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Social Cost Benefit Analysis of HL-LHC

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Study of the socio-economic impact of CERN HL-LHC and FCC

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REPORT SOCIAL COST BENEFIT ANALYSIS OF HL-LHC

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LIST OF ABBREVIATIONS

CBA	Social Cost Benefit Analysis
CFS	Counterfactual scenario
CHF	Swiss Francs
ESR	Early Stage Researchers
FFS	Florio, Forte, Sirtori (2016)
HL	High Luminosity
LHC	Large Hadron Collider
MCHF	Millions of Swiss Francs
NPV	Net Present Value

EXECUTIVE SUMMARY

- We present a Social Cost–Benefit Analysis (CBA) of the High Luminosity upgrade of the Large Hadron Collider (HL-LHC), assessing its economic costs and benefits up to 2038.
- The Net Present Value (NPV) of the HL-LHC project is positive at the end of the observation period.
- The ratio between incremental benefits and incremental costs of the HL-LHC with respect to continue operating the LHC under normal consolidation (i.e. without high-luminosity upgrade) is slightly over 1.7, meaning that each Swiss Franc invested in the HL-LHC upgrade project pays back approximately 1.7 CHF in societal benefits.
- Simulations based on 50000 Monte Carlo rounds show that there is a 94% chance to observe a positive NPV (i.e. a quantifiable economic benefit for the society).
- The attractiveness of CERN for Early Stage Researchers (ESR) is key for a positive CBA result. Given that benefits to ESRs are the single most important societal benefit, CERN should invest more in activities facilitating the transition to the international job market.
- Technological spillovers are another very important ingredient in the CBA evaluation of CERN research infrastructures. Relations with firms in the supply chain and development of Information and Communication Technologies (ICT) are strategic levers CERN should use to boost these social benefits.
- Cultural effects, especially those related to onsite visitors, have a great development potential for generating societal benefits. This part needs to be quantified in greater detail to understand, how this benefit potential can be further increased efficiently in cooperation with the host states.

1. AIM OF THE REPORT

CERN and its accelerator complex represent a unique international research infrastructure whose societal impacts go well beyond the scope of advancing the frontier of knowledge in High Energy Physics (see [1]; [2]; [3]). This report presents a social Cost–Benefit Analysis (CBA) of the High Luminosity (HL) upgrade project of the Large Hadron Collider (LHC) programme, assessing its economic costs and benefits until 2038. This work extends the initial CBA study concerning the LHC [1].

Since the aim of the HL-LHC project is to extend the discovery potential of the LHC after 2025, it is also expected to prolong its impacts on the society. The project schedule of HL-LHC is shown in Figure 1(b).¹ A CBA is an appropriate methodology for assessing the multi-dimensional nature of benefits ascribed to the HL upgrade of the LHC [4]. The “Horizon 2020 – Work Programme 2018-2020 on European research infrastructures” mentions that the preparatory phase of new ESFRI projects (www.esfri.eu) should include a CBA [5].²

The structure of the report is as follows. Section 2 briefly presents an overview of the CBA methodology applied to RI. Section 3 details the main assumptions underlying the CBA. Sections 4 and 5 present the results for social costs and each category of benefit. Section 6 summarizes the results of the CBA. A set of Annexes with more details and technicalities complete the report.

2. THE CBA METHODOLOGY

Assessment of the socio-economic impacts of RIs has been included in the latest edition of the “Guide to Cost-Benefit Analysis of Investment Projects” of the European Commission [6]. The theoretical background of the CBA model for a RI is presented in [7] and [8], while details concerning the CBA analysis of the LHC programme are presented in [1]. A broad overview of the CBA methodology is offered by [9], [10] and [11]. A CBA model for the evaluation of a RI focuses on the estimation of its expected Net Present Value (NPV_j) at the end of a defined observation period:

$$E(NPV_j) = E[DB_j - DC_j] \quad (1)$$

While details underling the CBA methodology are presented in Annex A and Annex C, the interpretation of results is straightforward: a RI passes the CBA test when benefits exceed its costs for the society, that is when the expected NPV is greater than zero. The cumulative sum of discounted social costs and benefits of project j over its lifespan are denoted as DC_j and DB_j . Discounted costs and benefits are calculated as follows: suppose that $t = 0$ is the “base year” of the project – 2016 for the CBA of HL-LHC - and r , is the social discount rate.³ $DC_{jt} = C_{jt} / (1 + r)^t$ with $t = -23, \dots, 0, \dots, 22$, is the discounted cost at time t and $DC_j = \sum_{t=-23}^{22} DC_{jt}$. In this case $t =$

¹ <https://home.cern/topics/high-luminosity-lhc>

² Successfully passing a CBA test is required also for co-financing major projects with the European Regional Development Fund and the Cohesion Fund. According to Article 100 of EU Regulation No 1303/2013, a major project is an investment operation comprising “a series of works, activities or services intended to accomplish an indivisible task of a precise economic and technical nature which has clearly identified goals and for which the total eligible cost exceeds EUR 50 million.”

³ The “base year” does not necessarily correspond to the starting year of the project.

-23 corresponds to 1993 and $t = 22$ to 2038, therefore all costs and benefits until 2015 are integrated. Those from 2017 onward are discounted.

Each RI involves a set of benefits, costs and stakeholders. In the case of HL-LHC, we limit the analysis to the discounted value of the following, most relevant benefits:

1. The value of training (or human capital formation) for students and early stage researchers (DH_j),
2. Technological or industrial spillovers for collaborating firms and other economic agents (DT_j),
3. Cultural effects for the public (DL_j)
4. Academic publications and pre-prints for scientists (DS_j).
5. Existence or public good value of the RI for non-users.

