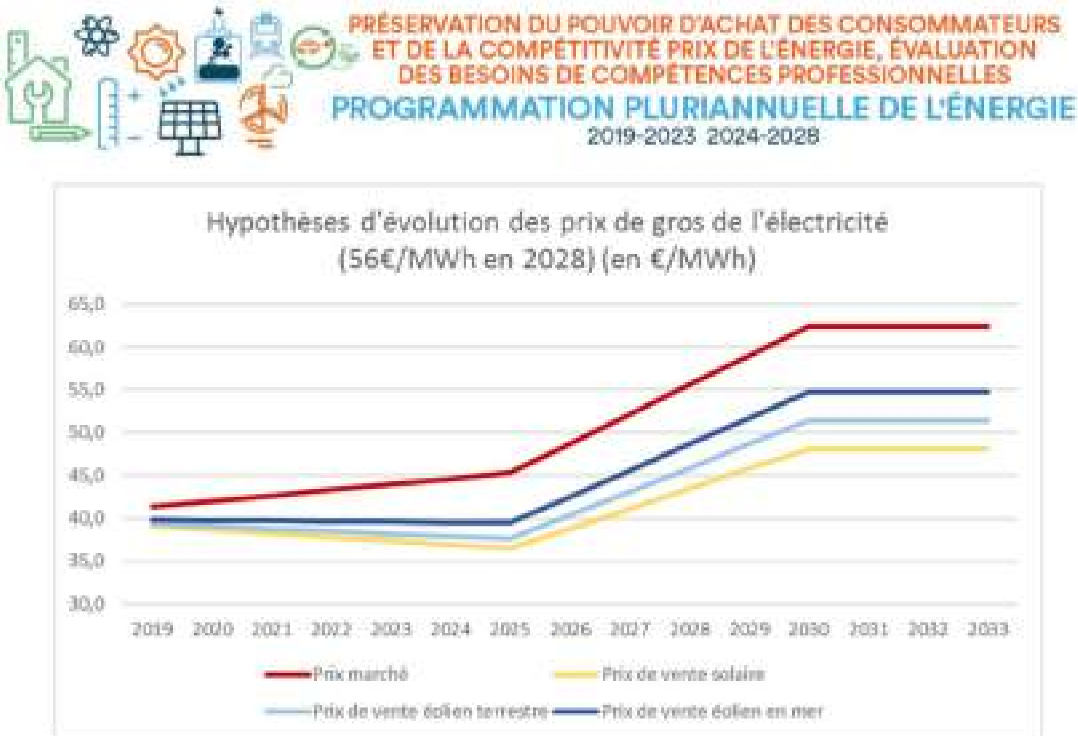

Fig. 3.7 Stated electricity market price targets for 2030 published by the French government in the pluri-annual energy programme [65])

The subsequent project preparatory phase must include the preparation of the power purchasing strategy and a plan for the construction phase. This will serve as a learning experience to develop and negotiate the power purchasing agreement portfolio for the operation phase, which is assumed to start after 2045.

3.2.6 Waste heat use

Almost all of the energy used to operate the technical infrastructures and subsystems of a particle accelerator is eventually converted into heat. Energy used to operate accelerator magnets, amplify radiofrequency energy, absorb synchrotron radiation, air management systems, operate electronics and data processing equipment is almost entirely converted into low-grade heat, typically below 45°C. Temperatures above 50°C, but still below 70°C, can rarely be reached, for instance, when cooling cryogenic refrigeration system equipment and electrical transformers and substations. This heat is typically dissipated in the ambient air via water-cooling and free-to-air cooling systems and is thus lost. Given the amount of heat that particle-accelerator based research infrastructures generate, there is an interest to explore ways to recover that heat and convert it into a valuable resource. The use of the heat for other purposes inside and outside the project boundaries has the following socio-economic benefit potentials:

- Reduction of electrical energy consumption and associated costs due to reduced cooling system operation requirements.
- Reduction of raw water consumption and associated costs due to reduced cooling system operation requirements.
- Increased cooling system lifetime and reduction of associated maintenance and repair costs due to lower operational load on equipment.
- Reduction of heat-generation-related carbon emissions due to the avoidance of dedicated heat production.
- Lower heat costs for consumers.
- Opportunities for creating new economic activities in the vicinity of the heat source.

However, heat recovery and supply also require additional efforts and costs:

- Additional components to recover the heat.
- A dedicated network to transport the heat to where it is needed.
- Potential additional components to raise the temperature of low-grade heat supplied for specific needs.

- Short-term and long-term heat storage systems to ensure supply stability and provide heat when needed.
- The need to refurbish existing buildings and the need for new buildings that are equipped with heating and cooling that function with the low-grade heat.
- The need for a heat supply operator if the heat is used outside the research infrastructure boundaries.

A technical-economic study has been carried out by an expert engineering company to create an inventory of the heat sources in the research infrastructure, to confirm the technical and financial feasibility and, most importantly, to draw up a detailed cartography of the heat demand within the surface sites perimeters. The study also included an assessment of how far heat recovery and supply is technically feasible and economically viable [73–75].

The information gathered was also integrated in the comprehensive, wider socio-economic impact analysis, estimating the contribution to the net present value of the project and subsequently reporting on the overall net benefit. This approach ensures that an informed decision-making process is implemented. If the system is put in place, it is strongly advised that the heat supply is continuously monitored to report on the efficiency of the approach and to be able to further optimise the waste heat recovery and supply process.

Whilst retrofitting heat recovery and supply to existing cooling systems is technically possible, it can be more costly than planning the concept from the onset. Depending on the existing equipment, infrastructures and environment around the particle accelerator facility, retrofitting may be less efficient since the operating temperature of the equipment supplying the heat may not be matched to the consumer needs e.g., magnet water cooling circuit temperatures too low, lack of data centre rack cooling infrastructure, mismatch of the waste heat characteristics with existing district heating networks or missing low-temperature district heating networks and finally lack of space and missing agreements with consumers. It is, however, preferred over no heat recovery. Therefore, from the outset, the FCC project has adopted an eco-design approach that integrates heat recovery and supply into the research infrastructure while embedding it within its broader socio-economic and environmental context.

Waste-heat recovery and supply are already implemented at CERN in the frame of the LHC project. One installation supplies waste heat from the cryogenic refrigeration system at LHC Pt8 in Ferney-Voltaire. A district heating network developed by the company Dalkia for the municipality, supported by the state, the region, and the French environmental organisation ADEME, connects to this surface site. The surface site PA in Ferney-Voltaire is envisaged as an immediate extension of this LHC site, leveraging not only the existing district heating network but also opening a window of opportunity to connect to structured heating networks [76] on the nearby Swiss territory that also supplies Geneva airport and major industrial and commercial facilities as well as residential buildings in the vicinity of the surface site. The second example is the newly constructed data centre at the CERN Prévessin site. Its recovered waste heat will largely cover CERN's campus heating needs. A third example is the heat recovery project at the CERN LHC surface site point 1 (ATLAS experiment) that will supply heat to the CERN Meyrin campus.

The following are examples of equipment that can serve as a starting point for the study of the functionality of integrating heat recovery and supply.

- Normal conducting magnets (recovery of cooling water at temperatures between 25-45°C).
- Normal conducting radiofrequency cavities (cooling water temperature between 25-45°C).
- Synchrotron radiation absorbers (cooling water temperature between 25-45°C).
- Rack mounted electronics (water cooled with a δT of 20 K and a temperature range between 27-49°C on the outer circuit with a temperature range between 39-60°C on the rack cooling circuit).
- Radiofrequency amplifiers of different types e.g., solid state, klystrons, IOTs with a cooling water circuit temperature range between 25-35°C with high stability and low-temperature fluctuation constraint – depending on the case, as tight as 0.1°C. By design, the maximum water temperature at the klystron's collector may be allowed to reach 63°C, but so far, applications operating in this regime are not known.
- Cryogenic refrigeration plants for superconducting components (e.g., magnets, radiofrequency cavities) with equipment cooling circuit water temperatures in the range of 50°C (e.g., compressors) to 75°C (e.g., oil separator).
- Power electronics and converters (temperature range of circuits between 30-60°C for directly water-cooled IGBT systems, for example).
- Electrical transformer stations with water cooling-based systems in the range of 20-70°C (e.g., oil-based transformers).
- Data centres [77] (recovery of 15-20°C air, 40-50°C heat from the CRAHs and 50-60°C from liquid cooling systems).
- Ventilation and air management systems (e.g., heat from motors and air-to-air transfer) from 25 up to about 40°C.

The initial equipment and heat load analysis will inform the designers which components are the ones that produce most of the heat and with which characteristics (stability, temperature). This permits the creation of a hierarchy of heat-producing components that can guide the development of the heat recovery and supply concept.

A multi-criteria analysis with different weights for the individual aspects is a suitable approach for this first step. The analysis process should at least include the following non-exhaustive list of aspects:

- Operational temperature requirements and constraints from the equipment components to be cooled and their temperature variation tolerances.
- Temperatures of the heat recovery potential for the different equipment to be cooled.
- Variability and stability of the heat generation (hourly, daily, weekly, monthly).
- Climatic and weather conditions in the environment of the research infrastructure (for instance, a particle accelerator facility and a data centre operated in the north of Europe permit the use of different heat recovery and supply technologies than in a southern European region).
- Use cases for the recovered heat inside the research infrastructure (e.g., pre-warming of water, offices, workshops, assembly halls, guest houses).
- Demand of industrial heat consumers outside the research infrastructure (e.g., food production and processing industries, offices, hotels, airports, shopping malls, theatres, cinemas, congress centres).
- Demand for heating public spaces and institutions (e.g., schools and universities, hospitals, prisons, train stations)
- Demand for heating of private spaces (e.g., apartment buildings and individual houses).
- Demand for hot water production (the required temperature is above 55°C for sanitary reasons and therefore priming with water boilers and heat pumps may be needed on an individual basis).
- Distances between heat production and consumers (note that distances up to 10 km are feasible with modern pipe technology for low-grade district heating systems in the 50°C range).
- Gap analysis concerning the need for heat buffering (e.g., capacity, space, duration, technology, investment costs, operation costs).
- Investment costs for heat recovery, buffering and supply.
- Operation costs for heat recovery, buffering and supply.
- Capital and operation expenditures outside the system boundary (e.g., district heating network operation host, private heat pumps and priming equipment).
- Public co-financing possibilities.
- Duration and observation period envisaged for the heat recovery and supply.
- Baseline for avoiding fossil energy sources for heating and the avoidance of primary energy for heating. Only the energy for stepping up the temperature for specific end-use cases needs to be considered.
- Definition of the interface between the heat recovery and supply system that is part of the research infrastructure and the segment that is outside the responsibility of the research infrastructure.
- Conditions of the heat supply operator which provides the infrastructure up to the consumer and that supplies the heat with guarantees or with contractual conditions that require the consumer to generate or obtain the gap between supplied and required heat.
- The proposed heat supply technology (e.g., direct, indirect via a loop, indirect via heating the soil or other approaches).

Based on technical designs in the subsequent development phase, all data need to be collected and the most promising heat sources that qualify for a heat recovery case have to be identified. The viable heat consumers have to be confirmed in the frame of a territorial co-development activity. Eventually, the following non-exhaustive list of aspects to tune the heat recovery and supply scenario should be considered:

- Increase of the heat supplied by relaxing the equipment cooling requirements (e.g., water-based magnet cooling up to 50°C, increase of ambient air temperature inside the facility up to 40°C and possibly beyond).
- Validation that mission-critical systems remain within their required operation margins (e.g., increasing the cooling water temperature of klystrons or relaxing their temperature stability may lead to unacceptable performance or render operation unfeasible).
- Total amount of CO_2 emission reduction potential as a result of avoidance of fossil fuel and any primary energy, based on a credible estimate for the energy required to prime the heat for the end-use applications.
- Optimisation of the heat supply by adjusting the operation schedule and introducing the possibility of reacting dynamically to heat needs.
- Adaptation of the particle accelerator operation schedule to the actual societal heat demand to increase the overall socio-economic performance.
- The potentially different energy costs for the research infrastructure operator when adjusting the operation schedule of the particle accelerator or when introducing the capability to dynamically react to both electricity supply and heat demand constraints.
- Additional societal and economic benefits that can be generated by creating new heat consumers in the vicinity of the supplied heat (e.g., food processing industries, agricultural producers, biogas production, thermal baths and recreational installations).

