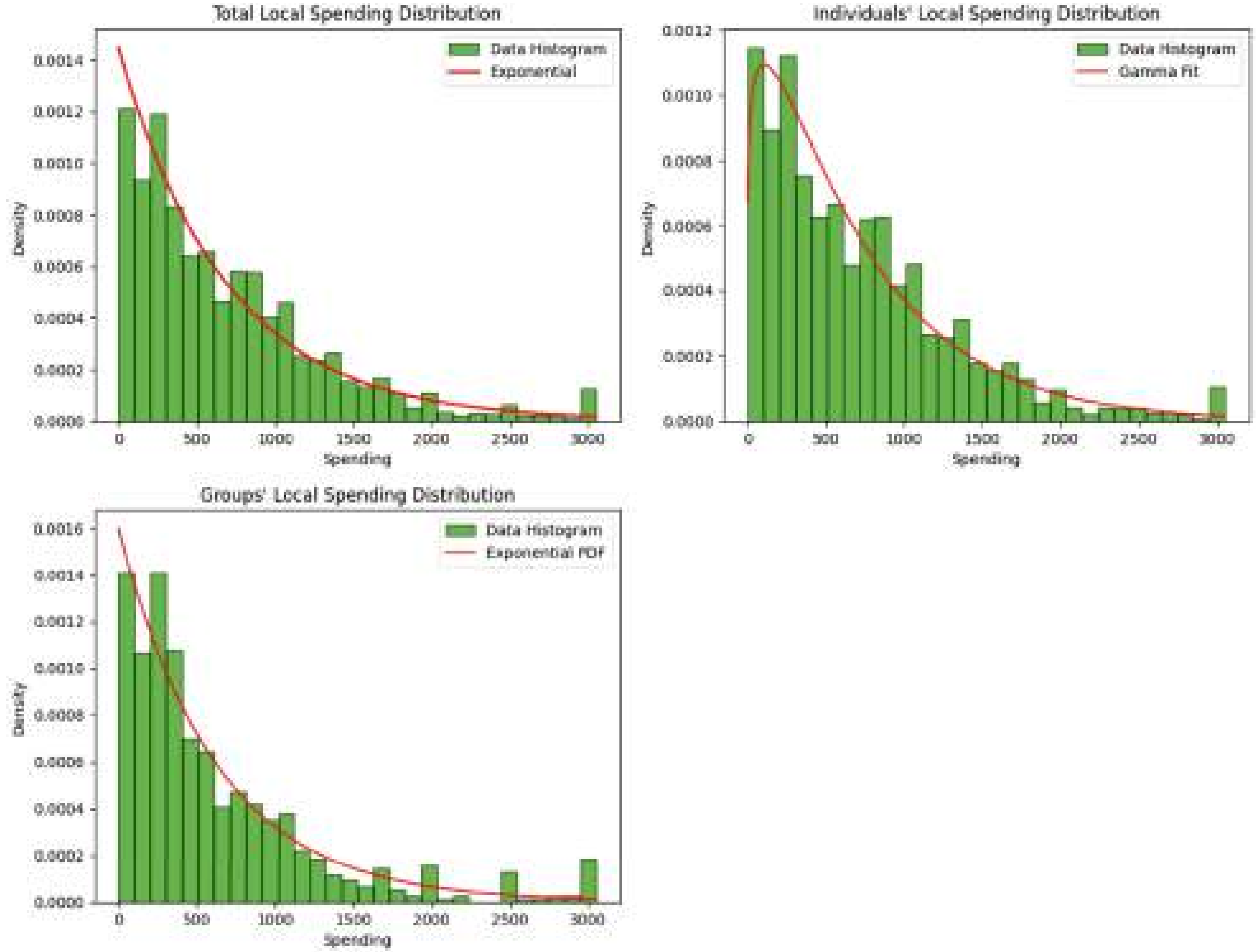


Fig. 4.14 Distributions of the spending of all on-site visitors, individual visitors and visitors that come to CERN as part of groups

rectly managed by CERN. The estimate, therefore, significantly underestimates the actual benefits generated by numerous online content that would be made available on a global scale.

The estimated number of online visitors is based on historical data collected by CERN's communication group regarding visits to the main CERN website and social media accounts. Assumptions were made about the number of visits specifically related to FCC-ee. This estimate has been revised to reflect changes in the project's timeline and to ensure consistency with the revisions made in the estimation of onsite visitors, particularly regarding the share of FCC-ee attribution. It is assumed that the highest attributable share of visits is approximately 50%, aligning with the assumption made for CERN visitors.

In the scenario without the FCC, it is assumed that the number of online visits to websites and social media will follow the same patterns as the on-site visitors in the absence of the FCC-ee. In the scenario with the FCC, the number of online visits corresponds to the trend of growth of scientific publications due to the projected FCC-ee research programme. The share of online visits attributable to the FCC-ee starts as a marginal share of the total CERN online visits. The main jump in online visits is expected to occur with the start of operation. This share is expected to grow further during the operative phase. The number of online visitors is expected to reach its maximum several years after 2050 and the end of operation. In these years, the share of the total CERN online visits associated with the FCC reaches conservatively about 50% and remains constant. This assumption is in line with survey results to onsite visitors about the reason to visit CERN today. Based on these assumptions, for the FCC-ee over the 2024–2064 period, impressions are estimated at 1.7 billion, engagements at 79 million, and CERN website visits at 175 million. These estimates are highly conservative and do not take into consideration future social medial developments and online platforms are likely to appear, but whose existence can today not be anticipated.

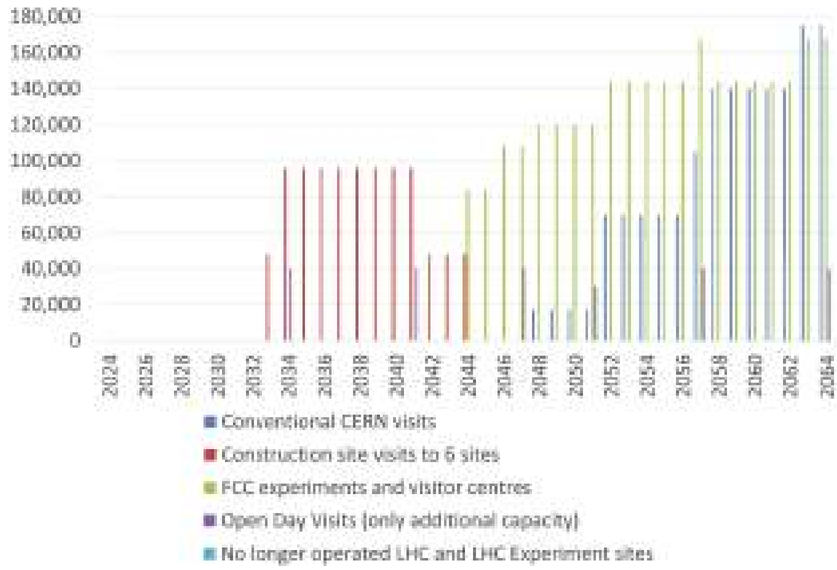


Fig. 4.15 Number of on-site visitors attracted by FCC-ee over the period 2024-2064 used for estimating the impact estimation

The monetisation of these visits is based on the actual observation of an online presence of a little over 3 minutes. Distributions are applied to different media types, such as social-media interactions and consuming online video snippets related to FCC. The value of time spent is determined using the ‘opportunity cost’ method, which suggests that time spent on social media and websites represents a missed opportunity to engage in other potentially profitable activities. Since not all virtual visitors are necessarily part of the economically active workforce, the opportunity cost of time was estimated by using per capita GDP (instead of wages), adjusted based on the geographical distribution of virtual visitors. The total undiscounted cultural benefit for online visitors is estimated to be approximately 229 million Swiss francs, which corresponds to 102 million Swiss francs discounted.

The sixth core impact pathway encompasses free and open-source software, systems, and platforms causally linked to the research programme. It is assumed that in particular software related to the experiment and detector projects generates incremental societal value due to the adoption by other science projects, research institutes, and companies with particular needs that cannot be easily satisfied by commercially available software. While the first user base is typically found in the physics, astronomy, and medical research domains, companies using such software can be very diverse. Recent examples of using software from the LHC experiments range from space-borne earth observation systems through medical imaging and mining to shipping container traffic and stock-market transaction analysis. In essence, in any application where massive amounts of data need to be processed, patterns need to be identified in background dominated environments, time-critical applications demand custom solutions, and data processing efficiency is key to success, the developments of particle physics scientists and engineers are sought after. Increasingly, these software systems also underpin advances in artificial intelligence (AI) and machine learning, both as training grounds for novel algorithms and as sources of specialised tools for large-scale, high-dimensional data analysis, thereby widening the spectrum of industrial and societal spillovers. This is an area of active and ongoing development.