A more precise definition of each category of benefits is provided in Section 5. Within the CBA framework costs do not only include operating and investment expenditures, but also indirect costs for the society. Any emission of pollutants, production of noise or traffic related with to construction and operation of the RI are examples of indirect costs for the society. Economists call these indirect societal costs negative “externalities”. Costs can thus be split into investment and operation expenditures (DF_j) and negative externalities (DX_j , e.g. pollution). Therefore, equation (1) can be written as follows:

$$E(NPV_j) = E[(DH_j + DT_j + DL_j + DS_j) + EXV_j - (DF_j + DX_j)] \quad (2)$$

We assume that negative externalities are negligible ($DX_j = 0$) and that the present value for non-users corresponds to the existence or public good value of the RI (EXV_j). Non-users are people who currently do not directly use the services of the RI, but are better-off simply because they know that new knowledge might be created. The existence value represents the benefits due to the fact that that new knowledge might be generated for the society. This is also known as “public good value” in that all individuals can eventually access and use it and the use by one individual does not reduce its value and availability to others. This is very much like the conservation of biodiversity, or of cultural heritage. It is therefore simply the benefit of knowing that something might be discovered. As shown in Section 5.5 this quantity can be estimated by quantifying the Willingness To Pay (WTP) for the creation of new knowledge by taxpayers (see also Annex B). The practical implementation of model (2) involves the following steps.

1. Identify which benefits and costs are relevant for the specific RI.
2. Estimate present and future benefits and costs.
3. Use Monte Carlo simulations to estimate the probabilities of costs, benefits and of the NPV of the project. See [9] and [10].

3. TIME HORIZON, BASELINE AND COUNTERFACTUAL SCENARIOS AND OTHER TECHNICALITIES

Assumptions. Since HL-LHC is an upgrade of the LHC, two scenarios are considered. The baseline scenario is CERN with the HL upgrade and the counterfactual scenario is the operation of the LHC until its end of life without the HL upgrade.

Figure 1. HL-LHC and Counterfactual scenario: 1993-2038
(a) Sketch of the CBA scenarios.

(b) HL-LHC project schedule

Notes: dates in panel (a) represent time schedules consistent with assumptions discussed with CERN experts. figure in panel (b) has been retrieved in February 2018 from: <https://project-hl-lhc-industry.web.cern.ch/content/project-schedule>.

The baseline scenario (HL-LHC). For the CBA assessment, the HL-LHC scenario and the CFS are identical during the 1993-2014 period; the first run of the LHC with the new HL upgrade is expected around 2026-2027. See Figure 1(b) for the project schedule of HL-LHC.

The counterfactual scenario (CFS). The CFS entails continuing to operate the LHC “with ordinary consolidation activities”; after 2031, data taking ends and CERN staff shift their engagement to other scientific activities. Planned maintenance and repair activities are considered. After the collider is switched off, the equipment remains in the tunnel and the underground infrastructure would be subject to appropriate monitoring and safety procedures without being operated. A minimum of cooling, ventilation, electricity and water supply would remain operational.

Time horizon. The horizon of the analysis spans the 1993-2038 period. From 1993 to 2014, the two scenarios overlap and hence the costs and benefits are identical to those considered in the CBA of the LHC by [1]. The two scenarios are sketched in Figure 1(a).

Currency, base year and discount rate. The analysis is carried out in Swiss Francs (CHF). The base year for social discounting and inflation adjustments is 2016, and the social discount rate⁴ r is 3%, as recommended by the European Commission’s CBA Guide [6]. See Annex A for details on the social discount rate. Values for the 1993-2016 period have been adjusted for inflation using the Consumer Price Index for Switzerland sourced from the 2017 release of the International Monetary Fund’s World Economic Outlook Database.⁵ After 2016 we assume that prices remain constant. No attempt has been made to model or forecast exchange rate variations.

4. OPERATING AND INVESTMENT COSTS

In both scenarios total costs include past (before $t=0$) and future expenditures (after $t=0$) that are attributed to the LHC accelerator complex programme and by the four main international LHC experiment collaborations: ATLAS, CMS, LHCb, ALICE (on the contrary, TOTEM, LHCf and MoEDAL have not been considered). For the 1993-2014 period, the costs are the same as those documented by [1]. For 2015-38, expenditure estimates have been provided by CERN’s Finance and Administrative Processes Department (FAP). Scientific CERN staff personnel costs are not considered. The rationale for not considering scientific personnel cost is that we assume this share of cost to balance the “production cost” of scientific publications, that is one of the benefits produced by the research infrastructure. Since we account for this benefit as a separate category, we remove it from costs to avoid counting it twice.

⁴ For the motivation of using of a 3% social discount rate also for Switzerland see e.g.: <https://trimis.ec.europa.eu>

⁵ Source: <http://www.imf.org> (last accessed October 2017)

Figure 2. HL-LHC and CFS cost estimates for 1993-2038 (in undiscounted 2016 million CHF).

(a) Total cost 1993-2038

Average	22568
Median	22517
Min	21517
Max	23883
Std. Dev.	496

(b) Monte Carlo cumulative distribution function for HL-LHC

Notes: panel (a) shows discounted costs over the 1993-2038 period for HL-LHC (thick line), CFS (thin line) and their difference (bars). Panel (b) shows the simulated Cumulative Distribution Function (CDF) based on 50000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the probability to observe a value not greater than the median is 50%. Panel b also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows

some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.
Data available in the Data Appendix attached to this report.