Table 3.1 Waste heat supply potential according to local demand, supply scenario and operation mode

Mode	Minimum supply potential	Adaptation of operation schedule to demand	Adaptation to demand and redistribution between sites
Z	223 GWh/year	308 GWh/year	414 GWh/year
WW	239 GWh/year	339 GWh/year	471 GWh/year
HZ	256 GWh/year	371 GWh/year	529 GWh/year
L.S.	60 GWh/year	60 GWh/year	60 GWh/year
$t\bar{t}$	296 GWh/year	441 GWh/year	710 GWh/year

Table 3.2 One scenario outlining the potential for avoiding carbon emissions by supplying waste heat based on an average of 165 t avoided CO_2 per GWh of heat supplied

Mode	Years	Heat supplied/year	Heat supplied	CO_2 avoided/year	CO_2 avoided
Z	4	308 GWh/year	1232 GWh	50,820 tCO_2/year	203,280 tCO_2
WW	2	339 GWh/year	678 GWh	55,935 tCO_2/year	111,870 tCO_2
HZ	3	371 GWh/year	1113 GWh	61,215 tCO_2/year	183,645 tCO_2
L.S.	1	60 GWh/year	60 GWh	9900 tCO_2/year	9900 tCO_2
$t\bar{t}$	5	441 GWh/year	2205 GWh	72,765 CO_2/year	363,825 CO_2
Total			**5288 GWh**		**872,520 tCO_2**
Operation Scope 2 emissions (for comparison, 20,350 GWh at 25 tCO_2/GWh)					**508,750 tCO_2**

- Introduction of temporary heat buffers (daily, weekly, monthly).
- Availability of specific public co-financing facilities and loans with specific conditions.
- Optimisation of the interface between research infrastructure, operator and heat consumers.

The recovered heat will not be consumed at all times and the consumption pattern will change. Therefore, care must be taken not to under-dimension the cooling, ventilation and evaporation systems for the research infrastructure. If the heat is not consumed or cannot be delivered, it must be possible to cool all components reliably to ensure operation for scientific research purposes.

The techno-economic analysis permitted establishing the demand-based waste-heat supply scenarios based on the three different assumptions shown in Table 3.1.

Based on this scenario, the potential of avoiding carbon emissions in the region by substituting conventionally created heat with waste heat that is largely produced from renewable energy sources can be estimated. Table 3.2 shows the estimates of carbon emissions avoided, based on the following assumptions: an average market-based carbon footprint of 25 tCO_2/GWh of electricity supplied to the FCC. A weighted average of about 190 tCO_2 per GWh of conventional heat produced that can be substituted with waste heat.[6] The resulting net carbon footprint avoided by supplying waste heat is 190-25 = 165 tCO_2/GWh. Comparing the avoidable carbon emissions by supplying waste heat with the range of total Scope 2 related carbon emissions of the collider operation between 305,000 and 509,000 tCO_2 shows that the supply of waste heat can be partially substitute conventional heat sources at the same level, thus generating substantial positive environmental externalities that are made visible in the comprehensive socio-economic impact assessment.

The 'minimum' scenario is based on the hypothesis that the particle collider starts operating in March and ends at the latest in November. Figure 3.8 shows as an example the weekly overview of the cumulative heat demand around a perimeter of 5 km around each surface site.

Figure 3.9 shows the heat demand and supply during the Z mode throughout the year, with a schedule that is better adapted to the heat demand.

Figure 3.10 shows the site PA in Ferney-Voltaire as an example for the heat demand study that permitted the development of the concept for the heat supply.

Several industrial and public heat consumers were identified in the vicinity of several surface sites. They include, for example, a hospital, a school, cheese production facilities, an airport, commercial zones and public housing. Such heat consumers are preferred over supply to individual houses that are more difficult to connect. Public,

[6] Regional heat production mix: 36% electricity at 147 gCO_2/kWh, 34% gas at 227 gCO_2/kWh, 16% oil at 324 gCO_2/kWh, 11% wood at 30 gCO_2/kWh, 0.3% heat at 49 gCO_2/kWh leads to a total footprint of 186.7 gCO_2/kWh = 186.7 tCO_2/GWh.

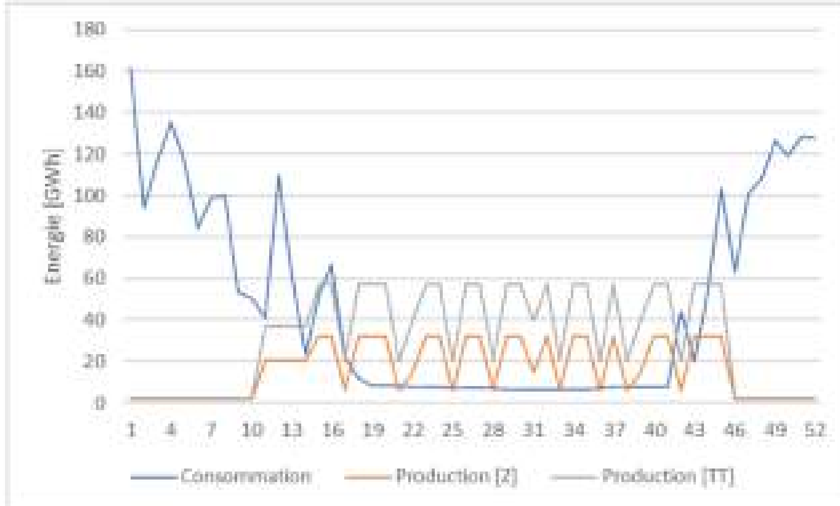

Fig. 3.8 Weekly heat demand and supply for an example schedule of the Z operation mode

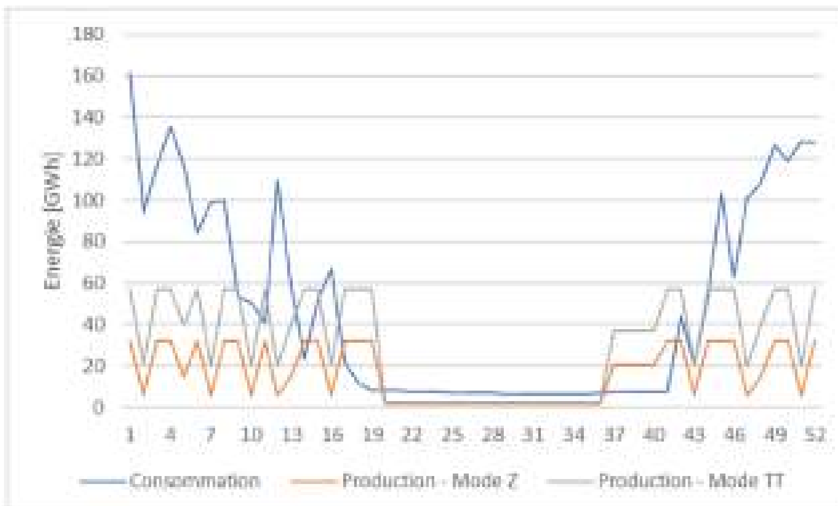

Fig. 3.9 Weekly heat demand and supply for an adapted schedule of the Z operation mode

industrial and commercial consumers typically have a higher and more stable heat demand. Site PD in Nangy (see Fig. 3.11) is one example where significant amounts of heat in the 10 GWh/year range can be supplied in the close vicinity of the surface site.

The techno-economical study revealed that waste heat supply is challenging at site PH (Cercier and Marlioz) and would be modest at sites PL (Challex) and site PB (Presinge). Therefore, a redistribution of the heat from PH to PG, from PL to PA and between PB and PD could be considered to improve the yield.

Table 3.3 gives an overview of the potential total waste heat demand that exists today in the perimeters studied around each site. Waste heat is best re-used with the creation of new consumers, such as healthcare facilities, thermal baths, greenhouses, industrial facilities, and residential buildings that are connected to the new network from the outset.

The supply of residual heat (or waste heat) from the FCC creates windfalls in three ways:

1. Balance the non-avoidable and non-reducible residual carbon footprint of electrical energy: supplying the FCC with electricity (the working hypothesis is based on using electricity partly from renewable sources) would represent an average carbon footprint of around 40,000 tCO_2(eq)/year. The yearly supply potential from residual waste heat is around 320 GWh of energy per year. The total maximum residual heat capacity is around 1600 GWh per year. Consequently the supply of waste heat can substitute for the carbon footprint of the electrical energy consumed, provided that this heat supply can be implemented and that the demand can be satisfied via a heat distribution infrastructure. The technical-economic study [73–75] showed that 220 GWh to 300 GWh of heat could be consumed within a radius of approximately 5 km around the surface sites. However, to increase the efficacy of waste heat supply, the particle collider operation schedule needs to adapt within acceptable limits to the heat needs.

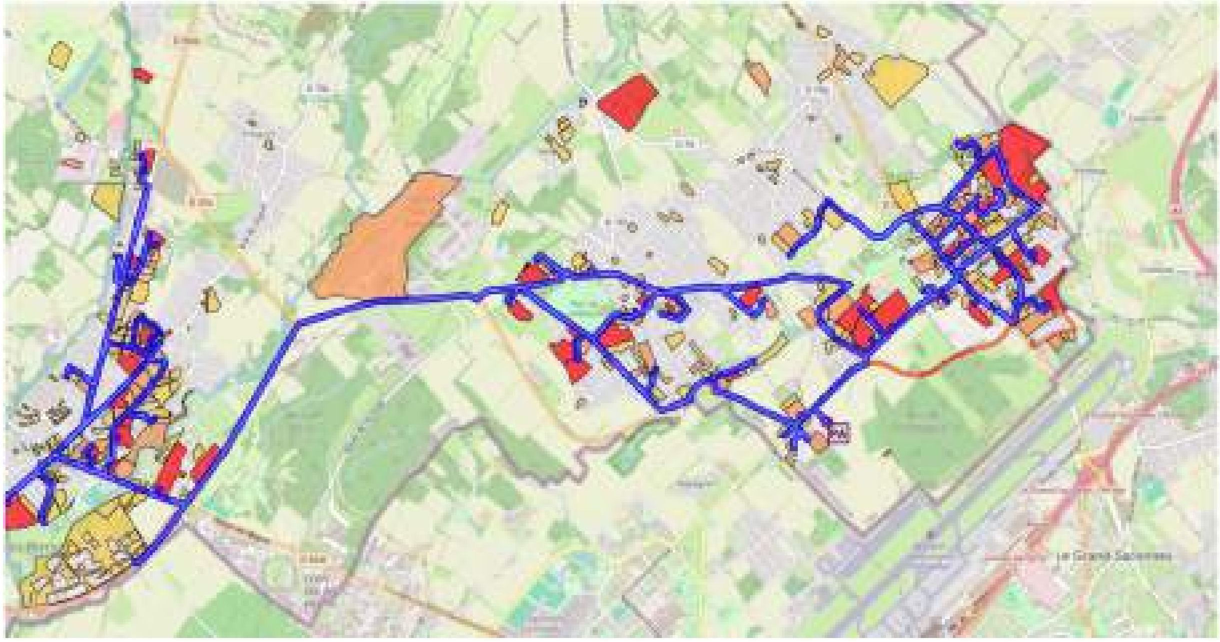

Fig. 3.10 Example from the heat demand study at site PA in Ferney-Voltaire, within a perimeter of ∼5 km around the site

Table 3.3 Overview of the total potential waste heat demand that exists today in the perimeters studied around each site

Site	Potential	Demand	Consumers
PA	High	200 GWh/year	Schools, commercial zones, residential
PA Extended	High	1700 GWh/year	Extension to Switzerland: airport, commercial and industrial activities, residential, hospitals
PB	Medium	30 - 200 GWh/year	School, greenhouses, penitentiary, hospital, commercial activities, housing
PB Extended	High	> 200 GWh/year	Commercial and residential demands in nearby France, sector Annemasse
PD	Low	14 GWh/year	Hospital, industrial
PD Extended	Medium	50 GWh/year	Schools, healthcare, residential
PF	Medium	60 GWh/year	Sector La Roche-sur-Foron: industrial expo center, schools
PG	Low	16 GWh/year	Schools, residential
PG Extended	Medium	35 GWh/year	Schools, residential
PG Annecy	High	860 GWh/year	Annecy at distance of 7 km: Industrial, commercial, residential
PH	Very low	14 GWh/year	At 8 km distance: Retirement home, residential
PJ	Low	20 GWh/year	Schools, commercial, residential
PL	Low	30 GWh/year	Spread over 5 km: school, commercial, residential