The estimation of this benefit pathway is based on the use of actual particle detector modelling and simulation software, for which the use outside the core community could be tracked over recent years. It serves as a ‘proxy’ for comparable developments for which the need during the development of FCC detectors and experiments has been confirmed. Like software package analysis, new software can find use beyond the core community, thereby generating a spillover benefit for society. A number of developments will concern the use of artificial intelligence in this area, configurable hardware, edge computing, and ever-evolving data communication technologies. Several of these developments are admittedly associated with uncertainties, but as the past has shown, it is likely that the collaborations around the FCC-ee experiments will be able to make significant contributions in the ICT domain.

For detector modelling and simulation software, approximately 50 research centres, space agencies, and companies were identified using software developed for the LHC experiments. This included 38 institutions beyond CERN that contributed in some way to the developments. Examples include but are not limited to the Fermi National Accelerator Laboratory, SLAC National Accelerator Laboratory, the Centre for Medical Radiation Physics, and the European Space Agency. Additionally, 12 other laboratories, institutes, and companies use such software without contributing to its development. They include, for example, NASA, General Electric, Philips, Siemens, Varian, Boeing, and General Motors. CERN does not systematically track the number of users and installations, but data available in 2023 suggest a current user community of about 95 contributing institutes (excluding CERN). Assuming the ratio of 3:1 between contributing and non-contributing institutions remains stable, the total number of non-contributing users is estimated to be around 30. In the absence of more reliable data, this estimate is considered reasonable and conservative.

The benefit is estimated as the avoided cost for the external users, and it is based on the cost of production of comparable new software. It was estimated that the production cost of existing detector modelling and simulation software was about 44.2 million Swiss francs up to 2013, covering the first 20 years of its development starting in 1994. CERN contributed about 50% of this cost (22 million Swiss francs), with the remaining amount funded by other external contributors. The estimates are based on the hypothesis of comparable cost figures for FCC-ee related software and assuming CERN's contribution remains at 50%. The avoided cost for each contributing organisation is the total estimated production cost minus their specific contribution, while the avoided cost for non-contributing users is the full production cost. It is assumed that new software would be first released after 5 years of development with developments continuing over the years, even during the operation phase, due to the continued interest by academia and industry.

In this scenario, the total cumulated avoided cost representing the total undiscounted benefit is estimated to be about 7.4 billion Swiss francs. The discounted benefit is about 4.4 billion Swiss francs. This benefit, in fact, would stand for a range of potential software developments that cannot be explored in detail at this early stage. It is advised that any future development foresees an open access mechanism for such software, actively promotes such software in areas outside the particle physics community in science and industry and, most importantly, includes a systematic tracking of active users to help make socio-economic impact estimates more accurate and reliable.

4.8.6 Wider benefits

A number of wider benefits have been analysed in detail in addition to the core benefits presented in the previous section. Due to uncertainties that are linked with the possibilities to actually turn the wider benefit potentials into tangible impacts, they are not considered in the calculation of the reference baseline net present value. The analysis and quantification of those benefit potentials is, however, based on factual observations of past effects and outcomes and is therefore solid with respect to monetisation. As with the core benefits, highly conservative working assumptions have been established, and only effects that can be credibly justified have been included. Therefore, a second net present value is presented that includes those wider benefits. To turn such potentials into tangible impacts, the preparatory implementation phase of the future project needs to include dedicated work that plans for such benefit creation. Voluntary objectives and commitments are needed by the project owners to put instruments in place to actually turn the potentials into impacts. Last but not least, monitoring and tracking will need to be put in place to follow up on the impact generation.

The following wider benefits have been studied and are briefly presented in this section:

1. Open information platform
2. Open collaborative software
3. Company spin-off generation in the information and communication technologies (ICT) sector
4. Build-up of renewable energy sources
5. Supply of waste heat
6. Avoidance of greenhouse gases by substituting traditional heat energy sources with recovered and supplied waste heat
7. Improvement and creation of habitats and increase of biodiversity
8. Strengthening of emergency services

A future, global collaborative research project relies on a long-term, open scientific and technical information platform that permits the community to make its knowledge widely available so that it becomes findable, accessible, interoperable and reusable (FAIR principle). CERN has a long-term track record in putting such infrastructures in place, the World Wide Web being the most prominent one. This technology subsequently permitted the development and making available of additional services, such as the CERN Document Server (CDS), which is based on the in-house developed Invenio platform. This development has led to the creation of the Zenodo service, which the European Commission has endorsed as the catch-all repository for all EU-funded research. Today CERN operates this platform that is entirely part of the European Open Science Cloud (EOSC) for the European Commission. By continuing to be at the forefront of big science, CERN can have a lead role in scientific and technical information provision in Europe and at a global scale. The launch of a new large-scale science mission, the FCC, justifies not only the continuation of ongoing developments, but will likely also lead to the development and implementation of a new generation of information systems, in line with past occurrences. Such a platform may offer functionalities that go beyond pure document and data management and long-term data preservation. It may offer services that are today impossible to conceive. In order to estimate the potential value of such a future development, the value of the Zenodo platform was estimated as a conservative reference with minimum functionality offered to society today. This was possible, because historic data of sufficient quality for relevant periods could be identified. An econometric model was constructed to estimate the socio-economic impact of the virtual information repository, designed to fulfil collaborative information storage and usage requirements. The estimated monetised value is derived from measurable benefits associated with comparable repositories, encompassing data storage, online usage, and downloads, net of the present value of its development, operation and maintenance costs.

The undiscounted value over the FCC-ee observation period of such a platform is 5 billion Swiss francs, and its discounted value is about 2.7 billion Swiss francs. To turn such an impact potential into reality, several preconditions apply: the global community participating in the project has to have a demand for such a platform, the community must be committed to use the platform, communities beyond the high-energy and particle physics domain must adopt the platform (as was the case with the Zenodo platform being endorsed by the European Commission). The fundamental requirements rely on an intent to play the role of developing and operating an information platform for several user communities. Long-term sustained resource engagement and a plan to disseminate the developments beyond the core community are also needed.

Another typical case for open platforms in the history of CERN's large international collaborations is the creation of tools that support collaborative work. The 'Integrated Digital Conference' (Indico) event management system is one example of such development. It revolutionised the management of physical and virtual meetings, lectures, conferences and led to a comprehensive documentation of collaborative work and can be considered a key enabler of global collaborative projects. Since its start of development in 2002, the platform has spilled over to numerous academic and international organisations worldwide. A future large-scale project not only has very similar needs, but will create demands beyond those that are satisfied with this platform today. The integration of collaborative writing, sketching, AI support for meetings and minute taking, translation among different languages, collaboration management, video conferencing, recording and media publication, real-time messaging, shared workspaces, integration with document management, approval and selected information distribution processes are just a few selected examples for which the need is already starting to appear in the frame of the studies related to the FCC.

For these reasons, the current Indico platform was chosen as a conservative, representative example of a collaborative platform that can enable and improve future collaborative work in the frame of a large-scale project. The value generated from developing a new service to facilitate the worldwide collaboration involved in the FCC project in terms of meetings, calls, and event management was assessed by considering the willingness to pay (WTP) by private users for a comparable toolset, totalling 7.5 billion Swiss francs undiscounted and 3.5 billion Swiss francs discounted. Since the potential of such a new ecosystem relies on a commitment for development, the adoption by communities beyond high-energy and particle physics, the value was only considered as a wider benefit.