To subtract the share of personnel cost from the overall expenditures, an estimation has been done using data from the “Final Budget of the Organization for the sixty-second financial year 2016”.⁶ For each cost item, we have taken a percentage that is attributed to the LHC programme. This percentage has been kept constant over the estimation period. Consistently, scientific personnel is assumed to 32% of the total personnel cost of CERN and is assumed to be 100% cost for the experiment collaborations (see [1]). “Total costs” are thus “total costs net of the share due to scientific personnel costs”.

Results. Figure 2(a) shows the evolution of total cost for the two scenarios as well as their difference. Figure 2(b) illustrates the result obtained by of 50000 Monte Carlo simulation rounds of the HL-LHC cost distribution⁷. These are derived relying on a triangular distribution⁸ for total programme costs with minimum of 96% and maximum of 111% of the baseline value that is equal to 22200 MCHF, corresponding to the mode of the distribution. The baseline value is the cost estimate before running the simulation. The shape of the triangular distribution is defined by three parameters the minimum, the maximum and the mode, that is the value that is expected to be observed more often. Providing reasonable guesses of the values of these three parameters is relatively easy and hence we use this distribution very often. These guesses are provided either by interviewing experts of a given topic or looking at previous evidence. Details are provided by [6], [1], [10], [11]. In this case, the parameters of the triangular distribution have been chosen using two scenarios for the evolution of HL-LHC costs provided by the CERN Finance Department. The difference between the total cost in the two scenarios is about 2900 MCHF.

5. BENEFITS

For both scenarios we consider the following relevant benefits over the observation period:

- Value of training or human capital formation, benefit created by the acquisition of additional knowledge, skills, competencies by students and Early Stage Researcher (ESR);
- Scientific publications that scientists use as basis for further research and career growth;
- Industrial spillovers for firms and other organizations;
- Cultural benefits for the public: this includes the economic value created through science tourism based on the visits of CERN and travelling exhibitions as well as benefits that emerge from media products, which can be causally related to the LHC and HL-LHC programme.
- Public good value of human knowledge advancements through scientific exploration for taxpayers.

⁶ More precisely, we used figures from pages 14-18 of document CERN/FC/5955 available online at: <https://cds.cern.ch/record/2126982>

⁷ There is considerable uncertainty involved in the estimation and forecast of social benefits and costs in that their quantitative assessment requires making assumptions on the value of some underlying “deep” or “structural” parameters. Treating these parameters as random variables with a given distribution allows to estimate – via Monte Carlo simulations - a statistical distribution for each cost and benefit. A separate report, currently in preparation, will provide a through discussion of Monte Carlo methods in the context of CBA. See Chapter 2 in European Commission (2014).

⁸ See [6].

Figure 3. Benefits for Students & Early Stage Researcher

Value of training	
Average	8546
Median	8542
Min	7036
Max	10151
Std. Dev.	546

(c) Monte Carlo cumulative distribution function (CDF) of human capital benefits for HL-LHC

Notes: panel (a) shows the number of Early Stage Researchers over the 1993-2080 period for HL-LHC (thick line) and CFS (thin line). Panel (b) shows discounted benefits over the 1993-2080 period for HL-LHC (thick line), CFS (thin line) and their difference (bars). Panel (c) shows the simulated Cumulative Distribution Function (CDF) based on 50000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the probability to observe a value not greater than the median is 50%. Panel c also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report.

5.1. Benefits for Students & Early Stage Researcher - The Value of Training

This benefit measures the salary increase or premium over the active work period for persons that have been involved in the LHC program as students or Early Stage Researchers.

Assumptions. This analysis considers only technical students, doctoral students and post-doctoral researchers younger than 30 years who are enrolled in a CERN education program. Moreover we also include those CERN registered “Users” who are between 30 and 35 years old.

We assume a maximum career length of 42 years.⁹ Given this assumption, the 2038 cohort of ESRs will enjoy a “salary premium” due to their experience at the HL-LHC or LHC until 2080. That represents the horizon for benefits related with human capital formation. The career length is calibrated to the years of contributions required to get a pension.¹⁰ Until 2025, the benefits are the same for both scenarios. Then the number of ESR in the CFS decreases steadily to reach zero in 2031. See Figure 3(a).¹¹

Methods. Using the yearly arrival rate of ESRs and the average time of stay at CERN, we estimate how many ESRs start a professional career elsewhere every year (see [12], [13], [14]). We then compute the time discounted value of the benefit for ERS, DH_j :

Results. Application of this methodology leads to the results displayed in Figure 3(b) and 3(c). In the case of HL-LHC, the value of training represents 33% of total benefits. Considering the benefits in this class produced by the HL-LHC minus the corresponding benefits produced under the CFS (i.e. $\Delta DH = DH_{HL-LHC} - DH_{CFS}$), this percentage rises to 40%.

5.2. Benefits to firms & other organizations –Industrial spillovers

Industrial spillovers arise for firms working with CERN by resulting in new products, services, creation of new business opportunities and more efficient operation for companies. The generation of benefits in this category does not require the creation of new intellectual properties, new technical principles or designs. The mere gain of experience working in a large-scale international project with different parties, different

⁹ Setting a different number such as 38 years does not alter the analysis other than simply reducing the overall benefits in this category for both scenarios. Moreover, the uncertainty related with this benefit included in the Monte Carlo simulation is larger than a minor reduction of a lower assumed career length to 40 or 39 years

¹⁰ See <http://www.oecd.org/pensions>

¹¹ These assumptions have been discussed with many people at CERN, including: Andrzej Charkiewicz (CMS); Joel Closier (LHCb); Anna Cook (HR Dept.); Carmelo D'Ambrosio (LHCb); Fido Dittus (ATLAS); Laure Esteveny (Alumni); Nathalie Grub (LHCb); Adriana Talasca (Alice).

methodologies, cultures and methods is the main driver of economic benefits, as a company survey and interview series with suppliers in the frame of the LHC project revealed. See [15].