2. Reduction of the carbon footprint of heating and cooling in the region: the supply of energy by a heating network using a high proportion of renewable energies (including residual heat) avoids the need for other sources of heat. Based on the minimum reuse hypothesis (220 - 300 GWh/year), the production of 27,500 to 38,500 tCO_2(eq) could be avoided each year. Reasonable adaptation of the operating schedule throughout the year would be required to make this approach an effective lever.
3. Increasing the purchasing power of the local population: The organisation operating the FCC is not a profit-making organisation. Energy can, therefore, be supplied by network operators at very competitive prices. According to the French multi-annual energy programme (PPE), waste-to-energy plants (which recover waste heat) sell this heat at a very competitive price, between 10 and €25/MWh. As a result, the heat supplied can

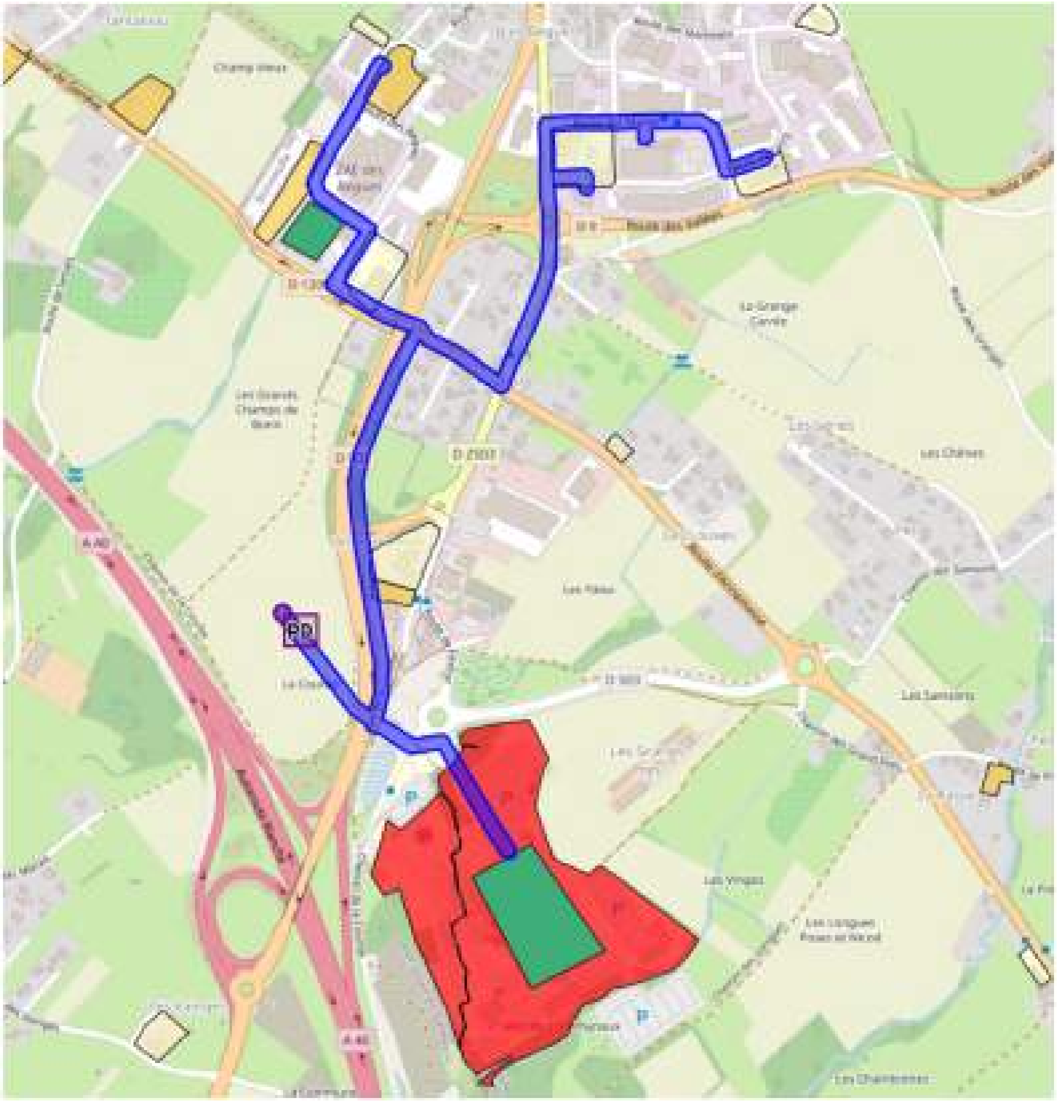

Fig. 3.11 Example from the heat demand study at site PD in Nangy, concerning a nearby hospital (south), a cheese producer (north) and a mixed industrial/residential zone (north-east)

then be the preferred choice for heating, hot water, and cooling. In the Anergie network (Ferney-Voltaire), the price of waste heat supplied by CERN equipment is even lower. According to a study by AMORCE and ADEME, the average selling price for networks supplied mainly by renewable and recovered energies ("EnR&R") was €78.2 /MWh, incl. tax, in 2020 (these prices do not take into account the initial investment costs of the networks). According to the waste heat supply study carried out for this project by the engineering firm Ginger BURGEAP, the average price was at the same level more recently. Based on this model, the potential savings are currently estimated at €50/MWh compared with gas heating and €140/MWh compared with electricity, using energy prices of 1st November 2023 as a reference.

4. Limiting water consumption: reusing residual heat would also reduce the need for cooling water. The potentials are described in Sect. 3.2.9.

3.2.7 Construction related carbon footprint

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. Carbon budget analysis, as part of a more comprehensive Lifecycle Analysis (LCA) (see Fig. 3.12), has emerged as an essential tool for measuring and managing these emissions effectively.

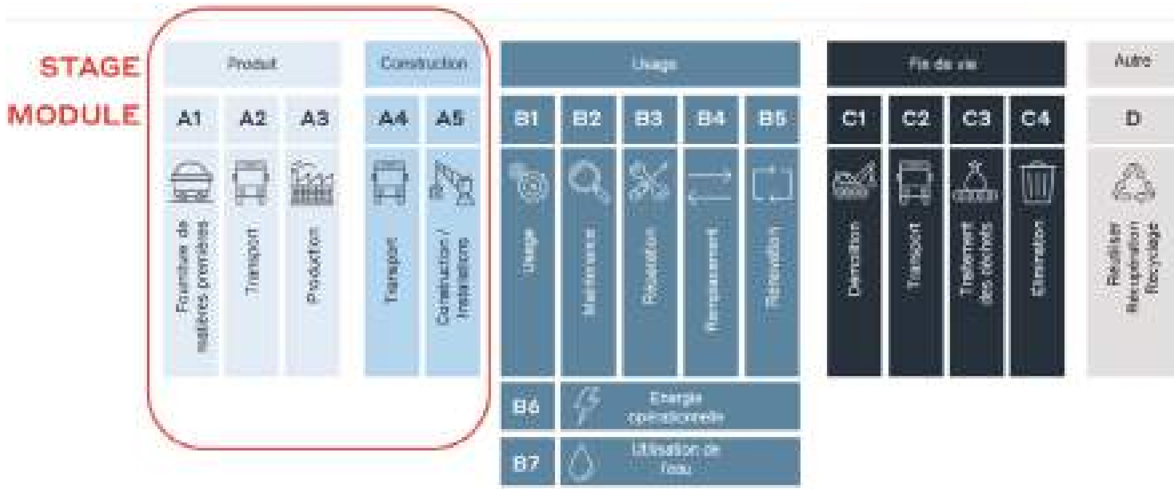

Fig. 3.12 Stages considered for the LCA of the infrastructure construction

A comprehensive lifecycle analysis (LCA) conforming to the applicable ISO standards and European Norms, EN 14040 and EN 14044, has been carried out [59]. For the construction sector, the EN 17472 norm has been followed. In addition to the use of generic databases, a specific procurement scenario has been analysed, based on currently available Environmental Product Declarations (EPD) conforming to the European Norm, EN 15804+2, and the French 'Fiche de Déclaration Environnementale et Sanitaire' (FDES).

The goal of the work was firstly to identify the key drivers for quantitatively estimated environmental impacts of the construction and, secondly, to establish a credible reference scenario for the carbon budget as a baseline for further designs and optimisations. It is important to note that a generic LCA cannot provide adequate indications for the carbon footprint, but is limited to the capability of identifying drivers. A specific and geo-localised project scenario with a particular sourcing scenario is necessary to be able to report absolute and credible estimates. The methodology adopted comprised the following steps:

1. Identification of components: a detailed inventory of materials was compiled based on the bill of quantities for the subsurface construction, the 4 experiment sites and the technical sites. The products concerned are used throughout the infrastructure's lifecycle.
2. EPDs acquisition: EPDs were sourced for each material and product identified, ensuring compliance with EN 15804+A2, the foundation of EN 17472. The materials were selected based on expert knowledge of the local environment and state-of-the-art products. The availability of the products was confirmed by the suppliers.
3. Software Tool: A certified tool compatible with French and Swiss Environmental Product Declaration, One Click LCA, was chosen, ensuring robust and accurate calculations.
4. Data Entry: data was imported into the tool and project-specific data was entered, including material quantities and lifecycle phases, transportation 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: the results were analysed to pinpoint major emission sources, comparing them against benchmarks and reduction targets.
7. Guidance: the results were used to sensitise engineers and scientists to include a carbon budget as a further input to the subsequent design phase and to ensure that requirements are well formulated and justified so that the infrastructure corresponds to what is required, thus limiting the environmental impacts.

The analysis provided a breakdown of GHG emissions and additional quantitative potential environmental impacts across the various lifecycle phases, products and materials. The key emission sources are reinforced steel (14%), precast concrete (49%) and concrete (23%). This highlights opportunities for emission reduction by designing the infrastructure with carbon reduction in mind, making careful material selection, optimising the construction process and making energy efficiency improvements. The most effective environmental impact management approach is a combination of the establishment of technical requirements for the infrastructures with rationales for the requirement, design of the infrastructure based on the requirements with carbon reduction in mind, careful material selection in agreement with the requirements, construction process optimisation, and energy efficiency improvements. The GHG impacts of the initial and benchmark scenarios are given in Table 3.4.

The 526,188 tCO_2(eq) carbon footprint of the construction over a period of 10 years can be compared to CERN's current annual carbon footprint (184,173 tCO_2(eq) [78]. Thus, the construction corresponds to about

Table 3.4 Reference carbon footprint of the FCC infrastructure construction for a period of 10 years based on specific sourcing and procurement scenarios with EPDs

Item	Carbon footprint
Subsurface	477,388 tCO_2(eq)
4 technical sites	17,600 tCO_2(eq)
4 experiment sites	31,200 tCO_2(eq)
Total	526,188 tCO_2(eq)

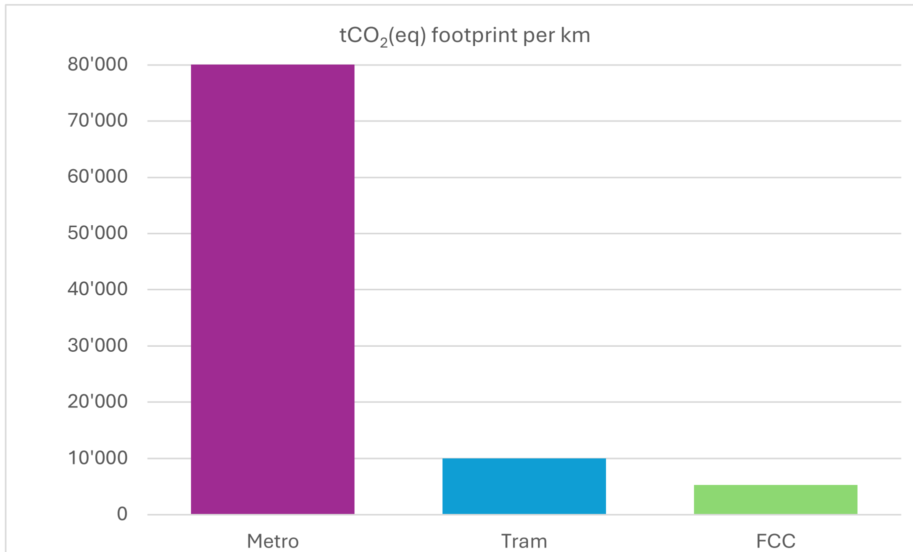

Fig. 3.13 The construction-related carbon footprint per km of the FCC tunnel compared to typical public transport linear structures [59]

3 years of CERN's annual footprint or about 30% of CERN's annual carbon footprint per construction year. The FCC construction carbon footprint can also be compared to that of the Olympic Games in Paris which had an estimated carbon budget of 1,580,000 tCO_2(eq) [79].