The knowledge-transfer office records of the last two decades have shown that a stable number of companies have been created every year by persons who were engaged in CERN's flagship particle collider project and the international experiment detector collaborations. A prominent example includes Proton AG with over 400 employees and more than 100 million customers, offering secure e-mail and VPN as an unparalleled service to other providers. Other examples are Advacam which specialises in imaging devices for various industrial applications based on particle detector technology, LightEye working on LiDAR technology for long-range wind speed measurements to improve aviation safety and PlanetWatch which specialises in data acquisition of environmental data. Based on these factual historical data, it is assumed that FCC-ee would generate approximately two new spin-off companies in the information and computing technologies (ICT) sector alone each year from the design and preparation phase until the end of the observation period. Considering the probability of company survival each year and the annual market value of companies in the ICT sector, the socio-economic benefit is estimated to be at least 832 million Swiss francs undiscounted and 409 million Swiss francs discounted. This figure does not include the economic benefits that are generated by numerous micro enterprises and independent consultants that carry out their activities thanks to the experience and skills they acquired in the frame of large-scale particle accelerator and experiment detector projects.

Some selected environmental benefits that the project could generate were also assessed. They include the voluntary goal of supplying the infrastructure with electricity from renewable energy sources. Entering specific energy supply contracts and long-term power purchasing agreements (PPAs) can serve as a lever to build up new renewable energy sources since the power supplier can secure long-term funding of new renewable energy investment projects before making a financial investment decision. A scenario of a portfolio of complementary energy supply contracts for the FCC construction and operation has been analysed in terms of this value-generation pathway. Assuming that after 2050, society is largely de-carbonised and conservatively, no growing demand for such a funding instrument is assumed on a time horizon of more than 30 years, the reported benefit remains limited: 227 million Swiss francs discounted and 117 million Swiss francs discounted. The development of a renewable energy portfolio can, in principle, begin with an investment decision for a new particle collider project and with a commitment of the project to engage renewable energy sources. In this case, the potential benefit can rapidly turn into a tangible economic benefit. It is suggested that this benefit be revised by that time and reconsidered under the evolving project implementation boundary conditions.

A large part of the energy used to operate the particle collider and its experiments is converted into heat. Traditionally, the heat is dissipated via water-based cooling systems that connect to evaporation towers. A study has been conducted to prove the feasibility of recovering and re-using waste heat. Recovery and supply of waste heat is a concept that is built into the design of the particle collider from the onset. Recovered waste heat will be supplied via district heating networks to consumers in the vicinity of the FCC-ee sites. The environmental benefit stems from the fact that the energy used by the FCC research infrastructure is reused and supplied for heating and cooling purposes, avoiding the use of alternative, mainly non-renewable, sources with higher carbon intensity such as gas, wood, oil and conventional electricity mix. The environmental benefit of waste heat reuse is derived from the avoided GHG emissions in the project scenario, where CERN supplies waste heat—produced using a cleaner electricity mix—to district heating networks serving consumers near the FCC-ee sites. This is compared to the emissions from alternative heating and cooling methods typically used in the CERN region. The total benefit is estimated at 170 million Swiss francs undiscounted, corresponding to 74 million Swiss francs after discounting.

However, turning this potential benefit into tangible socio-economic impacts requires the adaptation of the operation schedule to the demand curve, agreements with district heating operators to establish and operate networks, and customers who commit to using the heat. Since such developments are typically time-consuming, entail territorial developments that last one to two decades, and depend also on local developments around the future surface sites, the benefits are not included in the core net present value calculation. In addition, the potential benefits emerging from the avoidance of greenhouse gas emissions by replacing conventional heat sources are uncertain for the timescale after 2050, when in principle the economy aims at being largely de-carbonised. Together the benefit potentials, i.e., the costs saved by using waste heat instead of conventional heat sources and avoiding greenhouse gas emissions, add up to about 313 million Swiss francs undiscounted and 132 million Swiss francs discounted. Once a decision to move forward with a project has been taken, a revision of these impacts can take place, since a stronger commitment from the project owner also enables regional stakeholders to plan for waste-heat district heating networks and this eventually will lead to significantly increased benefit potentials.

The project only consumes land due to the development of eight surface sites, but it also opens opportunities to create new natural spaces in the immediate vicinity of the sites. Creating or improving those habitats to integrate the surface sites well in their environments can strengthen the natural spaces around the sites, protecting them from further artificialisation and helping to improve the biodiversity, partially compensating for the effects of the loss of space. While today rewilding projects are foreseen in connection with the surface sites, they have not yet been discussed with the local stakeholders and they have not yet been designed. Therefore, this benefit remains potential and is not included in the calculation of the core net present value. The rewilding of habitats and biodiversity could represent an undiscounted value of 0.4 million Swiss francs corresponding to 0.2 million Swiss francs discounted.

The future particle collider will be embedded in a territory that spans an area of roughly 30×30 km. Care has been taken to select locations for surface sites that are in the vicinity of major transport routes. Nevertheless, the current concept implemented at CERN to provide emergency, rescue and fire-fighting services to surface sites of existing particle accelerators from a central fire brigade at CERN becomes unfeasible for a future infrastructure of the FCC scale. Therefore, the safety concept foresees a strong and lasting collaboration with local emergency services. This concept can be based on support with equipment, training, and personnel made available by the research infrastructure. It could help to increase the expertise and skills of local emergency services, contribute with state-of-the-art equipment, strengthen the number of specialists in the region and increase the cooperation and coordination among different emergency services. This benefit potential has an undiscounted value of about 30 million Swiss francs and represents a discounted value of about 16 million Swiss francs. Since it relies on the development and implementation of a safety concept and plan at the territorial level which can require significant amounts of time and adjustments that make the concept implementable, the benefit is not included in the core net present value calculation today.

Furthermore, two other classes of benefits described in the subsequent sections have not been directly included in the overall formula to determine the project's net present value: the economic creation of value added and the public good value.

Complementary analysis of economic value added The economic value added has been estimated in addition to the socio-economic impact by analysing the economic linkages (indirect, direct and induced) during the entire 30-year period covering design, construction and the operation phase of the FCC-ee using the established Input-Output Table methodology [237]. The study estimated the economic and employment effects that are connected to the construction and operation of the new research infrastructure. They are not included in the incremental cost-benefit analysis, since they do not represent the creation of new economic goods and services beyond the research infrastructure, but they lead to economic value added due to the activation of numerous economic sectors in the frame of the research infrastructure-related activities.

These effects primarily arise from the construction of civil structures, particle accelerators and colliders, technical infrastructures, experiments, operating expenses, and personnel-related consumption. This economic analysis was conducted for an infrastructure with two experiments and has not been updated to reflect the current baseline.

Using an economic input-output model, the cumulated expenditure of about 21 billion Swiss francs over a 30-year construction and research operation period could be connected to some 800,000 person-years of employment opportunities, corresponding to almost 30,000 jobs per year via global value-adding chains. In addition to about 6000 directly project-related science, engineering, administration, and management jobs globally, more than 20,000 jobs are needed to provide the goods and services for construction and operation. The host countries, Switzerland and France, and especially the canton of Geneva and the Departments of Ain and Haute-Savoie could benefit most from the operation phase-related expenditures. In total, around 13,000 jobs would be filled or created annually on average in France and Switzerland.

An initial, construction-related investment of 12.1 billion Swiss francs directly generates 5.4 billion Swiss francs of value added globally, generating almost 80,000 person-years of employment, i.e., more than 8000 jobs per year over a ten-year investment period. Including the indirect effects in the production process, value added linked to the investment rises to 11.6 billion Swiss francs, leading to about 180,000 person-years of employment or 18,000 jobs per year during the investment period. Widening the system boundaries to include depreciation (i.e., the capital stock firms need to build up or replenish in order to cope with the FCC-related production), the FCC-related value added grows to more than 14 billion Swiss francs and leads to more than 230,000 person-years of employment opportunities or 23,000 jobs per year during the investment phase. All types of companies, large, medium and small, can enjoy the benefits from the value added. The countries that can profit from these benefits depend on the procurement strategy chosen. The construction sector benefits the most, as almost half of the investment volume can be attributed to civil engineering. Along the cycle, however, its share steadily declines, while the shares of most other sectors rise.

The operation of the FCC generates value added by paying wages and social security contributions and through the depreciation of the investment. No (net) operating surplus is considered since CERN, a purely scientific research organisation, is not profit-oriented. The direct value added during the operation phase is estimated at around 455 million Swiss francs annually. For operation, a mix of inputs (intermediate goods and services) is needed, whose procurement will provide suitable firms with the opportunity for sales and employment and thus generate about 165 million Swiss francs of indirect value added annually. The total direct, indirect and induced value added during the operation phase of more than 620 million Swiss francs per year supports 8400 jobs, the majority in France and Switzerland. The buildup and supply of renewable energy sources for the operation of the research infrastructure would raise Europe's value added by another 500 million Swiss francs, securing an additional 7400 person-years of employment in Europe. By economic sector, the structure of the consumption effects is markedly different from the effects of the investment and operating expenditures: real estate activities, (retail) trade, personal services and the hospitality sector are the main beneficiaries of the consumption of project-related employees.