Two benefit categories related with industrial spillovers have been considered in this study:

1. Additional earnings increase for companies involved in the HL-LHC programme,
2. The estimated value of free software developed in the frame of the HL-LHC programme.

These two estimates represent a conservative and lower-bound, limited estimate of the potential industrial spillovers.

Results. the case of HL-LHC, these two benefits represent 40% of total benefits.

5.2.1. Benefits for hi-tech firms

Assumptions. The benefits are proportional to the value of hi-tech procurement contracts. The classification of orders into high and low-tech follows [1] and is based on a sample of 300 LHC orders exceeding 10000 CHF. These orders have been classified with the help of experts at CERN according to a five-point scale 1) “very likely to be off-the-shelf products with low technological intensity”; 2) “off-the-shelf products with an average technological intensity”; 3) “mostly off-the-shelf products, usually high-tech and requiring detailed specifications”; 4) “high-tech products with a moderate to high specification activity intensity to customize a product for LHC”; 5) “products at the frontier of technology with an intensive customization work and co-design involving CERN staff.” Notice that the term “product” also includes material treatments, consultancies, constructions, installations and other services. An average technological intensity score has been attributed to each CERN activity code; we have classified as high-tech the codes with average technological intensity equal or greater than 3. This led to the identification of 23 high-tech activity codes. In the case of the LHC the procurement value for orders related to these codes was 35% of the total of procurement expenditures.

For the HL upgrade the undiscounted values are the same as those in [1] until 2014; we extend these benefits over the 2015-2038 period under the assumption that the share of hi-tech procurement represents 100% of for the experiment collaborations and 85% for the CERN managed activities. For HL-LHC, the share of hi-tech procurement is assumed to be higher than under the CFS. Uncertainty regarding these percentages is dealt with the Monte Carlo simulations.

For the CFS the undiscounted values are the same as those in [1] until 2025. Then, between 2026-30 these percentages decrease steadily until they are set to zero from 2031 onwards. This assumption builds on the fact that after the switch-off, the equipment is not operated or maintained.

Methods. Given the total yearly procurement ($PROC_t$), we compute the share of hi-tech procurement $PROC_t$ and then multiply it by a sales multiplier S^{Mult} . The resulting number is multiplied by the average incremental expected profit¹² $\Delta\Pi$ of a representative sample of collaborating firms $Share^{HT\,PROC}$. This can be summarized as follows:

¹² Profits are estimated relying on the EBITDA, that represents Earnings before interest, tax, depreciation and amortization.

$$PROC_t \times Share^{HT\,PROC} \times S^{Mult} \times \Delta\Pi \quad (4)$$

In the Monte Carlo simulations, we consider $Share^{HT\,PROC}$, S^{Mult} and $\Delta\Pi$ as stochastic. The modal and baseline value of S^{Mult} is 3. S^{Mult} is assumed to have a triangular distribution with support in the 1.4 – 4.2 range (see [16], [17], [18], [19]).

Figure 4. Benefits for hi-tech suppliers: 1993-2038

(a) Benefits for hi-tech suppliers

Industrial spillovers	
Average	5055
Median	4621
Min	0
Max	24404
Std. Dev.	3733

(b) HL-LHC: Monte Carlo cumulative distribution function (CDF)

Notes: panel (a) shows discounted benefits over the 1993-2080 period for HL-LHC (thick line), CFS (thin line) and their difference (bars). Panel (b) shows the simulated Cumulative Distribution Function (CDF) based on 50000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median

the probability to observe a value not greater than the median is 50%. Panel b also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding. Data available in the Data Appendix attached to this report.

$\Delta\pi$ is assumed to follow a Normal distribution with a mean equal to 13% and standard deviation equal to 10% for all technology domains. This assumption implies that simulated values of $\Delta\pi$ can be negative, representing losses for the collaborating firm. In practice, to avoid applying a multiplier to losses, we truncate the distribution of $\Delta\pi$ to zero so that benefits for collaborating hi-tech firms cannot be negative.

Results. In the case of HL-LHC, incremental profits for firms represent 16% of total benefits because of sales to customers other than CERN. This percentage increases to 29% if we consider the difference between HL-LHC and the CFS. As it can be seen from Figure 5(b) the long right tail of the distribution suggests that these benefits can be potentially much larger than our baseline value.

5.2.2. Information and Communications Technologies

Assumptions. Our assumptions are mainly based on interviews with experts in of Information and Communications Technologies (ICT) at CERN¹³, working in different departments and groups. HL-LHC needs additional developments related to software, storage, networking and computing solutions (see e.g. [20]).¹⁴ The interviewed individuals reported that the quantification of ICT benefits is still an ongoing subject (e.g. see also [21]). For this reason, we choose to extend only the already estimated benefits deriving from the two software packages ROOT and GEANT4 to 2038. Even if those particular software packages were replaced or evolved into new software packages, such developments would continue to create benefits. We include a third category, labelled “other ICT benefits”, to capture further positive externalities deriving from the development of additional software and services for storage (e.g. scalable file system services) and computing (e.g. Cloud and Grid computing management tools) solutions necessary for the HL upgrade.¹⁵ For the CFS scenario, we assume that benefits associated with GEANT4 will remain constant, but we set the benefits associated with ROOT to zero from 2026 onward. We did not consider further ICT related benefits in this scenario. The discounted benefits associated with software and ICT are shown in Figure 4(a), where for the HL-LHC scenario we can see three peaks due to ROOT, GEANT4 and other ICT developments.