With respect to conventional construction projects, the carbon footprint of a research infrastructure is significantly lower (see Fig. 3.13) than a small-scale metro line or a tramway line. For instance, the construction of the U5 Metro line in Berlin, Germany had a carbon footprint of 98,000 tCO_2(eq) per km [80]. On average, per km of underground transport line construction, the carbon footprint is 80,000 tCO_2(eq). The construction of a tram line has a carbon footprint between, 7600 and 10,850 tCO_2(eq) per km.

Based on the analysis, a number of recommendations were developed with the help of the expert company that carried out the LCA.

Although CERN's annual carbon footprint will gradually be reduced, in line with the established environmental goals, national climate protection plans and IPCC recommendations, it would be advisable to limit adding construction-related climate impacts to the operation-related carbon budget. Hence, while the construction of a new facility ramps up, it would be prudent to reduce the activities related to other carbon-intense activities. With respect to the construction, the following strategies can help to reduce the potential impacts further:

- Implementation of a thorough systems engineering methodology to develop well-justified and fully documented technical requirements for both subsurface and surface structural elements. These requirements will represent the absolute minimum necessary to accomplish the scientific research programme effectively (for example, determining the precise dimensions and volumes of structures that meet the essential technical and physical requirements).
- Integration of an eco-design in the comprehensive systems engineering process with carbon reduction in mind that matches the established requirements (e.g., appropriate sizing of the caverns, shafts, alcoves).
- Structural modification of the scenario by reducing the inner line thickness of subsurface structures by at least 5 cm, leading to a reduction of 16% for precast concrete and rebar steel.
- Material substitution, considering low-impact materials which meet the established requirements and working with industrial partners to innovate and produce locally wherever possible.
- Construction process optimisation to minimise emissions.
- Reuse of excavated materials, for instance, in concrete production.

With respect to the initial baseline scenario, the reduction of the circumference to about 91 km and the suppression of 4 shafts have led to a significant reduction of the construction-related carbon footprint during the scenario development phase. Furthermore, the carbon footprint must be seen in the context of establishing an infrastructure that serves a worldwide community of about 15,000 scientists for two subsequent particle colliders until the end of the century. Although according to international norms the quantities reported by the LCA must be entirely accounted for the first project phase only (FCC-ee), it can be seen as an investment that benefits the second phase, the high-energy hadron collider phase (FCC-hh).

3.2.8 Operation related carbon footprint

Detectors While the carbon footprint of today's scientific research facilities, such as the LHC and its experiments, is largely caused by gases used in the detectors, this contribution will be only marginally relevant for the FCC era: gases with significant climate effects are already being banned, and the list of such products is growing rapidly.

Today's working gases will largely be unavailable by the year 2050 when the first collider enters its operation phase. The performance and long-term operation of gaseous detectors rely primarily on the use of the optimal gas mixture, which is the active medium where the primary ionisation happens in the detector. Several gaseous detector technologies make use of gas mixtures containing expensive or greenhouse gases, which have specific properties that allow optimal detector performance and avoid ageing effects. The GHGs most in use are the $C_2H_2F_4$ (known as R134a, GWP of 1430) and SF_6 (GWP of 23,900) for the Resistive Plate Chambers, the C_4F_{10} (GWP of 8860) for Cherenkov detectors and the CF_4 (GWP of 7390) for wire chambers, Cherenkov detectors and micro pattern gaseous detectors (MPGDs). These gases are necessary to mitigate ageing phenomena, to act as a Cherenkov radiator and to contain charge development (thanks to their electronegative properties) or to improve time resolution.

The detector volumes range from a few m^3 to hundreds of m^3 making the use of gas recirculation systems compulsory to reduce operational costs and GHG emissions. Even with the implementation of these systems, in some cases, emissions can be present mostly due to detector requirements or the presence of leaks. Residual leaks are mainly due to failures of plastic pipes and connectors that break due to built-in fragility and mechanical stress. These leaks are not accessible during run periods and, in some cases, during regular technical stops. Big leak search and repair campaigns usually take place during long shutdown periods, but leaks typically keep developing.

To reduce emissions, today's strategy [81] is based on three lines of action:

- **Gas Recirculation.** The gas mixture is taken at the output of the detectors, purified and sent back to the detectors. It is technically possible to recycle 100% of the gas mixture.
- **Gas Recuperation.** The gas mixture is sent to a recuperation plant where the GHG is extracted, stored and re-used. This system is always used in combination with a gas recirculation system to allow a further GHG reduction.
- **Alternative gases.** Search for alternative gas mixtures suitable for particle detectors that do not contain or have limited use of GHGs.

The substitution of fluorinated gases (F-gases) is fundamental because of the implementation in Europe of the F-gas regulation that will render such substances unavailable by 2050. Also in 2023 the European Chemicals Agency (ECHA) released a proposal regarding restriction on PFAS, i.e., per- and polyfluoroalkyl substances, which contain at least one fully fluorinated methyl (CF_3-) or methylene (-CF_2-) carbon atom (without any H/Cl/Br/I attached to it). The proposal covers over 10,000 different PFAS, which are considered environmental pollutants with links to harmful health effects. Most of the so-called 'eco-friendly' gases belong to the PFAS family.

In addition, devices and circuits using gases either for cooling or for particle detection purposes must be designed to be leak-tight and use a re-circulation principle.

Scope 2 The principal cause of carbon footprint will be the use of electrical energy.

The same approach will be used for the optimisation of all other resource use, such as electrical energy. The adoption of the hierarchical 'Avoid-Reduce-Compensate' principle guides the iterative planning, implementation, checking and taking action cycle that leads to continuous optimisation.

A comprehensive technical requirements gathering process has to be established to document and scrutinise where and when electrical energy is needed. Following a baseline scenario, the eco-design approach helps to conceive designs and choose products that lead to reduced energy consumption. A review of the operation model that will be guided by overall sustainability goals integrating economic, ecological and societal aspects will guide the development of different scenarios. Some measures require another iteration of the eco-design cycle by introducing new requirements that foster sustainability, such as the integration of waste-heat recovery and supply functionality. It permits, for instance, substituting fossil energy used inside and outside the project, but it comes with constraints such as additional investment and operation costs, the necessity to buffer energy, the need to dynamically adapt operation, requirements on financial and ecological accounting and the requirement to establish administrative

Table 3.5 Examples of some official electrical energy carbon footprint sources

Country	Source	Energy	Carbon footprint gCO_2/kWh tCO_2/GWh	Year
France	Ademe Base Empreinte	Offshore wind	15.6	2023
France	Ademe Base Empreinte	Unqualified energy mix	52.0	2022
Germany	Umweltbundesamt (UBA)[a]	Unqualified energy mix	380.0	2023
Italy	ISPRA	Unqualified energy mix	257.2	2022
Switzerland	BAFU/OFEV[b]	Unqualified energy mix	54.7	2018
Switzerland	BAFU/OFEV	Renewable energy mix	15.7	2018

[a]https://www.umweltbundesamt.de/publikationen/entwicklung-der-spezifischen-treibhausgas-10.

[b]https://www.bafu.admin.ch/bafu/de/home/themen/klima/fragen-antworten.html.

and commercial frameworks for successful implementation. All relevant ESG parameters need to be taken into consideration, and it is therefore recommended that experienced companies be employed for the overall energy optimisation of the infrastructures.

Official national values for the selected base year of the sustainability analysis must be used to determine the carbon footprint of the electricity consumed during the design and planning phases. Consequently, the carbon footprint depends on the technology (offshore wind, onshore wind, photovoltaic, hydro, nuclear) and the geographical location of the energy production. Even if all electricity is transported and supplied to the FCC by the French electricity grid, operated by RTE, this does not mean that the electrical energy needs to be sourced solely from French territory. Studies carried out with experts in the domain [51] showed that a comprehensive portfolio of energy supply contracts or power purchasing agreements (PPA) would be best established with sufficient lead time (order of 10 years). It must be able to respond to the evolving needs of the commissioning and operation phases. In order to foster the use of renewable energy sources and exploit the waste heat supply functionality, the particle collider would need to adapt to the energy supply contract conditions that eventually are determined by commercial conditions on the one hand and by the availability of renewable energy capacities on the other.

Depending on the country of origin, the carbon intensity of electricity is made available from different sources. Table 3.5 provides an illustration.

Once a specific energy supply contract is active, emission accounting will be carried out using supplier-provided emission information. For instance, a typical consumer-oriented electricity contract based entirely on renewable energy sources (62% hydro, 31% wind and 7% PV, 100% are certified to be of renewable energy sources) in France today has an actual carbon footprint of 34 $kgCO_2$(eq)/MWh [82]. This value is higher than the ADEME indicated emission factor for renewable energy sources to be used for the planning and design phases since the consumption of electricity in the frame of a live contract includes all emissions along the value chain and not only the production-related emissions. In addition, renewable energy that is potentially sourced from physical PPAs is not accounted for in the carbon footprint.

Different assumptions were taken to estimate the Scope 2 carbon footprint related to the operation. One assumption is based on today's energy mix, including nuclear energy and renewable energy sources with a varying contribution of up to 75% and a carbon footprint of 24 gCO_2/kWh. This configuration leads to an average annual indirect carbon footprint of about 500,000 tCO_2 or approximately 35,000 tCO_2 per year depending on the renewable PPA and energy supply contract portfolio.[7]

For an optimistic reference estimate, it was assumed that an energy mix based on a portfolio of physical and non-physical PPAs and energy supply contracts on the 2050 time horizon, entirely sourced from French territory via the national grid operated by RTE (see Table 3.6). Based on this mix, the total carbon footprint of about 300,000 tCO_2(eq) was estimated[8] for the entire scientific research period over 15 years. This corresponds to an annual average of about 20,500 tCO_2(eq). Using a pessimistic estimate of 25 tCO_2(eq)/GWh leads to a carbon footprint of 522,500 tCO_2(eq) of an annual average of about 34,800 tCO_2(eq).

The residual carbon footprint can in principle also be offset by the supply of waste heat. Depending on the amount of waste heat re-used, this opens an opportunity to evolve towards net-zero operation scenario after 2050. Such a scenario requires the careful development of energy supply contracts and/or long-term PPAs and the creation of district heating and industrial heat supply networks, with an adaptation of the accelerator operation to the energy supply and the heat demand. Introducing temporary heat buffering will help achieve the goal.

[7]20,900 GWh * 24 tCO_2(eq)/Gwh = 501,600 tCO_2(eq).

[8]20,900 GWh * 14.74 tCO_2(eq)/GWh = 308,066 tCO_2(eq).

Table 3.6 Lowest carbon footprint energy mix assumption used for the estimate of the carbon footprint for operation on a 2050 time horizon. The carbon intensity figures were obtained from the Ademe Base Empreinte database, 2023

Energy Source	Contribution	Carbon intensity
Nuclear	10%	3.7 $gCO_2(eq)/kWh$
Offshore wind	55%	15.6 $gCO_2(eq)/kWh$
Onshore wind	10%	14.1 $gCO_2(eq)/kWh$
Photovoltaic	15%	25.2 $gCO_2(eq)/kWh$
Hydro power	10%	6.0 $gCO_2(eq)/kWh$
Total	100%	**14.74 $gCO_2(eq)/kWh$**

Table 3.7 Overview of the raw water needs for cooling for each operation mode, waste water re-use potentials for sites PD, PF, PG and the residual treated water that can be made publicly available

Mode	Years	Initial FCC water need	Waste water used at PD, PF, PG	Residual water needs	Treated waste water available to society
Z	4	1,604,861 m^3/year	560,304 m^3/year	1,044,557 m^3/year	2,049,792 m^3/year
WW	2	1,928,943 m^3/year	619,017 m^3/year	1,309,927 m^3/year	1,991,080 m^3/year
ZH	3	2,165,458 m^3/year	705,173 m^3/year	1,460,285 m^3/year	1,904,924 m^3/year
L.S.	1	163,817 m^3/year	78,840 m^3/year	977 m^3/year	2,531,256 m^3/year
$t\bar{t}$	5	3,077,591 m^3/year	897,334 m^3/year	2,180,258 m^3/year	1,712,763 m^3/year

3.2.9 Water use and saving

Drinking water from the existing local distribution networks will only be used for drinking and sanitary purposes. All raw water required for industrial cooling systems will be sourced from CERN's existing water supply (SIG) in Switzerland, which sources the water from Lake Geneva.

From a quantitative point of view, the reference scenario for water consumption is technically, financially, and territorially feasible since water extraction and consumption represent quantities lower than CERN's actual consumption in 2022. The availability of a supply representing twice the total needs was confirmed by SIG in 2023.