The lower limit for annual tourism spending due to the project in the wider Geneva region is at least 130 million Swiss francs per year. Switzerland and France share the bigger part of the total effects, with around 1700 jobs linked to visitors only. Another 500 jobs are European; the rest – around 600 – are filled outside Europe. Globally, tourism effects would sustain about 2700 jobs.

The consumption of electrical energy in the frame of long-term power purchasing agreements would generate a direct value added due to the capacity build-up activities of about 200 million Swiss francs, linked to 3500 person-years of employment. Including intermediate inputs and investments needed to produce and install the equipment, the contribution to Europe's value added rises to 510 million Swiss francs, securing 7400 person-years of employment in Europe. Worldwide added value effects related to the electricity supply sector amount to 620 million Swiss francs or 11,600 person-years of employment.

These figures must be interpreted with some caution. Most importantly, the indirect jobs are derived under the assumption of a steady state. The estimates do not project major economic variables into the future (exchange rates, price levels and productivity being the most important ones). Therefore, the effects are estimated as if the FCC were constructed and operated today. This should not be considered a shortcoming, as it helps decision makers to grasp the effects of the estimates more easily when referring to a familiar frame of reference – the economy as it is today. The resulting figures on value added are less compromised by this simplification, due to the fact that the evolution of economic key performance parameters cannot be forecast on the timescale of an FCC project with construction starting in the mid-2030 s and coming into operation in the late 2040 s. The employment figures linked to the expenditures represent reliable upper bounds since labour productivity is expected to rise. Even under changing economic conditions, the FCC would remain what it is today – a major undertaking for the scientific community and society at large, with likely significant scientific, technological, engineering and economic impacts.

The analysis shows that the costs that a project like the FCC entails are also connected with tangible economic impacts in terms of sales 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. Therefore, even though the narrow economic linkages of the construction and operation are not larger than would be expected for a project of this size, the potential for spillovers into quite unrelated areas of technology and business is certainly much more pronounced – for example, only a few projects would have the touristic attractiveness, not to mention their technological and scientific potentials.

Also, by estimating the regional structure of the effects linked to the construction and operation of the FCC, the analysis has shown that the connection between contribution to CERN, direct contracts, and indirect benefits is not always clear-cut. For example, China and the United States, which are not member states of CERN, are estimated to have sizeable economic benefits due to their prominent roles in global value chains. This information could form the basis for negotiations between CERN and countries such as China on intensifying and formalising closer collaborations in the future, which would be beneficial for both parties.

Public good value To gauge the volume of the societal benefits, a comprehensive survey was conducted among nearly 10,500 individuals across nine countries [176], including both CERN member and non-member states potentially contributing to the future particle collider project at CERN. The survey aimed to assess public awareness of CERN and its research activities, to evaluate the perceived value of a new research infrastructure, like FCC, to the public, and to compare this monetised value with the per-capita annual contributions made by CERN member states.

The public good value should not be integrated in the estimate of the project's net present value, since the perceived value of the project, i.e., the value that taxpayers associate with the project, is orthogonal to the actually estimated incremental benefits. Measured through the willingness to pay, the public good value also depends on the knowledge of the project, its costs, negative externalities, and likely incremental benefits. Hence, the value of it is affected by some cognitive biases, such as, for instance, an information bias. The presence of such bias is not negative and cannot be avoided. They are part of the mechanism that permits people to associate a value to an asset to which they have no direct access.

Results indicate that 41% of the respondents are aware of CERN and its mission, which, although lower than some other international organisations like NASA, remains generally positive. Over 80% of respondents believe that scientific research at CERN advances our understanding of the universe and contributes to improving quality of life. The hypothetical willingness to participate financially in the development of the new research infrastructure project was assessed, revealing varying distributions by country. Median values range from 2 Swiss francs per person per year in France to 20 Swiss francs in Switzerland, both CERN member states. For non-member states, the median willingness to pay (WTP) varies from zero in Japan to 24 in the USA (although the mean value for Japan is 10 Swiss francs, meaning that a significant fraction of the Japanese adult population values that type of scientific research). The total value was estimated by multiplying the estimated per capita yearly WTP by a total adult population of about 380 million persons over 30 years in the CERN Member States, starting with the first relevant investments.

In all observed cases, the perceived public value in CERN's member states is higher than CERN's annual operational budget of 1.4 billion Swiss francs. The average per capita contribution in these states is approximately 2.5 Euro per year or about 5 Euro per income taxpayer per year. The total estimated WTP for a future collider project at CERN surpasses the estimated total costs of the FCC by a factor of 20 and exceeds its quantified benefits by over 11 times.

These findings robustly support the conclusion that the decision to invest in a future particle collider programme at CERN can be considered justified from a societal perspective since the people who potentially fund the endeavour assign more value to it than it costs in total.

4.8.7 Conclusions

The socio-economic impact analysis is based on a social cost-benefit assessment conducted on the first phase of the FCC programme, spanning a time frame of 40 years from the financial investment decision to the end of operation. The FCC-ee has quantified costs, negative externalities and conservative benefit potentials and wider benefit potentials across various domains. Costs of about 20 billion Swiss francs discounted and negative externalities of about 354 million Swiss francs can be compared to the benefits that this research infrastructure can generate. The total present value of the monetised core socio-economic benefits associated with the FCC-ee research infrastructures has been conservatively estimated at a discounted value of 24 billion Swiss francs. Additional wider benefits amount to about 7 billion Swiss francs discounted. The infrastructures would represent a residual value of about 2.5 billion Swiss francs for a subsequent hadron collider, made available as a 'gift' to this second project.

The conservative estimate for the net present value (NPV) of the project over its entire observation period is about 4 billion Swiss francs, yielding a positive benefit-cost ratio of about 1.20. Including the residual asset values can bring the NPV to about 6.5 billion Swiss francs. Extending the estimates with wider benefit potentials, the project provides an opportunity to reach an even higher NPV. However, achieving such a performance requires the design, planning, and implementation of benefits, as well as generating measures with commitments and continuous monitoring and tracking at the level of CERN and international collaboration. Proper risk management and cost control must be in place to manage costs and negative externalities.

Costs were based on the currently available investment cost estimates and on the experience of operating CERN's particle accelerator and collider complex over the last two decades. The most noteworthy negative externalities were identified, quantified and monetised using lifecycle analysis methodologies and guidelines at the European level for wider socio-economic impact assessment and project appraisal. Cost values were currency and time value adjusted for 2024 as the base year.

Benefits have always been appraised through a conservative methodology, drawing on the current understanding of the project, insights garnered from analogous past research infrastructures, and socio-economic impact analyses on the LHC [192] and the HL-LHC [118] that were carried out as pre-cursors, anticipating the need to eventually produce an FCC socio-economic impact study.

Additionally, recent data collected between 2020 and 2024 has played a crucial role in shaping these estimations. To ensure a comprehensive perspective, data gathering efforts included over 16,000 individuals through online surveys. This diverse group included members of the public, visitors to CERN, users of platforms like Zenodo and Indico, as well as former researchers.

In a likely scenario between optimistic and pessimistic assumptions, the quantified benefits exceed the total costs associated with the design, construction, and operation of FCC-ee, resulting in a net positive socio-economic impact for the project.

Should a financial investment decision be taken to proceed with a construction project, it will be necessary to update the assessment during the coming years and to compile all the materials necessary to obtain funding from participating countries and seek authorisations from the host states.

The approach used in this analysis intentionally entirely excludes the uncertain and unforeseeable impacts of knowledge increase generated by the science mission on society because of their inherent unpredictability.

The assessment of the public good value of the research infrastructure for the public offers an insight into the overall benefits of a future particle collider project at CERN for society, gauged through the public's perspective and willingness to financially contribute to a project's implementation. The insight that the perceived value of a future research infrastructure project exceeds the costs of the FCC is important evidence that the public values such scientific research more than it actually costs and thus helps obtain the Social Licence to Operate (SLO).