Methods. For both GEANT4 and ROOT the benefit is proportional to the avoided cost to purchase, or develop from scratch, an alternative software or ICT solution. Details on the estimation of these benefits are provided in [1]. The best guess at the point of making the assessment was to multiply the estimated avoided cost due

¹³ We thank Stefano Carrazza (Theoretical Physics Dept.), Gabriele Cosmo (ROOT and GEANT), Alberto Di Meglio (CERN Openlab), Ben Farnham (Quasar OPC-UA project), Pedro Ferreira (INDICO), Pere Mato (Root and GEANT), Piotr Nikiel (Quasar OPC-UA project), Alberto Pace (EOS Storage system), Stefan Schlenker (Quasar OPC-UA project) and Nick Ziogas (Quasar OPC-UA project).

¹⁴ See also (last accessed: 22/02/2018): <http://cerncourier.com/cws/article/cern/70139>; <https://home.cern/about/updates>; <http://openlab.cern/>.

¹⁵ Given the difficulties to quantify the impact of such ICT technologies, we conservatively assume that these benefits are the same as those produced by ROOT. We thus posit that they are zero until 2025 when they peak and then remain constant until 2038.

to the free software as opposed to paid software by the number of users outside the HEP community. That figure was estimated using the number of downloads for ROOT and by the number of organizations using GEANT4.

Figure 5. Benefits related with software and ICT: 1993-2038

(a) Benefits related with ICT and software

ICT	
Average	7603
Median	7239
Min	3536
Max	21125
Std. Dev.	2023

(b) Monte Carlo cumulative distribution function for HL-LHC

Notes: panel (a) shows discounted benefits over the 1993-2038 period for HL-LHC (thick line), CFS (thin line) and their difference (bars). Panel (b) shows the simulated Cumulative Distribution Function (CDF) based on 50'000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the probability to observe a value not greater than the median is 50%. Panel b also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows

some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report.

Results. In the case of HL-LHC, ICT related benefits represent 24% of total benefits. This percentage shrinks to 9% when we consider the difference between benefits produced within the HL-LHC scenario and those produced within the CFS. We are aware that the number of downloads does not reliably reflect the actual number of users. Interviews with persons in charge of different software projects at CERN suggest that our estimate of benefits from software and ICT might indicate only a lower bound of their true value. In fact, the value of open source software goes well beyond money saved for purchasing alternative commercial software. However, as shown in Figure 5(b) we have included the impact of such uncertainties in the Monte Carlo simulations. The very long right tail of distribution of benefits in this category testifies that our baseline estimate can be interpreted as a very conservative lower bound.

5.3. Scientific publications

Assumptions. These benefits extend until 2063 to consider the life-cycle of scientific publications and citations beyond the lifetime of the particle collider programme. For scientists, publications and pre-prints impact their curricula vitae, giving evidence of their performance. The benefits of publications are thus measurable looking at their impact on the scientific community as measured by the number of citations. See [22] for a theoretical background on these issues. If each publication written by LHC scientists (L_0) has a value proportional to its production cost, the benefits of L_0 publications cancel out with their cost of production, represented by the scientific personnel cost. We thus exclude the value of L_0 publications and consider only the value of papers by scientists who are not involved in the LHC program and cite L_0 papers (L_1) and the value of these citations. We also consider the value of their citations in other, subsequent, papers (L_2), but do not consider the value of L_2 papers. Given that forecasting the value of these benefits hinges on the prediction of the number of papers and cites, as well as on the scientific importance of papers, we simply assume that for HL-LHC there might be a second peak in these benefits whose discounted value is comparable to the one recorded in 2013 after the discovery of the Higgs Boson. The year 2031, five years after a HL-LHC operation start, was chosen following the LHC history that was characterised by a publication peak five years after start of data taking. It is worth pointing out, that this second peak is rather the result of an increase of scientific publications after the availability of data rather than a breakthrough discovery, which is an event that cannot be predicted. See [23] and [22] for more details on the statistical analysis of scientific publications. For the CFS we extrapolate the value of the benefits in [1] that shows an exponential decaying trend. See Figure 6(a).

Results. Being 2% of total benefits in the HL-LHC scenario, these benefits represent the smallest overall socio-economic benefit category. They relate to the quantity of publications and citations, not to their contents. CBA does not consider scientific benefits, which cannot be quantified ex-ante. This is true also if we consider the difference between HL-LHC and the CFS.

Figure 6. Benefits for scientists: 1993-2063

(a) Benefits for scientists

Scientific publications	
Average	522
Median	533
Min	343
Max	613
Std. Dev.	64

(b) Monte Carlo cumulative distribution function for HL-LHC

Notes: panel (a) shows discounted benefits over the 1993-2038 period for HL-LHC (thick line), CFS (thin line) and their difference (bars). Panel (b) shows the simulated Cumulative Distribution Function (CDF) based on 50000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the probability to observe a value not greater than the median is 50%. Panel b also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report.

5.4. Cultural effects

We list exemplary cultural effects below and provide their percent contribution to the benefits associated with cultural effects for the HL-LHC scenario¹⁶:

- onsite CERN visitors and visitors of CERN travelling exhibitions (57%)
- the reach of media reporting on LHC (25%);
- visitors of CERN and LHC experiment Websites (12%)
- users of LHC-related social media (YouTube; Twitter; Facebook; Google+) (2%);
- participants in two volunteer computing programs (2%)
- other media-related benefits such as movies and non-scientific books (2%).