During the subsequent design phase, it will be necessary to verify aspects relating to the sharing of water with the other local stakeholders who use the same water sources, particularly with regard to related catchment areas which currently experience chronic deficits (Pays de Gex, La Roche-sur-Foron and possibly the Usses). Numerous synergies can be considered with local authorities in the vicinity of surface sites in terms of the reuse of residual heat and released water.

Therefore, a study has been launched recently to determine the feasibility and the conditions to also source water from a water treatment station near the site PD in Nangy (STEP SRB in Scientrier, see Table 3.7). Initial results are promising, requiring, however, a reduction of the non-soluble content in the water and an effective treatment of bacteria. A demonstration will be required for such an installation. If considered viable, it can lead to substantial raw water reduction and can help supply treated water for other industrial purposes when the particle accelerator does not require it.

The preliminary analysis has been carried out based on the water supplied to the treatment plant during a typical year and an assumption of a treatment capacity of up to 400 m^3/hour. Although a water treatment plant has, in principle, the capacity to provide more water than is needed for the cooling of the particle collider, it is prudent to assume that the water is mixed with ordinary raw water, that the treated water is not always compliant with the needs, and that the treatment is not always fully efficient or available. Figure 3.14 gives an impression of the typical annual operation of the water treatment plant in Scientrier close to site PD and how wastewater recovery would map to the collider cooling needs for the Z mode as an example.

It should be noted that ultimately the feasibility of this approach and the actual capacities depend on the technical designs and the possibility of implementing the concept in cooperation with the national, regional and local stakeholders in France.

Furthermore, water reduction can be achieved with the recovery and supply of waste heat, since less heat needs to be dissipated with evaporation towers. The reduction potential estimated in the dedicated engineering study was approximately 1.6 m^3 of water per MWh of waste heat supplied. Table 3.8 outlines the potential amount of cooling water savings for each operation mode and for one of three different waste heat supply scenarios:

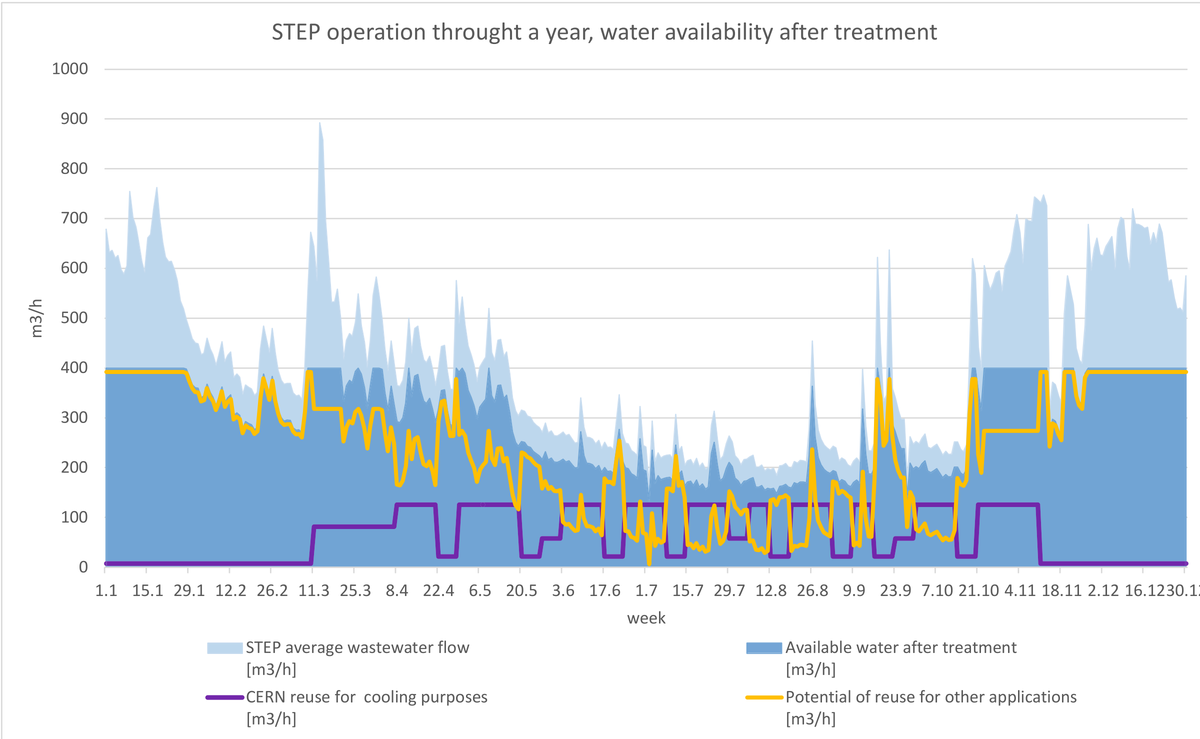

Fig. 3.14 Operation of the STEP in Scientrier throughout a typical year, matching with FCC Z mode water cooling needs and the capacities made available by water treatment to the FCC and society

Table 3.8 Water saving potential related to waste heat supply (scenario 2, adapting the collider operation to seasonal demand)

Mode	Years	Heat supplied	Water saved
Z	4	308 GWh/year	477,000 m^3/year
WW	2	339 GWh/year	523,000 m^3/year
HZ	3	371 GWh/year	571,000 m^3/year
L.S.	1	60 GWh/year	96,000 m^3/year
$t\bar{t}$	5	441 GWh/year	678,000 m^3/year
Total		**5288 GWh**	**8,155,200 m^3**

Scenario 1: the heat is distributed in a 5 km radius with no adaptation of the schedule. This means that the FCC would be operated from April to September, when the heating needs are low.
Scenario 2: the heat is distributed in a 5 km radius with an adapted schedule. This means that the FCC would be operated from October to March, when the heating needs are high.
Scenario 3: the heat is distributed in a 5 km radius with an adapted schedule and distribution. This means that the infrastructure would operate from October to March, when heating demand is highest, and the heat would be distributed to areas where there is higher demand than in scenario 2.

The water savings also translate into a modest reduction of operating cost of about 6 million CHF. Whilst this is not a noteworthy financial sustainability contribution, together with some annual electricity savings of 4 GWh per year, in total about 60 GWh which is worth another 5 million CHF, financially and economically compensating the additional effort to operate the waste heat recovery system.

3.2.10 Induced road traffic

To estimate the additional traffic induced by the construction activities, a traffic analysis has been carried out using up-to-date traffic data in approximately 5 km wide perimeters around the surface site locations and comparing different standard trucks used for construction (Fig. 3.15). Based on this traffic analysis (Fig. 3.16) and the

	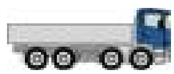			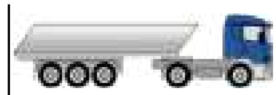
Axles	**4**	**5**	**3 + 2**	**2 + 3**
Total weight (t)	32	40	40	40
Capacity (m^3)	12	17	24	24
Capacity (t)	18	24	24	25

Fig. 3.15 Capacities of different standard trucks used to analyse the construction site induced additional road traffic

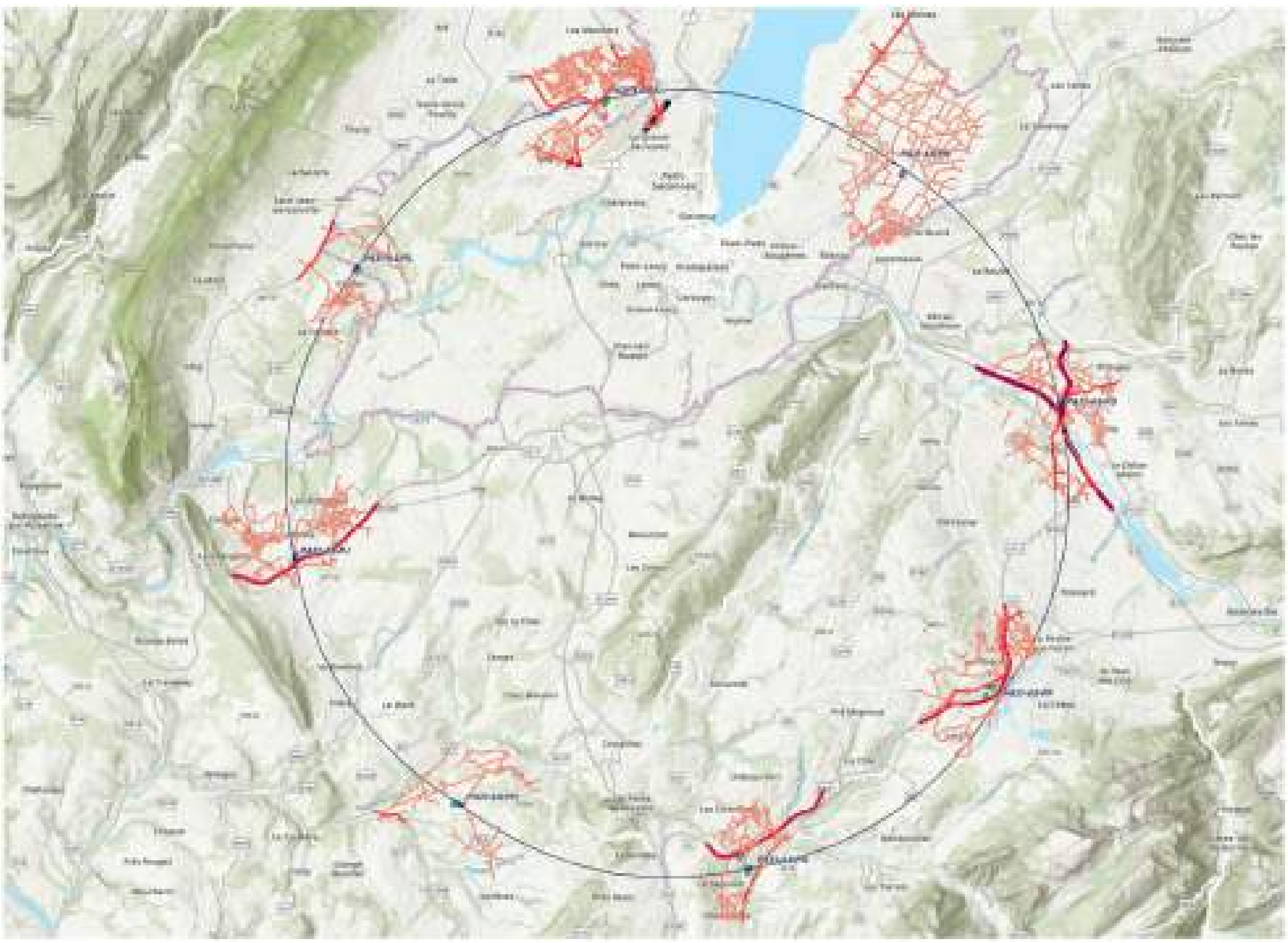

Fig. 3.16 Perimeters of the traffic studies for each construction site. The bolder lines indicate the traffic recorded on major transport routes

assumption of a worst-case scenario in which all materials need to be transported by trucks on roads, it can be shown that the additional traffic induced by the project, distributed over nine construction sites and more than eight years is only marginal (Table 3.9). Traffic is assumed to be limited to working days and regular working hours, avoiding morning and evening peak hours.

The subsequent project design will emphasise reducing road-based transport requirements. The traffic can be further reduced by using larger trucks (2+3 axles or 3+2 axles). Conveyor belts are the preferred means to bring excavated materials to major road and rail transport networks so that no local traffic is induced. Where possible,

Table 3.9 Worst case scenario during the construction period for excavated material transport using trucks only. The traffic can vary with different excavation scenarios, leading to less traffic at PL and PB and more traffic at PA

Site	Traffic per day	Additional 5-axle trucks per day	Additional traffic in percent	Additional 5-axle trucks per hour
PA	7803	46	0.5%	4
PB	5918	37	0.6%	3
PD	20,475	93	0.4%	8
PF	11,331	12	0.1%	1
PG	13,681	100	0.7%	8
PH	1709	23	1.3%	2
PJ	13,954	95	0.7%	8
PL	3380	46	1.4%	4
Injector	7803	9	0.1%	1

Table 3.10 Number of people on-site during various different activity periods

Site	Installation 5 years	Operation 10 months per year	Maintenance 2 months per year	Shutdown every few years
PA, PD, PG, PJ	200 - 300 people	15 to 20 people	100 people	200 - 300 people
PB, PD, PH, PL	100 people	0 to 10 people	15 - 30 people	Up to 100 people

construction materials are brought in via autoroutes to site connections or via major roads to avoid passing through residential areas.