While recognising the need for refinement, this analysis serves as a tool to inform decision-making, optimise user engagement, identify and mitigate risks, and enhance social acceptability for the FCC-ee project. The findings emphasise that the FCC-ee project holds the promise of positive impacts not only for the scientific community but for all of society, thereby contributing to the project's long-term sustainability.

4.9 Returns to participating countries

4.9.1 Overview

Several economic analysis organisations (e.g., LSE [179], WIFO [238]) have been consulted to analyse how potentially participating nations can increase the likelihood of benefiting from financially contributing to the project. An example set of those proposals is compiled in this section.

There exists a consensus among experts that international organisations, including CERN, generate significant economic and societal impacts beyond their core activities in their host countries and their participating nations.

One existing concept to ensure a continuous return to the participating countries is the International Liaison Officer (ILO) approach for integrating national companies in the procurement processes of the international organisation. This approach was studied by economists, and it was found that for a future large-scale project, a more structured and comprehensive approach could lead to better returns for the participating nations.

The recommended measures [179] to ensure good returns to the financially participating nations revolve mainly around three topics:

1. Industry benefits
2. Training benefits
3. Cultural benefits

One lever to ensure good returns is to increase the sustainability of spreading the benefits of procurement, by enabling more firms across the various regions to successfully participate in future collider-related procurement and to tap into the value chain created by the contracts. This concerns:

- Levelling the playing field so that more firms can participate in the procurement process, for example by adopting standard tendering procedures (e.g., publishing opportunities on the EU TED platform using NACE codes) or by unbundling large contracts into smaller lots, thereby facilitating the participation of SMEs (see Sects. 3.3 and 3.5 in Ref. [179]).
- Supporting SMEs as these are the firms that are most likely to face barriers in the procurement process.
- Embedding more firms in the procurement value chain.
- Decarbonising the procurement supply chain through aggregated energy supply contracts or power purchase agreements (PPAs) and energy communities that permit pooling renewable energy contracts for groups of suppliers and larger procurements.

Another lever is to foster brain circulation. CERN is an attractive place for people from across the world to study and work. However, many of these talented individuals end up remaining abroad once their project involvement ends, leading to what is often referred to as brain drain for their country of origin. In order to ensure that more places benefit from human capital formation in a virtuous process of brain circulation, the following policies can help:

- Understanding the local needs for talent so that Member States and their regions can target the repatriation of people better.
- Attracting CERN alumni through tailored initiatives.
- Boosting connectivity so that sending and receiving regions benefit from human capital development.

A further lever is to extend the benefits of tourism and to increase it to more regions. With the new Science Gateway, each year 300,000 to 400,000 people visit CERN. However, most of the benefits accrue in a small geographic perimeter in Switzerland and France, where CERN is located. One way for more regions to tap into this is to ensure that the larger FCC perimeter benefits from the on-site visits. Then, further developments can take place to turn CERN into a gateway for science tourism.

Economists have developed proposals that can be considered in the project development phase to help participating nations to reap the most from the opportunities that a new large-scale project offers. One possibility for a contributing country would be to establish a national organisation with dedicated staff that aims to develop the most suitable matches between the country's competencies and interests and the project. This activity goes beyond classical industrial liaison. It aims to integrate schools, universities, research centres, companies of all sizes and national funding agencies through development policies and concrete actions with the project. This requires in-depth knowledge about the project, ensuring that the organisation's personnel is involved long-term to be able to build up durable links and gain comprehensive knowledge of the landscape of national competency and capacity. While the remit of such an organisation would be broader than existing liaison structures, its format could build on comparable initiatives such as CERN's Industrial Liaison Officers (ILOs) and the EU's National Contact Point (NCP) networks, which are explicitly referenced in the policy recommendations of both the LSE [179] and WIFO [238] reports as effective examples of small, dedicated coordination mechanisms.

The direct revenue from procurement contracts is only considered the tip of an iceberg of potential impacts. Long-term returns can exceed those from direct contracts by far. They include:

- Repatriation of people and acquisition of highly skilled and trained personnel from the project.
- Training nationals at all levels for limited periods abroad.
- Using the project as a pilot factory, demonstrating technologies, bringing technologies to market and entering new markets.
- Build durable transnational value chains, using the project as a motor for national innovation, leveraging national funds.
- Connect companies of different sizes.
- Break up research silos by bringing universities and institutes from different disciplines together around a single science project.

The entire concept aims to overcome the information asymmetries that privilege only a few companies and universities that benefit from historical links, which enable them to benefit from CERN's large-scale science projects.

All efforts to plan for a good return on investment for financially participating countries rely on a systematically established analysis, tracking, and regular evaluation of socio-economic performance that can adapt the project. Sufficient evidence exists regarding the socio-economic benefits of CERN's activities through various pathways; however, a gap remains in understanding what is needed to increase and sustain these effects. Making data gathering and evaluation an integral part of the FCC project can help set goals for data collection and the methodological approaches to measure these effects.

The recommendations documented by LSE and WIFO for ensuring good returns for participating nations provide specific and tangible examples of successful cases for each policy recommendation based on past initiatives. A significant advantage of several proposals is their standalone nature: they can be implemented individually. Many of them can also be implemented independently by countries and regions, allowing them to reap benefits from a project without involving other participating nations.

4.9.2 Local employment opportunities

A future research infrastructure with additional territorial development can lead to territorial benefits through direct employment, goods and services supply, as well as indirect and induced job opportunities in a wider perimeter than currently covered by CERN's activities. Indirect and induced impact not only concern the value chain of regionally supplied goods and services, i.e., further materials and service suppliers to satisfy the needs of

FCC suppliers and jobs that satisfy the needs that emerge from the presence of personnel associated with FCC construction and operation in the vicinity of the surface sites. The federation of certain activities that relate to the construction and operation, i.e., services that are research infrastructure enablers at certain locations, can also create new and durable territorial employment opportunities. Such services include, for example, during the construction project planning, project management, construction site preparation and operation, and business services (e.g., accounting, human resources, IT, land plot management). Services for the operation phase include, for instance, surface site surveillance and safety, technical operation services, technical maintenance, operation of visit facilities and general business services, as is the case with the construction phase.

The economic impact potentials, in particular the employment-related effects, are still under study and development of the relevant supplies and services as well as the locations where they would be supplied. Preliminary analysis points to opportunities in the range of 1000 to 2000 jobs over a sustained period of time until the end of the century. The effects are mainly linked to household expenses generated by those persons, representing per year about 219 million euro for the region Auvergne-Rhône-Alpes. Direct tax-related benefits are estimated to be in the range of 2.6 (regional) to 3.3 (national) million euros per year. Indirect and induced tax-related impacts range between 3.6 (regional) and 4.1 (national) million euros. The main sectors that would benefit from these are trade, housing, specialised construction works, civil engineering and public works, commerce, manufacturing and specialised equipment, materials processing, financial and insurance services, chemical processing, energy production and distribution, cultural goods and services, restoration, and telecommunications.

These preliminary results should be taken with caution, as the project scenario, construction, and operational organisation are at a very early stage and are subject to ongoing development.

4.9.3 Opportunities for impact generation

The following policy recommendations to generate regional returns in a global project are examples drawn from studies conducted by independent economic research organisations.

- Participating nations build up national support organisations to connect various actors (companies, universities, research centres, innovation hubs, national funding agencies) to the new research project to leverage beyond pure contract acquisition as much as possible:
  - Piloting technologies.
  - Bringing technologies to market.
  - Training people.
  - Exploit the scientific research opportunities.
  - Leverage national funding for developments motivated by the new project.
  - Attracting highly qualified and trained people via job fairs.
  - Transferring knowledge from the project to universities and companies.
- Move to a standard tendering approach, which includes adopting standard keywords and codes and publishing tendering opportunities to a wider audience, such as in the Supplement to the Official Journal of the European Union (TED). This can reduce search costs for firms and increase the opportunities for small and medium enterprises (SMEs).
- Use the standard international NACE[22] code system to ensure that companies receive requests for participation that match their competencies well and to ensure that countries can make an efficient match of their specialisations to the project's needs.
- Establish dedicated support centres within local business association offices in regions with concentrated clusters of firms active in the project relevant sectors. These centres will offer specialised support to regional SMEs aspiring to engage in the procurement process.
- Unbundle large contracts to enhance the possibility of SMEs to participate in the procurement process while making the supply chain more resilient.
- Set aside lower value contracts for SMEs, if they meet competitiveness criteria for quality and price.
- Conduct value chain mapping for the different technologies required to understand the spatial distribution of procurement activities and for regions to better understand the local competitiveness opportunities.
- Set up Local Content Units (LCUs) as separate bodies or functions to be developed within existing regional development agencies in areas where important CERN suppliers are located. They may also be established and coordinated directly by CERN as a 'local economic impact acceleration unit'.
- Create alliances between regions with project-relevant sectors to facilitate interregional collaboration and the sharing of knowledge.