Results. In the case of HL-LHC, these benefits represent 13% of total benefits.

Assumptions and methods. Given that most of the benefits in this category are due to the “touristic” effect of CERN, we focus on this benefit. The estimation of the remaining benefits follows [1].

For onsite visitors we assume that for the 2026-2038 period there is no increase of visits at CERN. Hence we keep the 2025 benefit value constant until 2038. For the CFS, we assume a slight increase of tourists after the accelerator shutdown (5% from 2031 onwards), since the infrastructure can be visited. Estimation of benefits has been done using the Travel Cost Method (see e.g. [24] and [25]). See Annex B for details on the Travel Cost Method.

5.5. Public good value

Assumptions and Methods. Estimation of public good value is based on contingent valuation methods (see e.g. [26], [27] and Annex B). The “public good value” for non-users (i.e. people who currently do not directly use the services of the RI, but are better-off simply because they know that new knowledge might be created) refers to the fact that that individuals cannot be excluded from the use of new knowledge produced by it and that use by one individual does not reduce availability to others. It represents the benefits due to the fact that that new knowledge might be generated for the society.

The public good value is estimated based on the taxpayers’ Willingness To Pay (WTP) for a particle collider research infrastructure. A first estimate has been carried out in [1] and a refinement of the value is currently ongoing in France and Switzerland (CERN’s host states). We have divided the benefits computed in [1] for the number of years in which the LHC is expected to be operated, that is from 2008 to 2030 for a total of 23 years. The resulting figure represent the yearly benefit for non-users.

¹⁶ We thank Panagiotis Charitos (CERN Communications), Kate Kahle (CERN Content and Social Media), Rolf Landua (CERN Global Engagement) and Renilde Vanded (CERN Press Office) for helping us to collect data and for sharing their expertise with us.

Figure 7. Benefits for the public: 1993-2038

Cultural Benefits	
Average	3319
Median	3320
Min	2660
Max	3981
Std. Dev.	272

Notes: panel (a) shows the percentage contribution of each category of benefit in the HL-LHC scenario to the total cultural benefit. Panel (b) shows the simulated Cumulative Distribution Function (CDF) based on 50000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the

probability to observe a value not greater than the median is 50%. Panel b also shows the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report.

Then, in the CFS we assigned this yearly share to each year in the 2008-2030 period (i.e. the WTP is the same as in the LHC case). For the HL-LHC phase, we assigned the same share over a longer time period that spans 2008-2038 to keep into account that the discovery potential of the LHC is extended in time.¹⁷

Results. These benefits 12% of total benefits in the HL-LHC scenario.

Figure 8. Public good value of HL-LHC

Notes: the figure shows the simulated Cumulative Distribution Function (CDF) based on 50'000 runs. The CDF is the probability that a random variable *X* takes on a value less than or equal to *x*. For instance, at the median the probability to observe a value not greater than the median is 50%. We also show the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report..

¹⁷ New estimates of the public good value of discovery will follow based on a new survey of about 1000 French taxpayers.

6. CBA RESULTS AND CONCLUSIONS

The NPV of HL-LHC is positive and greater than the NPV of the counterfactual scenario (see Table 1). The ratio between benefits and costs of the difference is positive. See Annex C for methodological details.

The difference between the NPVs of the two scenarios is the benefit of the HL-LHC project, since the alternative scenario is to continue the operation of the LHC until it reaches its end of life. The ratio between the HL-LHC and CFS total cost difference and the HL-LHC and CFS total benefit difference is 1.76. this means that every CHF spent on the HL-LHC project generates 1.76 CHF of benefits for the society. The main benefits stem from training and industrial spillovers. The probability of a negative NPV is negligible (6%), even under very conservative assumptions on the potentials for the generated benefits.

In conclusion, the HL-LHC project yields significant socio-economic value, well in excess of its costs and in addition to its scientific output.

Table 1. Cost Benefit Analysis

Discounted MCHF 2016	HL-LHC	%	CFS	%	Difference	%
Total cost	22292		19356		2936	
Total Benefit	25608		20453		5155	9.894
Human Capital	8379	33%	6302	31%	2077	40%
Publications	613	2%	322	2%	290	6%
Technological Spillovers	10187	40%	8244	40%	1943	38%
- Software	6029	24%	5591	27%	438	9%
- Hi-tech Suppliers	4158	16%	2653	13%	1505	29%
Cultural Benefits	3319	13%	3028	15%	291	6%
Public Good Value	3110	12%	2557	12%	553	11%
NPV	3316		1097		2219	
Benefit/Cost ratio	1.15		1.06		1.76	

Figure 9. HL-LHC: Cumulative Distribution Function of the Net Present Value

NPV	
Average	1757
Median	1489
Min	-15844
Max	24314
Std. Dev.	4637

Notes: the figure shows the simulated Cumulative Distribution Function (CDF) based on 50'000 runs. The CDF is the probability that a random variable X takes on a value less than or equal to x . For instance, at the median the probability to observe a value not greater than the median is 50%. We also show the baseline value (i.e. the vertical black line; the value resulting from the CBA), the median simulated value (vertical grey line) and a 68% confidence interval (CI) for the baseline value (i.e. the area between the two vertical dashed lines). The table shows some descriptive statistics for the simulated values. Discrepancies in figures appearing in figure and those in the table are due to numerical rounding.

Data available in the Data Appendix attached to this report.