The traffic for the five years of installation of the particle accelerator equipment is small. It ranges between 9 and 18 trucks per site and day, i.e., between 1 and 2 trucks per working hour. No traffic is foreseen during the night and non-working days. The limitation to traffic during the installation is due to the limited capacity of transferring equipment through the access shafts. The handling speed between surface and underground and in the constrained underground environment determines the amount of equipment that can be brought in. Between about 200 and 300 people per day are expected to be present on experiment sites and about 100 people on technical sites (see Table 3.10). This leads to daily work-related traffic of about 100 to 200 cars. This traffic can be significantly reduced by organising the work and providing the possibility of carpools and bus transport.

During operational periods, technical sites are expected to have minimal personnel presence, based on system requirements, resulting in minimal traffic impact. For experiment sites, the highest projected staffing scenario involves small teams of up to 20 people working across three shifts. Transportation should be organized to limit daily vehicle movement to several dozen cars entering and exiting each site. However, visitor traffic at sites PA, PD, PG, and PJ may be substantially higher.

3.2.11 Environmental monitoring

An environmental monitoring system will be put in place once the new research infrastructure is completely constructed. Such a system will help track compliance with the initially set goals and support safe operation. Such a system typically comprises the following functionalities:

- Clear water monitoring: Measurement stations for effluent water integrate continuous monitoring of temperature, pH, hydrocarbons, foam, turbidity, conductivity and flow rate. Alarms are triggered based on threshold and trend conditions. Where a surface site is equipped with water retention facilities, additional monitors will be installed to activate retention when needed.
- Sewage water monitoring: Measurement stations integrate continuous monitoring of temperature, pH, conductivity and flow rate for water released into the public sewage network. Periodic sampling is also implemented.
- Process water sampling: Such stations serve periodic sampling of residual effluents from the processes such as for instance water recycling and treatment.
- Air quality monitoring: Such stations continuously monitor the air, including oxides (nitrogen oxides and ozone) that may be byproducts of the synchrotron operation. Those systems are coupled to air recycling functions. Continuous comparison with the existing background air conditions will be implemented.
- Noise monitoring: Such stations measure and record continuously the noise levels at the surface site locations and in sensitive areas in the vicinity.

- Meteorological monitoring: These stations are equipped with anemometers and pluviometers for assessment of hazards due to potentially radioactive substances and fumes in case of fire. Cooperation with the national metereological services will be considered for data exchange.
- Radiological monitoring: Monitoring of radiological parameters during and after the operation to provide evidence for compliance with the dose constraints and limits. The system comprises equipment for on-site monitoring for the safety of workers and on and off-site monitoring for the environment.

In addition to the stationary environmental monitoring facilities, additional portable devices will be used for periodic in-field monitoring. Samples such as water, soil and plants will be analysed regularly by environmental laboratories.

3.3 Current state of the environment

3.3.1 Methodology

The current state of the environment in the perimeter of the reference implementation scenario and at the surface site candidates has been analysed following the national regulations in the two Host States, France and Switzerland. The resulting single, integrated report [30], complemented by interactive maps, audio, image and video materials as well as by an Environmental Information System based on the ESRI geographical information system, is an essential preparation work for the subsequent environmental authorisation process that has to include an environmental impact assessment in a transnational context. This work has been carried out between 2023 and 2025 with a consortium of expert companies. The following section gives a glimpse of the scope of the work carried out and provides the basic conclusions. The initial state of the environment is only valid for a limited period of time since the environment is constantly evolving. Therefore, further complementary studies (e.g., hydrogeological investigations, further studies on fauna and flora, more comprehensive environmental measurements) and studies for potential alternative site locations have to be engaged during a subsequent environmental impact assessment phase.

3.3.2 Air and climate

Climate The climatic conditions and their foreseeable evolution have to be considered for a long-term programme like the FCC that will extend until the end of the century. The environmental state analysis includes the collection of climate data from bibliographical sources and climate observation facilities in Geneva (Switzerland) and Annecy (France). Despite the limited distance of about 30 km between the extreme sites of the FCC, the climatic conditions are notably different. The north is characterised by a subcontinental climate with hot summers, but moderate weather conditions due to the protective effects of the mountains and the moderating effect of Lake Geneva water mass. The south experiences a mountain continental climate with greater weather and temperature differences between the summer and winter seasons. Winds are rather constant in all areas. The climate evolution shows a sustained and evolving temperature anomaly between +1.7° and +2.5°C compared to the pre-industrial period. The number of frosty days has decreased significantly by 20% since 1950. Precipitation is highly variable, without noteworthy changes over the time period. Extreme heat conditions during summer periods are expected to evolve further until the end of the century. They are typically accompanied by dry periods with effects on the soil and the amount of precipitation is expected to decrease. Rain is expected to intensify during the wet periods.

Lake temperatures have risen in recent years due to climate change. Since 1980, the surface water in most lakes has warmed by about 0.4°C per decade. The warming of the deep water is more variable and mostly ranges between 0.0 and 0.2°C per decade in the deep lakes. A further increase in the temperature of the surface water layer down to 1 m deep is expected in all Swiss lakes: for a scenario without climate change mitigation of between 3 and 4°C in most lakes towards the end of the century. The water temperature at depths where raw water intake occurs will only slightly increase.

The evolution of climatic conditions is, however, not expected to lead to noteworthy effects on the particle collider, for instance the water cooling systems. Nevertheless, the FCC must account for climate evolution in its design and the development of an operational concept. In the presence of an average envisaged temperature increase of around 4°C until the end of the century, these steps concern in particular, the adoption of operation to conditions that permit efficient work (e.g., avoiding periods that are too hot) and increasing the benefits of waste-heat reuse project, both internally and in the region (e.g., shift operation to a colder season).

Air The air condition within the perimeter of the FCC is generally good, and the air quality is improving constantly. The main cause of air pollution is road traffic, mainly diesel-powered trucks. Fine dust particles have their origin mainly in the agricultural sector and industry, in particular construction and quarries. All typical air pollutants

Fig. 3.17 Air quality measurements carried out using monitoring equipment to assess atmospheric pollutants in the vicinity of the surface site

have been studied to document baselines, and air quality measurements have been carried out to establish references in the vicinity of the surface site. These references serve as valuable input for the development of the construction process and the design of the infrastructures in order to be able to properly and adequately ensure the protection of the air quality and meet the EU zero pollution vision for 2050. If it is decided to go ahead with the project, continuous air monitoring (using devices like that shown in Figs. 3.17 and 3.18) has to be implemented at the surface sites to monitor the evolution and to be able to control the impacts on the air quality during the construction and operation phases.

Climate protection plans France has reduced its emissions by 27% with respect to 1990, in line with an average reduction of the emissions in Europe by about 31%. The per capita footprint in 2022 was about 6.5 tCO2(eq) per year [83], a value that is below the European Union average of 8 metric tons per capita. While the energy and industry sectors were able to reduce their footprints considerably, the transport sector did not yet see the same improvements. Emissions due to transport even slightly increased. This situation is also reflected at a regional scale, with the transport sector remaining the main producer of greenhouse gas emissions. France has adopted the 2015 Paris Agreement, aiming for a reduction of the net emissions by 55% with respect to 1990 by the year 2030 and climate effect neutrality by 2050. Locally, the climate protection goals can differ. For instance, for the Pays de Gex around CERN today, the goals established are −66% by 2050 with respect to the year 2015. For 'Grand Annecy' the goals are −55% by 2030 and −87% by 2050.

In Switzerland, greenhouse gas emissions have decreased continuously since 2010. Transport, agriculture, and industry remain the main emission contributors. As of 2025, two laws are in place that impose requirements: the law on CO_2 and the law on climate and innovation. The established goals are a reduction of 60% of the greenhouse gas emissions by 2030 with respect to 1990. The long-term goal for the country is to achieve net carbon neutrality by 2050. Also, at the cantonal level, an operational climate protection plan is in place. It prescribes goals and 41 specific measures to be implemented by 2030. The emission reduction objectives are in line with values established at the federal level.

Summary and conclusions The planning, construction and operation of a future research infrastructure at CERN takes into account the plans and regulatory requirements that have been established at the national levels to achieve the goals of the Paris Agreement. Aspects related to energy and greenhouse gas emissions are considered according to the current policies established by CERN, aiming at keeping the energy required for its activity as low as possible, ensuring that the established research programme goals can be achieved. This includes continuous improvement of its energy efficiency, recovering and supplying waste heat and reducing greenhouse gas emissions. CERN is committed to demonstrating that appropriate measures are taken with respect to energy and greenhouse gas emissions during all phases of a future research infrastructure, in line with the plans and regulatory requirements established by the Host States.

Fig. 3.18 Air quality measurements conducted to assess atmospheric pollutants in the vicinity of the surface site

At the end of 2019, CERN established a target for the reduction of its direct CO_2 emissions by 28% with respect to 2018 (baseline year) by the end of the Large Hadron Collider Operation Run 3 (around 2026). This target has been highlighted since September 2020 in the CERN public environment reports that are published biennially. Recently, CERN has adopted a target for the reduction of its direct CO_2 emissions by 50% with respect to the baseline year 2018 for the year 2030 [84]. Indirect emissions related to electricity consumption and other emission categories, such as those related to procurement, are also reported and published. Associated reduction targets are under investigation.

If a new research infrastructure is approved and included in CERN's overall environmental performance management, emission reduction plans and goals, including the new research infrastructure, will be set with respect to the corresponding updated envelope of policies.

The integration of a new research infrastructure into CERN's environment will generate additional emissions that the organisation will strive to minimise within the established goals to be achieved for the scientific research performance. A rigorous eco-design approach applied to the construction activities, the technical infrastructures, the particle accelerators, and the detectors will be introduced at the level of the organisation and will be required from the entire international collaboration contributing to the project, ensuring that in-kind contributions will comply with the relevant environmental rules and regulations.

The proposed particle collider will not operate concurrently with the Large Hadron Collider. Therefore, the emissions generated by the operation of the new collider and its experiments will replace those linked to the LHC operation. The new collider and its experiments will technologically be significantly more advanced, and the eco-design will make it a research infrastructure with lower emissions than the LHC today.

Together with continued efforts to technologically upgrade other CERN research facilities and activities, effective support of the Host States efforts to meet their climate protection goals remains achievable.

In the context of the environmental authorisation process, a climate protection plan integrating the new project is expected to be included as part of the environmental impact assessment.

3.3.3 Water

Context The situation of surface and subsurface water within the perimeter of the scenario has been analysed based on bibliographical data, databases, maps, and reports. The legal frameworks in France and Switzerland are very different with respect to this topic, which makes the comparison and integration of data challenging. Whilst in France, the European Union definitions and directives are applied, different water protection frameworks exist in Switzerland at federal and cantonal levels. For this reason, the current state of the water has to be looked at separately for each of the two countries. In addition, subsurface water tables have to be distinguished from surface water. However, both water masses, subsurface and surface, extend across the national borders and lead to

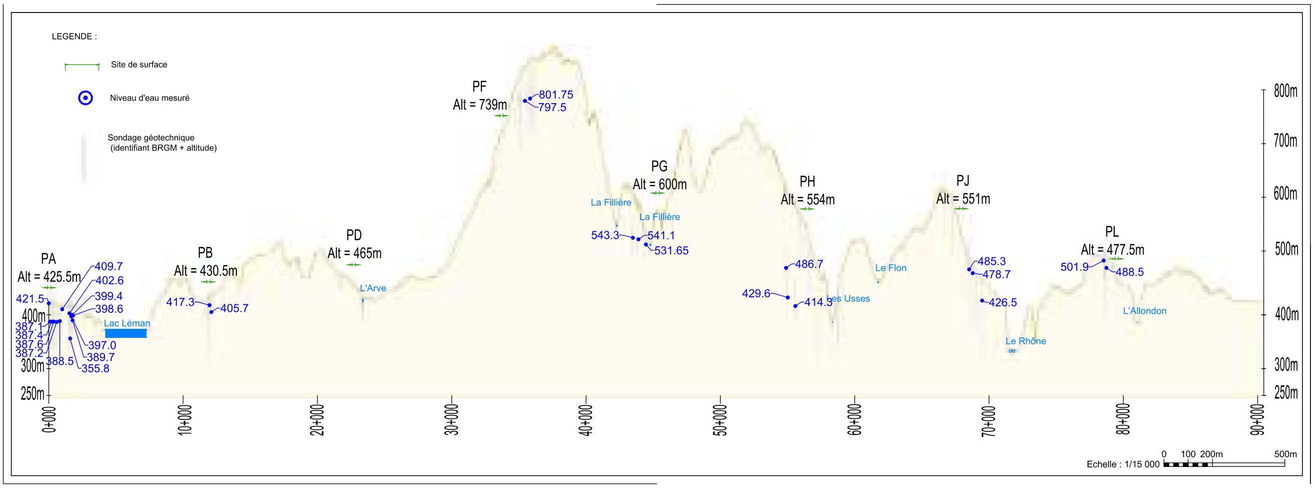

Fig. 3.19 Overview of surface and subsurface water bodies in the scenario perimeter. In this conceptual drawing, the subsurface structures are assumed to be at an elevation of 250 m. The uncertainty of the water table heights is indicated in grey. The surface site locations and elevations are indicated

cross-border aspects with respect to subsequent analysis of potential environmental aspects: effects and impacts that will need to be considered during a project preparatory phase.