[22]The Statistical Classification of Economic Activities in the European Community, commonly referred to as NACE (for the French term 'nomenclature statistique des activités économiques dans la Communauté Européenne'), is the industry standard classification system used in the European Union.

- CERN could facilitate energy supply contracts or aggregate power purchase agreements (PPAs) by acting as an anchor tenant or encouraging the creation of consortia. Alternatively, energy supply contracts or PPAs can be created for larger procurements and groups of suppliers can be created in the frame of dedicated supplies. Also, energy communities that exist in other countries are an effective example of obtaining electricity for production and manufacturing purposes from renewable energy sources. Conditions can be included in procurement requirements.
- Regions identified as talent contributors should conduct a comprehensive analysis of the type of skills that the region needs to attract with a special focus on profiling homegrown talent that has left the region to join CERN.
- Create and promote opportunities through grants and fellowships targeting high-skilled individuals to move to their regions.
- Provide repatriation incentives to return to their home region for individuals who stayed at CERN.
- Engage with CERN staff and alumni abroad through knowledge exchange and entrepreneurship programmes, mentorship schemes and awards.
- Together with tourism boards and other research facilities, develop science tour packages that feature additional scientific attractions across Europe and technology hubs in combination with other activities.
- Establish a funding stream for sustained socio-economic impact evaluation and data collection from the outset of the FCC project.
- Operate an Open Data portal that attracts social scientists to use CERN to continue to evaluate the socio-economic impact of investment in science.

4.10 Requirements and constraints for a preparatory phase

The subsequent design and preparatory phase requires a more detailed design of the technical infrastructures, based on systematically identified and properly structured and documented requirements for the particle collider and the experiments. This documentation must be used to conduct a life cycle analysis (LCA) in accordance with the standards and best practices already employed for the analysis of the construction footprint.

Due to the absence of a detailed design, the long time scales, and the need to develop a particular procurement scenario for a study, a more high-level approach can be taken for the estimation of the potential climate effects of the particle accelerators and experiments. However, much care must be taken to avoid an approach that is too simplistic and only focuses on the generic analysis of the carbon footprint of the assumed materials. As far as possible, full systems should be considered; where this is not feasible, reasonable assumptions about the manufacturing, assembly, and installation processes must be made and included in the analysis.

Concerning the use of renewable energy, it is important to establish an energy procurement team that can anticipate the development of supply contracts or purchase agreements. The team needs to develop a strategy and prepare for establishing an energy supply portfolio, taking into account the test, commissioning, and operational phases. The preparation for procuring energy for the construction phase is to start as soon as possible. A time frame of ten years is considered adequate for the preparatory and procurement process of renewable energy for the operation phase.

The potential of waste heat supply and reduction of water consumption depends on national stakeholders putting district heating networks in place and working with CERN on water treatment and supply of treated water at a regional level. Therefore, dedicated local designs, operational plans and pilot schemes will need to be put in place before the research infrastructure is assumed to enter the operation phase. A time window of 20 years is adequate, considering authorisations, financing, the establishment of local operators and the connection of consumers to the district heating network.

With respect to landscape integration, the development of rewilding projects, the use of excavated materials and the design of compensatory actions need ample time for working with local and regional stakeholders. This also requires the allocation of dedicated project-internal resources to establish contracts with external partners and to work together with them, the communities, and public administration. Several years should be allocated for building up these capacities. Hence, a schedule that provides flexibility in working with local and regional stakeholders is needed, thereby avoiding the build-up of excessive pressure. Such pressure can be counterproductive to achieving mutual agreements and consensus on territorial development projects, as well as generating socio-economic benefits at all levels.

4.11 Recommendations for a preparatory phase project

This section presents a set of recommendations that have been derived from the work presented in this analysis. Their purpose is to ensure that the benefits can be monitored and regularly reported so that the updated findings can be integrated in the infrastructure's design, construction, and operation phases.

The socio-economic study showed that a break-even of costs and benefits can be achieved with the FCC-ee research infrastructure with the impact pathways documented so far. However, the potential can only be fully exploited if a continuous tracking of socio-economic impacts is integrated in the infrastructure's design, construction, and operation phases. To achieve this objective, nine recommendations have been made to the FCC project owners by the expert group of economists (CSIL, LSE, WIFO, University of Milano, Economic University of Vienna) who have been involved in the socio-economic studies so far.

1. **Allocate adequate personnel and material resources for the impact identification, design, planning, implementation, monitoring, and assessment** to help fully leverage the impact potentials and make FCC a socio-economically sustainable endeavour. The personnel need to be empowered so that the results of the impact assessment and the impact generation recommendations are accommodated in the design where appropriate, that they are implemented, and that they are continuously and systematically monitored. Also, the analysis should be carried out with the help of all participating project members. This requires that the socio-economic impact assessment is implemented across the entire organisation, with the direct involvement of the highest managerial level and reporting directly to CERN's key stakeholder, the Council. This approach is expected to secure the sustainability and effectiveness of the process, as well as help enhance project acceptance among financially contributing countries.
2. **Encourage participants to publish scientific and engineering works via gold open access channels** (as opposed to self-publishing) **and reputable outlets** (as opposed to depositing information in preprint servers only). This ensures proper identification of work for tracking purposes and increases the likelihood of their uptake. This socio-economic impact assessment study has revealed challenges in identifying all the scientific output associated with the research infrastructure activities. It is essential to track the scientific production of researchers involved in experiments and monitor citations across papers and other scientific products. However, scientific outputs lacking proper unique digital identifiers and citation references, as is often the case with workshop proceedings and presentations available on platforms like the CERN-developed Indico [239], cannot be adequately identified and considered for socio-economic valuation. These types of outputs should, whenever possible, be replaced or supplemented by citable reports or papers. Establishing strategic partnerships with leading publishers, as exemplified by the SCOAP3 [240] project, is a suitable approach to ensure the presence of citable publications. Open-access platforms used for dissemination could integrate download, citation and reference tracking if they do not already offer those functions (e.g., Zenodo [241] and ArXiv [242] currently lack these functions). Furthermore, additional research is necessary to expand the monitoring and tracking of scientific content beyond scientific and engineering articles and presentations to include books to better understand the societal uptake of knowledge acquisition within the FCC programme.
3. **Foresee a framework to monitor the movement of people after they leave the project**, to facilitate the analysis of future career developments. Every individual contributing to the project for a minimum duration should be encouraged, on a voluntary basis, to engage in a comprehensive monitoring programme. Thanks to mechanisms to reconnect with them periodically, this initiative would entail long-term follow-up and periodic collection of a set of basic information concerning their current work position.
4. To ensure the effective analysis of industrial spillovers generated during project implementation, **incorporate systematic monitoring of the incremental economic impacts on suppliers** resulting from procurement actions over multi-year periods. Given that these effects may not manifest immediately and can extend beyond the duration of the procurement contract, it is crucial to obtain feedback from the companies involved. This necessitates the establishment of a comprehensive procurement monitoring framework that facilitates ongoing engagement. Such a framework should include provisions for storing information on the individuals initially involved in the contract, enabling periodic follow-up after the contract's conclusion. Additionally, it should facilitate the collection of essential information regarding the spillover effects on the company generated by the procurement experience with CERN. This can be achieved through mechanisms such as short online surveys designed to gather pertinent data. By implementing this approach, the FCC programme can gain valuable insights into the long-term economic impacts of its procurement activities, fostering continuous improvement and enhancing collaboration with industrial partners.
5. **Information and Communication Technologies (ICT) have been identified as a key impact pathway that should be better leveraged** through society-targeted transmission actions, accompanied by systematic monitoring of uptake. CERN and the FCC represent a globally unparalleled environment for the development of software and platforms to serve the needs of global collaborations, which are in high demand across societal and industrial sectors as well. By identifying the specific requirements of such collaborations and initiating dedicated development projects, the potential for widespread adoption beyond the FCC project can be created. Examples include collaborative event management, document creation, communication (both one-to-one and one-to-many), file sharing, information management, social networks, remote operation, cybersecurity, distributed computing, and data processing. CERN and its member states should ensure that the technologies developed are accessible at no charge to users outside the high-energy and particle physics community, while also guaranteeing long-term maintenance and improvement. This requires making software and tools available on platforms that support download and installation tracking. The lack of such data has been identified as one of the limiting factors hindering the accurate estimation of ICT impacts.