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Annex A. DISCOUNTING, FINANCIAL AND SOCIAL DISCOUNT RATE¹⁸

Financial Discount Rate (FDR): definition and estimation

When private or public investors decide to finance a project they implicitly face a cost that corresponds to sacrificing a return from another project. This amount is called “opportunity cost”. Therefore, investors decide to commit their resources to a project only if its expected return is likely to exceed the opportunity cost. Inflows and outflows of a project are therefore discounted by means of a Financial Discount Rate (FDR).

The FDR is the opportunity cost of capital and is valued as the loss of income from an alternative investment. It accounts for the time value of money: the idea that money available now is worth more than the same amount of money in the future because it could be earning interest, and the uncertainty about the future cash flow, that might be less than expected.

Different approaches exist in the practice for the calculation of the financial discount rate:

A commonly used approach consists of estimating the actual cost of capital relying on the real return on government bonds (the marginal direct cost of public funds) or the long-term real interest rate on commercial loans (if the project needs private finance), or a weighted average of the two rates. The latter approach is convenient when a project needs the financing both of public and private funds. Although being very practical and widespread, it does not reflect the actual opportunity cost of capital, because the best alternative investment could earn more than the interest rate paid on public or private loans. Moreover, there exists no credible approach to forecast reliably a financial interest rate over time horizons of decades that is typical of RIs.

A second, more accurate, approach is to consider the return lost from the best alternative investment to determine the maximum limit value for the discount rate. In this case, the alternative investment is not the buying back of public or private debt, but it is the return on an appropriate portfolio of financial assets.

Social Discount Rate (SDR): definition and estimation

The Social Discount Rate (SDR) is used in the economic analysis of investment projects to discount economic costs and benefits. It reflects the opportunity cost of capital from an inter-temporal perspective for the whole society. In other words, it reflects the social view of how future benefits and costs are to be valued against present ones.

A nil social rate of time preference derives from the assumption that equal weights are given to the benefits occurring at any point in time. A positive discount rate, on the other hand, indicates a preference for current over future consumption, whereas the opposite is true if the discount rate is negative.

When a perfectly competitive economy is in equilibrium, the SDR coincides with the financial discount rate and with the financial market interest rate. However, this does not apply in the practice because capital markets are in fact distorted (e.g. due to “asymmetry of information”, namely the fact that a party of a transaction possesses greater knowledge than the other party).

¹⁸ This section is draws heavily on [6].

Different approaches have been proposed by the literature to estimate the SDR. The most popular one is the social rate of time preference (SRTP). This is the rate at which the society is willing to postpone a unit of current consumption in exchange of more future consumption. The logic of this approach is that the government should consider the welfare of both, the current and future generations and solve an optimal planning program based on individual preferences for consumption.

A broadly used approach to estimate the SRTP is based on the following formula obtained from the Ramsey economic growth model [28]:

$$\text{SRTP} = \rho + e \cdot g$$

where ρ is the pure time preference. e is the elasticity of marginal utility of consumption, i.e. the percentage change in individuals' marginal utility corresponding to each percentage change in consumption. g is the expected growth rate of per capita consumption. Each term of the formula is discussed more in detail below.

The two components of this formula (the one related to time preferences and the other related to consumption growth) reflect the two reasons why future consumption may have a lower value than in the present. First, present income or consumption is usually preferred because of uncertainty about the future and impatience. Second, future consumption may be valued less because of the probability of income and consumption grow through time. Indeed, if per capita consumption is growing, then the value of additional consumption in each year in the future is declining at a rate related to the rate of growth of per capita consumption and the elasticity of diminishing marginal utility of consumption.

The pure time preference term (ρ) can be decomposed into two elements, one related to individuals' impatience and myopia and the other one related to the risk of death or human race extinction. This latter component reflects the life chance and it is often simply measured as the ratio of total deaths to total population. The former component instead refers to the observation that individuals favour present over future consumption and this is reflected in a positive value of ρ . A positive value means that future generations would be worse off only because they are born at a later point in time, which would be unacceptable from the point of view of society. The consensus value in the economic empirical literature is to assume a value for ρ between 1% and 3%. See [6] for details.

The elasticity of the marginal utility with respect to consumption (e) captures the dynamics of consumption over time. This parameter reflects the fact that if tomorrow consumers are a bit richer, marginal utility is decreasing. In other terms, it reflects how consumption should be transferred across different generations and it is a planning parameter for the social planner in that it reveals his preference for income inequality aversion.

An approach to estimate the elasticity term is to consider the social judgement about how consumption should be transferred across people at different times. In this case, the elasticity tells us how much more worthwhile it is to transfer income from a rich person to a poor one. This can be determined by analysing the progressivity of national personal income tax rates. The following formula can be used to describe the elasticity:

$$e = \ln(1 - t') / \ln(1 - t)$$

where t' and t are respectively the marginal and average income tax rates for an average taxpayer.

One is the neutral value of the parameter: when $e = 1$, then 1 Euro of additional future consumption adds 1 Euro to social welfare. If $e < 1$, consumers are not so interested in future growth. If $e > 1$ consumers are interested in it.

The expected per-capita consumption growth (g) is a welfare-related variable. From the point of view of inter-generational equity, this term implies that if future generations are expected to be wealthier than the ones of today, and thus if consumption rises over time, this would result in an increase of the discount rate in order to shift the priority to the poorer current generation. Usually very long-run growth rates of real per capita consumption are used to estimate future growth to smooth out possible short-term distortions. Empirical estimates for the rate of growth of per capita consumption are usually based on growth models, which take into account both the past long-term development path and expected future growth. A way to estimate g is to consider as proxy for consumption growth another welfare correlated indicator such as real per capita Gross Domestic Product (GDP) growth, consumption growth or personal income growth.