Subsurface

France Concerning subsurface water, five distinct relevant water masses have been identified. FRDG517 extends from Gex across the Geneva basin to the Grande Côte de Bonmont and the Usses sector. FRDG208 lies below the FRDG517, extending from the Jura to the lake and towards the Usses sector in a calcareous geology. FRDG231 is located north of the Genevois zone in France, partially under the FRDG517, partially limited like a river between the Rhône and Divonne-les-Bains, touching the Swiss border at the height of Versoix. FRDG511 is located in the Savoie alpine region, south of FRDG517. FRDG364, corresponding to the Arve valley, passes at about 100 m of the site PD in Nangy.

With respect to the European legislation, a goal has been set to maintain the so-called 'good state' level quality attained in 2015 of all water masses. The standard needs to be maintained both in qualitative and quantitative terms.

Water-bearing layers exist in relation to these water masses. All apart from in the implementation perimeter are 'free', i.e., there are no water-tight layers towards the surface. None of the hydrogeological entities is characterised by an aquifer.

Because of the need to maintain the quality levels and the potential interactions between water masses, particular protection measures are in place that will need to be observed with respect to subsurface works.

Switzerland In Switzerland, various types of water-bearing layers are distinguishable based on their water capacity and depth. Deep layers can also exist in the molasse layer which is preferred for tunnel construction. Today, four water-bearing layers are identified in the canton of Geneva, and two of them are used for providing drinking water: Allondon and Genevois. Montfleury and Rhône are currently being studied in terms of capacities and quality with respect to serving as a drinking water supply. The deep layers are today not mapped and therefore dedicated subsurface investigations are required for a future particle collider project. A multitude of shallow and temporary layers that are between 2 and 10 m below the surface is spread over the entire canton. They need to be analysed where shafts and surface sites are planned. One of them is at a distance of about 140 m from site PB in Presinge at a depth of 2 m. No potential mutual effects could be determined.

Another water-bearing layer is at about 90 m from site PA in France. The Montfleury layer at a depth of about 45 m is located 800 m south of the main site. One shallow layer is directly at the surface site location PL in Challex in France. It spans the border, and no information is available on this layer. Sites PL and PA require particular analysis to take these layers into account for the choice of the shaft location and the shaft construction technique. All three sites, PL, PA and PB, need to consider the potential water layers in the vicinity of their surface site and consider cross-border aspects.

Surface

France Four main surface water bodies are within a radius of 1 km of the surface sites. Three of them are in good state (FRDR11960, FRDR559, FRDR537) and one has moderate quality (FRDR555c) with a goal to achieve good quality by 2033. The site PF in Éteaux is located in the vicinity of a stream (50 to 100 m). Also, site PH is in the vicinity of a small creek (30 m). Other sites such as PD (600 m from the Arve) and PG (300 m from the Fillière) are further from rivers.

Switzerland Lake Geneva in Switzerland is the most important water body at the surface. It is 4 km from the PA and PB sites. Site PB is located in the vicinity of a small stream (30 m).

Summary The projection from the line of the implementation scenario to the subsurface intersects with the geographical location of numerous subsurface water bodies. However, the tunnel will be located significantly below them (see Fig. 3.19). No intake from any subsurface water-bearing layer is expected for the construction and operation of the project. Water for drinking will be consumed from connections to the existing drinking water network. Raw water for cooling purposes will be taken from the existing water supply network for CERN in Switzerland, which takes water from Lake Geneva. Drinking water protection zones are largely avoided for the entire project so that any potential adverse effects can be excluded.

The majority of subsurface layers are not located under a watertight layer. Thus, they are potentially subject to pollution. Also molasse layers may include water-bearing volumes. Therefore, dedicated hydrogeological investigations will be carried out to optimise the location of the shafts to avoid potential adverse effects with water-bearing layers in PA (Ferney-Voltaire, France) at a distance of 35 m from a drilling ban zone (sector B in Switzerland) and PL (Challex, France). Particular attention will be devoted to avoid affecting nearby creeks and the biodiversity around sites PB (Presinge, Switzerland) and PH (Cercier and Marlioz, France). PH is, in addition, in an area with chronic lack of water and therefore subsurface works such as the creation of a shaft will have adequate protection measures in their design in case there is a risk of affecting any water bearing layers.

Concerning the release of water into the environment and particularly into nearby creeks, the design of the infrastructure will include filtering and cleaning before release. Connections to wastewater networks will ensure that all other water is released via the existing water treatment infrastructure at all times, ensuring compliance with the legal and regulatory frameworks in the two Host States.

3.3.4 Subsurface

Relief The FCC perimeter is constrained by noteworthy mountains (see Fig. 3.20). The Jura is located north and west of Lake Geneva with peaks of 1720 m. The south-east is characterised by the Bornes plateau evolving into the pre-alps that lead to Mont Blanc which has an elevation of 4806 m. The west is constrained by the Vuache mountain reaching 1112 m. The Salève (1379 m) is located in the centre of the FCC circular alignment. The Aravis mountain range is located just south of sites PD, PF and PG. Mont Sion (78t m) is located between the Vuache range and the Saléve. In the south, the tunnel crosses under the Mandallaz range (923 m), also called Balme, that is part of the pre-Alps. The Massif du Chablais is northeast of Lake Geneva and east of the PB and PD sites. Despite the presence of the numerous mountain chains and peaks, all surface sites are located on lower ground in flat areas at between 400 and 700 m elevation.

Topography Site PA is located at an elevation of approximately 425 m in an open area with a very slight slope of about 2 to 5%. Site PB is at an elevation of about 430 m on an even and open area. There are hills only a few kilometres to the north. Site PD at an elevation of approximately 460 m is located on a slope of about 5% towards the north. The zone is hilly in all directions, but the terrain is cut by major transport routes (A40 autoroute, D903 departmental road). The absence of bushes and hedges makes the terrain visible. Site PF reaches elevations of between 730 and 745 m on a slope of about 7% from west to east. This makes the area very visible towards the mountains and from the RD1203 road. However, it is not visible from the A410 autoroute. Site PG is separated from the A410 autoroute in the north by a forest on a slight slope of 5% in north-south and west-east directions at about 600 m elevation. At the southern boundary, the slope starts to become steep – from 25% to 40% towards the RD1203,:Annecy road. this area is avoided. Site PH is located on a slope of 10 to 20% at an elevation of between 517 and 591 m, falling off from the RD203 road. The entire area is located in a forest that covers the zone towards the Usses Valley in the west. The topography imposes a terracing approach for the site. The PJ site is located on a wide and long slope of 6% at an elevation of between 496 and 532 m that falls off from the A40 autoroute to the Rhône valley. This location also requires terracing. Tree lines that break the even space and slope exist in the vicinity. The PL site is located at 500 m elevation on a rather flat area. The absence of noteworthy trees or hedges in the vicinity makes the terrain highly visible. The land falls off steeply towards the Rhône valley on the opposite side of the nearby pathway towards Switzerland.

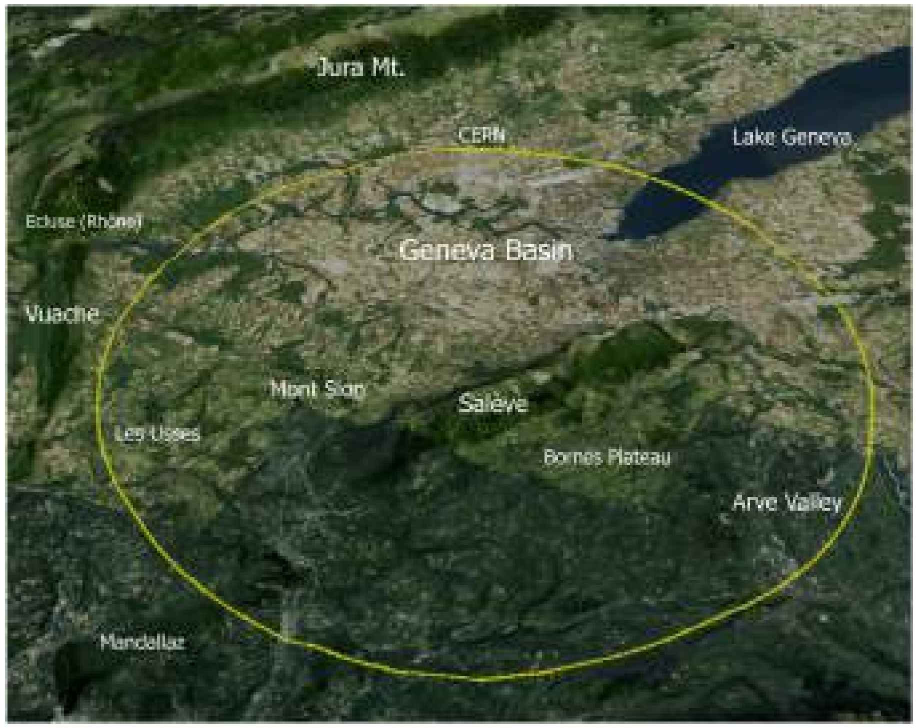

Fig. 3.20 Relief in the area of the FCC reference scenario

Geology The geology is covered in greater detail in the sections on civil engineering since it determines the placement of the subsurface works. Here, a general overview (as shown in Fig. 3.21) provides the context. The geological landscape of the Genève Basin spans between the Jura Mountains in the northwest and the Prealps in the southeast, with a Tertiary molasse basin overlaying Cretaceous formations. Shaped by Quaternary glaciations, the basin features deep valleys and sedimentary deposits up to 400 m thick, especially in the Grand-Lac, with Holocene sediments varying by river currents. The Rhône Delta sees Holocene sediments exceeding 100 m in thickness. The basin's geology includes three main units: Jura sedimentary rocks in the northwest, central Tertiary sandstone (molasse), and thrusted molasse with Prealpine units in the southeast.

The Ain department is located on two very different geographical and geological domains with, to the west, the large plains of Bresse and Dombes the western plains of Bresse and Dombes, a tectonic rift filled with Tertiary deposits, and to the east, Jura mountains, marking the southwestern edge of the Swiss molasse plain. In addition, the department is covered by three large geological units, Bresse and Dombes including Côtière and part of the Val de Saône; Bugey and the southern part of Revermont and finally the Pays de Gex. The Pays de Gex, where the PA and PL sites are located, features mountainous limestone formations (Middle and Upper Jurassic, Lower Cretaceous) with karst systems, bordered by faults and glacial deposits. Similarly, the surface sites PD, PF, PG, PH, PJ in Haute-Savoie in France and PB in Switzerland are part of the molasse basin and showcase diverse geological features from crystalline Alpine massifs to sedimentary molasse basins like the Plateau des Bornes. These molasse deposits, formed from Alpine erosion during the Oligocene to Miocene, vary in thickness and are tectonically influenced by Alpine uplift. The geological formations of the different surface sites are presented in Table 3.11.

Soil Field soil investigations were carried out in July 2023 for site PD and in April 2024 for the sites PA, PB, PF, PG, PH, PJ and PL. The primary objective was to analyse the pedological characteristics of the soil of these sites to determine their suitability for agricultural activities and other potential uses.

The work consisted in the identification and description of existing vegetation and crops, as well as the assessment of factors impacting agricultural productivity, such as accessibility, topography, non-cultivable areas, wet zones, and irrigation infrastructure. Soil samples were collected using hand augers (see Figs. 3.22 and 3.23) up to a depth of 120 cm to examine soil layers, coarse elements, and traces of waterlogging. The number of samples per site was determined based on plot size and soil diversity in order to ensure adequate representation. A total of 48 samples were collected across the eight sites.

The PA site is dominated by deep loamy soils (neoluvisols) with a low content of coarse elements, although areas near roads feature shallower and rockier soil.

At the PB site, the surface horizon consists of clay-loamy soils with low amounts of coarse elements, but signs of pseudo-gleying appear in deeper layers.