6. With respect to the impact of spin-off companies, **there is a need to establish a systematic method for tracking companies founded by former participants in the FCC programme, monitoring their evolution over time, and assessing their economic value**. The establishment of new companies that leverage knowledge acquired through the FCC programme represents a significant societal benefit. Notably, spin-offs often emerge from participants' amalgamation of different skills and experiences rather than the direct exploitation of a single licensed technology. In particular, the technologies developed in collaborative R&D projects cannot be attributed solely to CERN, and CERN does not track the technologies of its collaborating partners. However, to accurately gauge the economic and societal benefits generated, a voluntary, systematic tracking mechanism is essential.

   This tracking framework should facilitate a comprehensive assessment of the impact of spin-off companies. It could include the establishment of a centralised database to record information about spin-off companies (such as their founders, country, industry sector, products/services offered), and have the possibility to periodically contact them to provide updates on their companies' progress.
7. The study revealed the relevance of economic benefits due to on-site visitors. To ensure sustainable monitoring of the on-site tourism impact pathway, CERN and the FCC collaboration should **establish a unified framework to continuously collect essential data on visitors to CERN's exhibition centres, the experiments and any other relevant visit site**. A systematic tracking mechanism for visitors is indeed necessary to accurately report on the effects of on-site visitors. Visitors should be requested to provide a small set of basic information, including their country of origin, mode of transport to Geneva, the main purpose of the visit, duration of stay, visitor spending, and feedback on the exhibitions and the visit sites (e.g., their level of satisfaction). By implementing this monitoring framework, it will be possible to effectively track and evaluate the cultural impact of on-site visitors, as well as enable continual enhancement of visitor experiences.
8. The **identification and quantification of environmental benefit potentials and the development of dedicated projects should be intensified.** The identification and analysis of environmental benefits are important for social acceptability and for achieving a net-zero balance of the scientific research activities for society. This requires the establishment and empowerment of economic and environment experts in the upcoming project preparatory phase, as well as intensified cooperation with industrial partners and Host State services, to ensure a reliable identification of potential environmental benefits and costs associated with the project. In addition to the creation of renewable energy sources and the reuse of waste heat and excavated materials, further opportunities may be uncovered through additional research and extended discussions with project stakeholders. For instance, impact pathways related to water usage, land management, biodiversity conservation, and transport infrastructure need thorough investigation. Assessing potential negative environmental impacts is equally important. Understanding and mitigating adverse effects, such as pollution, is critical for achieving sustainable outcomes and ensuring the responsible use of natural resources.
9. **Continuous monitoring of the so-called 'common good value' has been identified as a suitable approach to validate the investments against the expectations of funders, ultimately the taxpayers**. This effort should be strengthened by conducting regular surveys across all potential funding countries, thereby deepening the understanding of how social acceptance can be not only sustained but also enhanced.

   A framework for streamlining this process has been developed within this project, enabling the activity to continue with only marginal additional resources. Expanding data collection to additional countries beyond those already surveyed can provide insights into the factors influencing the people's perception of the FCC science mission. The findings should be regularly shared with CERN management and the Council and summarised for broader dissemination to all stakeholders, including the public, through channels such as CERN's social media platforms and its main websites.

Funding information Open access funding provided by CERN (European Organization for Nuclear Research).

Data availability The authors declare that the data supporting the findings of this study are available within the paper and/or its supplementary information files.

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[243] UAZ, Universidad Autónoma de Zacatecas, Zacatecas, Mexico
[244] University of Jyväskylä, Jyväskylä, Finland
[245] Technische Universität Dortmund, Dortmund, Germany

[246] Overleaf, London, UK
[247] University of Virginia, Charlottesville, VA, USA
[248] Cornell University, Ithaca, NY, USA
[249] FIT, Florida Institute of Technology, Melbourne, FL, USA
[250] Shirokuma GmbH, Zurich, Switzerland
[251] National Centre for Physics, Islamabad, Pakistan
[252] Johannes Gutenberg Universität Mainz, Mainz, Germany
[253] PAEC, Pakistan Atomic Energy Commission, Islamabad, Pakistan
[254] Mathabhanga College, Mathabhanga, India
[255] Harish-Chandra Research Institute, Prayagraj, India
[256] MPIK, Max-Planck-Institut für Kernphysik Heidelberg, Heidelberg, Germany
[257] European Spallation Source ERIC, Lund, Sweden
[258] Centre de calcul de l'IN2P3, Villeurbanne, France
[259] GSI, Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[260] IBS, Institute for Basic Science, Center for Theoretical Physics of the Universe, Daejeon, Republic of Korea
[261] University of Warsaw, Warsaw, Poland
[262] University of Ljubljana, Ljubljana, Slovenia
[263] Jozef Stefan Institute, Ljubljana, Slovenia
[264] Microhumus, Bureau d'étude et d'ingénierie spécialisé dans la gestion des sols dégradés, Nancy, France
[265] Fakultät für Physik und Astronomie, Universität Heidelberg, Heidelberg, Germany
[266] Niğde Ömer Halisdemir Üniversitesi, Niğde, Türkiye
[267] Giresun Üniversitesi, Giresun, Türkiye
[268] University of Miskolc, Miskolc, Hungary
[269] NTUA, National Technical University of Athens, Athens, Greece
[270] Transmutex SA, Geneva, Switzerland
[271] DIAS, Dublin Institute for Advanced Studies, School of Theoretical Physics, Dublin, Ireland
[272] AGH, University of Science and Technology, Kraków, Poland
[273] University of Science and Technology of Mazandaran, Behshahr, Iran
[274] IPPP, Institute for Particle Physics Phenomenology, Durham University, Durham, UK
[275] Bursa Uludağ Üniversitesi, Bursa, Türkiye
[276] YU, Yonsei University, Seoul, Republic of Korea
[277] Affiliated with an international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
[278] CPT, Centre de Physique Théorique, Marseille, France
[279] Aix-Marseille Université et Université du Sud Toulon Var, Marseille, France
[280] KIAS, Korea Institute for Advanced Study, Seoul, Republic of Korea
[281] Carleton University, Ottawa, Canada
[282] FEAC Engineering P.C., Patras, Greece
[283] UPATRAS, University of Patras, Patras, Greece
[284] University of Kansas, Lawrence, KS, USA
[285] AUTH, Aristotle University of Thessaloniki, Thessaloniki, Greece
[286] IML, Fraunhofer-Institut für Materialfluss und Logistik, Dortmund, Germany
[287] RWTH Aachen, Rheinisch-Westfälische Technische Hochschule Aachen, Aachen, Germany
[288] ZHAW, Zurich University of Applied Sciences, Winterthur, Switzerland
[289] Universität Münster, Münster, Germany
[290] University of the Witwatersrand, Johannesburg, South Africa
[291] Fachhochschule Technikum Wien, Vienna, Austria
[292] University of California Irvine, Irvine, CA, USA
[293] Northeastern University, Boston, MA, USA
[294] ESI, European Scientific Institute, Archamps, France
[295] UOS, University of Seoul, Seoul, Republic of Korea
[296] KNU Kyungpook National University, Daegu, Republic of Korea
[297] KU, Korea University, Seoul, Republic of Korea
[298] Tampere University, Tampere, Finland
[299] University of Edinburgh, Edinburgh, UK
[300] BG Ingénieurs Conseils, Lausanne, Switzerland
[301] T.-D. Lee Institute, Shanghai, People's Republic of China