ANNEX B. WILLINGNESS TO PAY¹⁹

The Willingness To Pay (WTP) approach can be applied to quantify both the direct benefits and the impacts - negative or positive - of the external effects of the project. The WTP is an estimate of the total value of direct and indirect benefits and costs generated by a project based on the maximum amount of money that people would be willing to pay for outcomes that they view as desirable or, alternatively, relying on the maximum amounts that people would be willing to pay to avoid outcomes they view as undesirable.

To empirically estimate the WTP there are four main alternatives:

1. Revealed Preference Methods
2. Stated Preference Methods
3. Dose-response Functions
4. Benefit Transfer Method.

We focus on the first two approaches.

Revealed Preference Methods

This approach implies that the evaluation of non-market impacts is based on the observation of the actual behaviour and, especially, on the purchases made in actual markets. Consequently, the focus is on real choices and implied WTP. The strength of this approach is that it is based on actual decisions made by individuals. The main weakness is the difficulty of testing the behavioural assumptions upon which the methods rely. While there are different methods, we focus on the Travel Cost Method (TCM).

The TCM seeks to assign a value on the individuals' willingness to pay for an environmental good or service by the costs incurred to consume it. It originates from the observation that travels to nature parks and archaeological areas can correspond to the value of such a resource and that the value can be measured by the market value for trips and expenditures that relate to those areas. For zones located far from the nature park the number of visits is zero because the cost of the trip exceeds the benefit derived from the trip. Therefore, it is important to determine

- the number of trips to the site over a given time period;
- the costs of the trips from different zones, split into different components:
 - the monetary costs including travel costs, admission fees (if relevant), on-site expenditures, expenditures on capital equipment necessary for consumption;
 - the time spent travelling and its corresponding value (the value of the time of people).

Specific problems with this approach are related to 'multiple purpose trips'. Because trips can have more than one destination, it is difficult to identify which part of the total travel cost is related to one specific destination.

Since only the benefits of the direct consumption of the environmental services are considered in this approach, non-use values (option value and existence value) cannot be considered.

¹⁹ This section draws heavily on [6].

Stated Preference Methods

Stated preference approaches are surveys used to elicit people's intended future behaviour in the markets. Through an appropriately designed questionnaire a hypothetical market is described where a given good can be traded. A random sample of people is then asked to express their maximum WTP for (or willingness to accept) a supposed change in the good's provision level. Consequently, the focus is on real choices and implied willingness to pay.

The main strength of the methods based on this approach is represented by the flexibility they can assure. Indeed, they allow the evaluation of almost all non-market goods, both from an ex-ante and from an ex-post point of view. Moreover, this methodology captures all types of benefits from a non-market good or service, including the so-called non-use values.

The main specific methods are

1. contingent valuation method and
2. the choice modelling method.

Here we focus on the first one.

Contingent Valuation Method

The aim of the contingent valuation method is to elicit individual preferences in monetary terms for changes in the quantity or quality of a non-market good or service.

The key element in any contingent evaluation study is a properly designed questionnaire. The questionnaire aims to determine individuals' estimates of how much having or avoiding the change in question is worth to them. A well designed contingent valuation follows the following steps:

- it investigates the attitudes and behaviour related to the goods to be valued in preparation for answering the valuation question and in order to reveal the most important underlying factors driving respondents' attitude towards the public good;
- it presents respondents with a contingent scenario providing for a description of the commodity and the terms under which it is to be hypothetically offered. The final questions should aim to determine how much they would value the good if confronted with the opportunity to obtain it under the specified terms and conditions;
- it poses questions about the socio-economic and demographic characteristics of the respondents in order to check the extent to which the survey sample is representative of the population involved.

At the end of the survey process, analysts use appropriate econometric techniques to derive welfare measures such as mean or median willingness to pay and also to identify the most important determinants of willingness to pay. These data treatment methods also consider correlations of the responses with potentially significant motivators such as the personal income, the education level, age, gender, geographical region and others. Therefore a corrected set of data is used as a base to estimate an appropriate value indicator (i.e. the median or the trimmed mean can be used to reduce the impact of outliers, if any).

ANNEX C. NET PRESENT VALUE AND THE BENEFIT-COST RATIO²⁰

The Net Present Value of a project is the sum of the discounted net flows of a project. It represents the present amount of the net flow of benefits (i.e. benefits minus costs) generated by the investment expressed in one single value with the same unit of measurement used in the accounting tables.

It is important to note that the balance of costs and benefits in the early years of a project is usually negative and it only becomes positive after some years. The value of the discount rate and the choice of the time horizon are crucial for the determination of the NPV of a project. NPV is a very simple and precise performance indicator. A positive NPV ($NPV > 0$) means that the project generates a net benefit, because the sum of the weighted flows of costs and benefits is positive. This is generally desirable. When different options are considered, the ranking of the NPVs of the alternatives indicates the best one.

The benefit-cost ratio is the present value of project benefits divided by the present value of project costs. If $B/C > 1$ the project is desirable from a societal point of view, because the benefits, measured by the Present Value of the total inflows, are greater than the costs, measured by the Present Value of the total outflows.

This ratio is independent of the amount of the investment (cumulative sum of capital and operation expenditures over the entire project period) and can complement the NPV. In other words, if the benefits of a project eventually outpace the sum of its cost over the entire lifecycle, the total investment and operation costs are not relevant for a project decision. The B/C ratio can be used to assess a project's efficiency.

²⁰ This section is draws heavily on [6].

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