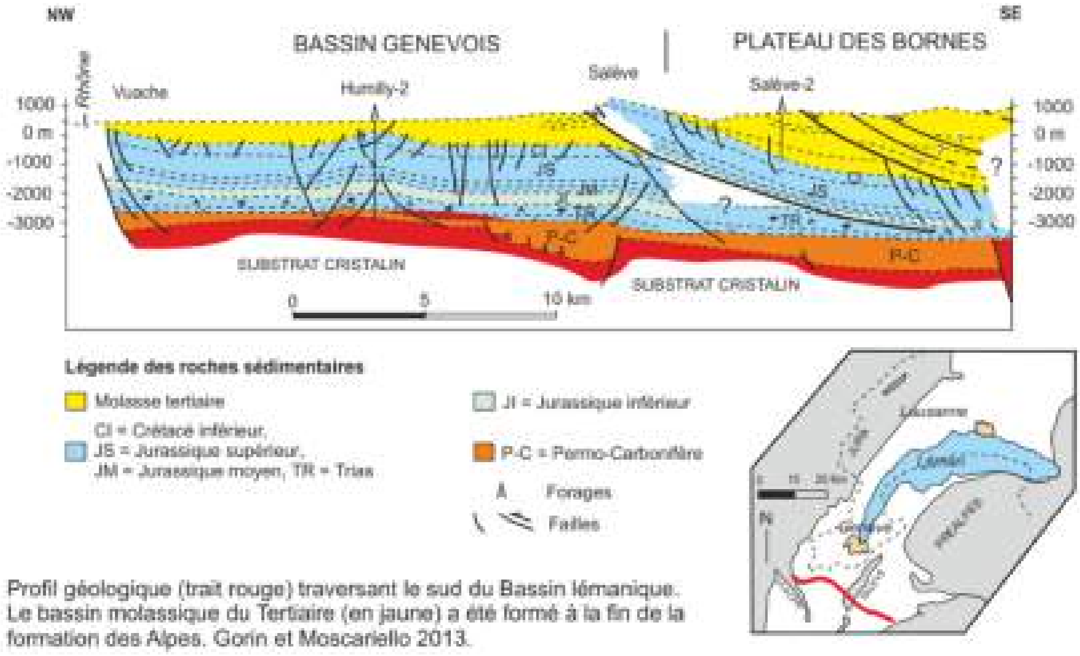

Fig. 3.21 Geological profile of the Geneva Basin, illustrating stratigraphic units, tectonic features, and sedimentary formations shaping the region

Table 3.11 Geological formations present at surface sites

Site	Deposits	Composition of materials
PA	Würmian glacio-lacustrine	Layered clays and silts
PB	Morainic	Clays, silts, and sands
PD	Glacio-lacustrine	Clays and silts
PF	Würmian to post-Würmian morainic	Silts, sands, pebbles, gravels, with localised presence of clays
PG	Würmian morainic	Clays, sands, pebbles, stones, and boulders
PH	Würmian to post-Würmian morainic	Clays, sands, pebbles, stones, and boulders
PJ	Würmian to post-Würmian morainic (or colluvium)	Silts, sands, pebbles, gravels, with localised presence of clays
PL	Würmian morainic	Pebbles, gravels, sands, and limestone with localised presence of clays

PD site is characterised by deep loamy soils, healthy and well-drained, with low, coarse elements throughout the soil profile and limited hydromorphy. The soil is highly suitable for agriculture due to its deep, fertile, and easily mechanisable soils.

At the PF site, the surface layer consists of loamy neoluvisols with low rocky content, while clay accumulation begins at around 70 cm depth. These parameters are suitable for permanent grasslands.

The surveys carried out at the PG site and its annexes show that the present soil does not match the soil recorded in the French GIS-Sol database. The soil of PG main site is deep, homogeneous, and range from clayey to clay-loamy textures, with low amounts of coarse elements and temporary hydromorphy traces. Annex sites have lighter, powdery soils, moderately deep with a clay-loamy texture.

The PH site is covered by deep Brunisol-type soils with Redoxisol characteristics, where strong hydromorphic features are already apparent near the surface, indicating limited drainage. The survey confirms that the permanent grassland at a small part of the PH surface site corresponds to the soil cover listed in the database.

PJ site is characterised by deep argilo-limoneux soils with minor coarse elements. Moderate hydromorphy is visible near the surface, with traces of altered limestone beyond 70 cm. The area is suitable for both permanent and temporary grasslands.

Fig. 3.22 The auger boring method used to obtain soil samples from different depths

Fig. 3.23 Soil sample obtained by using auger boring method

PL site at the border with Switzerland is predominated by calcosols with areas of colluviosols in southern regions. Soils vary from superficial to deep, with coarse elements more common in superficial areas. Hydromorphic features are less pronounced, and soils are generally suitable for agriculture.

Overall, most surface sites have deep soils with limited coarse elements, ensuring good agricultural potential, although hydromorphic tendencies and limited drainage at certain locations limits their agricultural use. Additional laboratory analyses of the soil are currently being conducted to assess its quality in terms of the presence of various mineral elements and their availability to plants, and potential contaminants.

Summary Concerning relief and topography only, site PH in Cercier and Marlioz exhibits significant issues due to the slope in the forest. PJ in Dingy-en-Vuache and Vulbens is also located on a slope, but it is in an open area and significantly less steep with good access. Sites PA, PB and PL on very open and flat areas call for particular integration with respect to visibility and co-visibility. Site PD and PF do not exhibit any particular challenges, although good landscape integration is advisable to reduce visibility and to blend into the terrain. Care needs to be taken at site PG to stay clear of the steep slope towards the Annecy road.

The geological context of the study area highlights the diversity of formations across the Geneva Basin and the Ain and Haute-Savoie departments. The basin features sedimentary deposits influenced by quaternary glaciations,

Fig. 3.24 Fiery Clearwing Moth *(Pyropteron chrysidiformis)* feeding on a plant

with thick holocene sediments in the Rhône Delta and Grand-Lac. The sites span different geological units: Pays de Gex (limestone formations with karst systems) and molasse basins (formed by Alpine erosion), showcasing a variety of materials, including glacio-lacustrine clays, morainic sands, gravels, and silts. These variations underline the region's complex geological history, which is crucial for subsurface work placement and excavated material management.

The pedological surveys confirmed diverse soil characteristics, ranging from deep, fertile, and well-drained loamy soils to hydromorphic and clayey profiles with drainage limitations. Sites such as PD and PL are highly suitable for agriculture due to their deep, fertile, and easily mechanisable soils. PA, PB, PF, and PJ show varying degrees of hydromorphy, particularly in deeper layers, making them more suitable for grasslands or selective agricultural practices. PH and PG present significant hydromorphic constraints, with PH showing pronounced surface water retention issues due to its altered limestone subsurface. Variations in texture, depth, and coarse element content reflect the influence of local geology and historical land use.

3.3.5 Biodiversity

Biodiversity refers to the diversity of species, ecosystems, habitats and ecological processes. It includes both natural and human-modified environments, which together create the conditions for the existence and functioning of various organisms. A variety of species in the natural spaces are not locally confined. They extend across fauna corridors and ecologically coherent zones that comprise the terrestrial and aquatic species, namely plants, insects, mammals, amphibians and reptiles, which are considered as an integrated whole.

To assess potential impacts on biodiversity, the current situation was analysed for all candidate surface site locations, first using bibliographical information. This includes, for example, the study of protection zones at regional, national and international levels, inventories of natural heritage, ecological corridors and their continuations. Then, field investigations were carried out by numerous experts over a time frame of more than one year, covering the four seasons. Various photographs from these field investigations are shown in Figs. 3.24 to 3.32. The investigations served not only to confirm and complement the existing bibliographic information but also as necessary input to establish a baseline for the avoid-reduce-compensation approach, the optimisation of the sites and the subsequent environmental impact assessment. The investigations were not restricted to the area within the perimeters of the surface site locations. They were extended to a perimeter of up to several hundred metres larger, depending on the topography, but the extension was investigated in less detail. An extended perimeter covering up to 5 km was analysed at a high level with the help of existing databases and cartographic materials.

Site PA in Ferney-Voltaire is in the vicinity of nature protection and humid zones as well as forests that serve as cross-border corridors for animals. Amphibian breeding zones are noted in the enlarged perimeter on the Swiss side. The forests also serve as retreat areas for migrating birds. There are nature protection and wetland zones, including amphibian reproduction zones, in the vicinity of the PB site in Presinge. There is a protection zone for migrating birds at some distance. For site PD in the Arve area there is a nature protection zone in the vicinity. Nature protection zones and ecological corridors have been identified in the vicinity of site PF in Éteaux. Several nature protection zones also exist in the vicinity of site PG in Groisy and Charvonnex. Further away, there is a biotope protection zone. Nature protection zones also exist in the vicinity of site PH in Cercier and Marlioz. At some distance, there is a biotope protection zone. Rare species are found in the immediate vicinity of the site and partially at the limit of the site, mainly close to a creek that passes at the site boundary to the north. There are

Fig. 3.25 Bocage hay meadow photographed during the field investigations

nature protection zones in the vicinity of site PJ in Dingy-en-Vuache and Vulbens. There are nature protection zones and cross-border ecological corridors, linking forest spaces and the Allondon zone with the Rhône river zone in the immediate vicinity of site PL in Challex. Strict bird protection zones on the Swiss side of the border extend into the forest on the French side. There, biotope protection zones are known.

None of the sites is directly affected by a nature protection restriction, a national park or international biodiversity protection regulations (e.g., Natura 2000, RAMSAR, UNESCO or national parks).

Natural habitats In the context of environmental analysis, a habitat refers to the natural environment or ecosystem where a particular species, community, or group of living organisms lives, grows, and thrives. It includes the physical, chemical, and biological components that support life, such as soil, water, air, terrain, other plants and animals and the interaction among all those components. The studies carried out comprised establishing an inventory of the existing habits at the surface sites, investigating the perimeters around them, and evaluating their characteristics and qualities. This work helped to determine the sensitivity levels associated with the larger zones concerned by the surface sites in order to apply the avoid-reduce-compensate scheme for further optimisation of the project scenario.

Site PA in Ferney-Voltaire, France is predominantly a peri-urban, open agricultural habitat of about 70 ha that is also closely linked to Geneva airport, agricultural spaces in Switzerland and forest spaces between Switzerland and France. Its mainly formed by prairie, bushes, trees, monocultures and artificial habitats (paths, roads, industrial and commercial buildings). The groves in the vicinity of the site exhibit high sensitivity. Overall, the sensitivity on the site is average to low, often only partially fulfilling the requirements of a habitat.

The site PB in Presinge, Switzerland, is also an open agricultural space dominated by monocultures with some nearby woodlands and isolated hedges. Only a thin strip in the close vicinity of the nearby creek exhibits a moderate to average habitat quality.

Site PD in Nangy, France is located in a rural context, constrained at the side by an autoroute and a departmental road and one side is bordered by a hamlet. Some isolated bushes and trees can be found in the vicinity. The habitat quality is very low to low. Only in a small patch at the southern end at the surface site border, the bushes represent a high value in this much-constrained space.

Site PF in Éteaux, France is in a mixed agricultural and prairie zone. Woodland starts to appear at the borders. The north is limited by a heavily used national road. The enlarged investigation zone includes a wetland. At the location of the surface site the habitat quality is low to average. The neighbouring wetlands and forest lands have a strong sensitivity.

Site PG in Groisy and Charvonnex in France is located in a mixed environment consisting of prairie, woodland, grassland and rural/forest paths. The enlarged space close to the autoroute is dominated by artificialised spaces such as retention basins, temporary inert waste buffering, roads, paths and constructed areas. The zone can, in general, be characterised as predominantly a forest habitat. On average, the whole zone studied exhibits a low to average level of habitat quality. Where areas can be considered wetlands, both inside and outside woodlands, the habitat quality can be considered average. Two forest areas that are outside the site perimeter, but in the immediate vicinity, have been identified to have a high sensitivity due to the quality of the trees.

Site PH in Cercier and Marlioz in France is almost entirely located in a woodland. There exist some cleared spots that host prairies and grassland. Overall, the habitat quality is low and where monocultures exist, it is very low. A zone exists that can be considered a wetland due to its characteristics south of the site. Its effects extend to a 0.4 ha large part of the site, making this area a high-quality habitat zone.

Site PJ in Dingy-en-Vuache and Vulbens in France is located in an open rural, agricultural space that is limited at two sides by treelines, a temporary creek, by an autoroute in the north and a rural path and further agricultural