[302] Shanghai Jiao Tong University, Shanghai, People's Republic of China
[303] CNR, Consiglio Nazionale delle Ricerche, Rome, Italy
[304] University of Michigan, Ann Arbor, MI, USA
[305] University of Pennsylvania, Philadelphia, PA, USA
[306] University of Minnesota, Minneapolis, MN, USA
[307] ESRF, European Synchrotron Radiation Facility, Grenoble, France
[308] SUSSEX, University of Sussex, Brighton, UK
[309] Università di Bari Aldo Moro, Bari, Italy
[310] University of Bath, Bath, UK
[311] Scuola Normale Superiore di Pisa, Pisa, Italy
[312] Universidade de São Paulo, São Paulo, Brazil
[313] Universität Graz, Graz, Austria
[314] Center for High Energy Physics, Fayoum University, Fayoum, Egypt
[315] Center of Theoretical Physics, British University in Egypt, Cairo, Egypt
[316] Cairo University, Cairo, Egypt
[317] Sorbonne Université et Université Paris Cité, Paris, France
[318] Università di Genova, Genoa, Italy
[319] IFIC-CSIC/UV, Instituto de Física Corpuscular, Consejo Superior de Investigaciones Científicas/Universidad de Valencia, Valencia, Spain
[320] Service de géologie, sols et déchets du canton de Genève, Geneva, Switzerland
[321] NICPB, National Institute for Chemical Physics and Biophysics, Tallinn, Estonia
[322] UT, University of Tartu, Tartu, Estonia
[323] Universidad de Salamanca, Salamanca, Spain
[324] UGTO, Universidad de Guanajuato, Guanajuato, Mexico
[325] Edaphos Engineering, Geneva, Switzerland
[326] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[327] Tata Institute of Fundamental Research Mumbai, Mumbai, India
[328] Universiteit Gent, Ghent, Belgium
[329] CNR-IOM, Consiglio Nazionale delle Ricerche, Trieste, Italy
[330] JKU, Johannes Kepler Universität Linz, Linz, Austria
[331] University of Stavanger, Stavanger, Norway
[332] Universidad Nacional de Colombia, Bogotá, Colombia
[333] Trento Institute for Fundamental Physics and Applications, Trento, Italy
[334] Caltech, California Institute of Technology, Pasadena, CA, USA
[335] Università della Calabria, Rende, Italy
[336] IFT, Instituto de Física Teórica, Universidad Autónoma de Madrid, Madrid, Spain
[337] UPC, Universitat Politècnica de Catalunya, Barcelona, Spain
[338] Departamento de Física, Universidade do Minho, Braga, Portugal
[339] Centro de Física das Universidades do Minho e do Porto, Porto, Portugal
[340] LaPMET, Laboratory of Physics for Materials and Emergent Technologies, Porto, Portugal
[341] University of Bergen, Bergen, Norway
[342] SAPHIR, Instituto Milenio de Física Subatómica en la Frontera de Altas Energías, Santiago, Chile
[343] Universidad Andres Bello, Santiago, Chile
[344] IIP, International Institute of Physics, Natal, Brazil
[345] Tokyo International University, Tokyo, Japan
[346] Izmir Bakırçay Üniversitesi, Izmir, Türkiye
[347] INFN, Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Gran Sasso, Assergi, Italy
[348] Universitá degli Studi di Cassino e del Lazio Meridionale, Cassino, Italy
[349] Vinča Institute of Nuclear Sciences, Belgrade, Serbia
[350] Kennesaw State University, Kennesaw, GA, USA
[351] Università di Pavia, Pavia, Italy
[352] Columbia University, New York, NY, USA
[353] Department of Energy of the United States of America, DOE, Washington, DC, USA
[354] IPSA, Institut Polytechnique des Sciences Avancées, Ivry-sur-Seine, France
[355] Università degli Studi del Sannio, Benevento, Italy
[356] UJ, Jagiellonian University, Kraków, Poland

[357] Universität Wien, Vienna, Austria
[358] Goethe-Universität Frankfurt, Institut für Angewandte Physik, Frankfurt am Main, Germany
[359] HFFH, Helmholtz Forschungsakademie Hessen für FAIR, Frankfurt am Main, Germany
[360] INCDTIM, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj-Napoca, Romania
[361] University of Arizona, Tucson, AZ, USA
[362] Technische Universität Dresden, Dresden, Germany
[363] RTU, Riga Technical University, Riga, Latvia
[364] Lancaster University, Lancaster, UK
[365] University of Cyprus, Nicosia, Cyprus
[366] Cosmos Open University, Nicosia, Cyprus
[367] CBPF, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[368] Universität Bonn, Bonn, Germany
[369] CMU, Chiang Mai University, Chiang Mai, Thailand
[370] JLAB, Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
[371] ESPOL, Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador
[372] IRB, Rudjer Boskovic Institute, Zagreb, Croatia
[373] Air Liquide Advanced Technologies, Grenoble, France
[374] VU Amsterdam, Amsterdam, The Netherlands
[375] INGÉROP, Groupe d'ingénierie et de conseil en mobilité durable, transition énergétique et cadre de vie, Lyon, France
[376] Warsaw University of Technology, Warsaw, Poland
[377] IFCA, Instituto de Física de Cantabria, Santander, Spain
[378] Institut für Beschleunigerphysik und Technologie, Eggenstein-Leopoldshafen, Germany
[379] Uşak Üniversitesi, Uşak, Türkiye
[380] ICEPP, International Center for Elementary Particle Physics, University of Tokyo, Tokyo, Japan
[381] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK
[382] All Souls College, University of Oxford, Oxford, UK
[383] Akdeniz Üniversitesi, Antalya, Türkiye
[384] Latitude Durable SARL, Geneva, Switzerland
[385] USAL, Universidad de Salamanca, Salamanca, Spain
[386] PRISMA+ Cluster of Excellence, Mainz, Germany
[387] Michigan State University, East Lansing, MI, USA
[388] Universidad Complutense Madrid, Madrid, Spain
[389] scMetrology SARL, Geneva, Switzerland
[390] IST, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal
[391] CeFEMA, Center of Physics and Engineering of Advanced Materials, Lisbon, Portugal
[392] Indian Institute of Science Education and Research Mohali, Mohali, India
[393] NIU, Northern Illinois University, DeKalb, IL, USA
[394] Banaras Hindu University, Varanasi, India
[395] Comenius University, Bratislava, Slovakia
[396] Monash University, Melbourne, Australia
[397] Slovak Academy of Sciences, Bratislava, Slovakia
[398] KAIST, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea
[399] Amberg Engineering Chambéry, Chambéry, France
[400] Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[401] University of Tennessee, Knoxville, TN, USA
[402] IFIC-CSIC/UV, Instituto de Física Corpuscular, Consejo Superior de Investigaciones Científicas/Universidad de Valencia, Valencia, Spain
[403] WIFO, Österreichisches Institut für Wirtschaftsforschung, Vienna, Austria
[404] Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[405] Mélica, NATURA SCOP, Études et expertises environnementales, Aubenas, France
[406] Università LUM, Casamassima, Italy
[407] University of Twente, Enschede, The Netherlands
[408] Arak University, Arak, Iran
[409] Università di Trieste, Trieste, Italy
[410] ForestAllia, Cabinet de gestion et d'expertise forestières, Besançon, France

[411] Universität Siegen, Siegen, Germany
[412] University of Oregon, Eugene, OR, USA
[413] Universität Rostock, Rostock, Germany
[414] CEGELEC SA, Geneva, Switzerland
[415] KTH, Royal Institute of Technology, Stockholm, Sweden
[416] OKC, Oskar Klein Centre for Cosmoparticle Physics, Stockholm, Sweden
[417] Brigham Young University, Provo, UT, USA
[418] Expert foncier et agricole, Chadrat, France
[419] ITSM, Institut für Thermische Strömungsmaschinen und Maschinenlaboratorium, Universität Stuttgart, Stuttgart, Germany
[420] École Normale Supérieure de Lyon, Lyon, France
[421] CTU, Czech Technical University, Prague, Czech Republic
[422] University of Chicago, Chicago, IL, USA
[423] Baylor University, Waco, TX, USA
[424] University of Birmingham, Birmingham, UK
[425] University of Southampton, Southampton, UK
[426] Swisstopo, Federal Office of Topography, Wabern, Switzerland
[427] Daresbury Laboratory, Science and Technology Facilities Council, Daresbury, UK
[428] IZTECH, Izmir Yüksek Teknoloji Enstitüsü, Izmir, Türkiye
[429] City University of Hong Kong, Hong Kong, Hong Kong