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Published in:
Scientometrics

DOI:
10.1007/s11192-014-1249-z

2014

Citation for published version (APA):
Hallonsten, O. (2014). How expensive is Big Science? Consequences of using simple publication counts in performance assessment of large scientific facilities. *Scientometrics*, *100*(2), 483-496. https://doi.org/10.1007/s11192-014-1249-z

Total number of authors:
1

This is a preprint version of an article published in *Scientometrics* (2014) 100: 483–496.
Doi: 10.1007/s11192-014-1249-z

How expensive is Big Science?
Consequences of using simple publication counts in performance assessment of large scientific facilities

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Abstract

Although the nuclear era and the Cold War superpower competition have long since passed, governments are still investing in Big Science, although these large facilities are nowadays mostly geared towards areas of use closer to utility. Investments in Big Science are also motivated not only by promises of scientific breakthroughs but also by expectations (and demands) of measurable impact, and with an emerging global market of competing user-oriented Big Science facilities, quantitative measures of productivity and quality have become mainstream. Among these are rather simple and one-sided publication counts. This article uses publication counts and figures of expenditure for three cases that are disparate but all represent the state-of-the-art of Big Science of their times, discussing at depth the problems of using simple publication counts as a measure of performance in science. Showing, quite trivially, that Big Science is *very expensive*, the article also shows the absurd consequences of consistently using simple publication counts to display productivity and quality of Big Science, and concludes that such measures should be deemed irrelevant for analyses on the level of organizations in science and replaced by qualitative assessment of the content of the science produced.

Key words

Big Science; publication counts; quality assessment; performance assessment; productivity

1. Introduction

The scientific utilization of very large infrastructures – commonly referred to as *Big Science* – did not cease at the end of the Cold War and the nuclear era. Rather, Big Science was transformed and renewed, and the past few decades have seen the boom of a number of Big Science utilizations that connect well to current preferences of science (and innovation) policy and societal expectations on science (e.g. Jacob and Hallonsten 2012; Hallonsten and Heinze 2012). Several large machines for particle physics and ground-based astronomy are still in operation but have been complemented by the use of accelerators and reactors for experimental work in predominantly the materials sciences and life sciences, broadly defined. The long- and short-term expectations on these fields of science are mirrored in the expectations on the Big Science labs that serve them: the construction of accelerator- and reactor-based facilities (the latter has become relatively less significant in recent years) is motivated not only by promises of scientific breakthroughs but also, to a large extent, by expectations (and demands) of measurable impact (e.g. Agrell 2012; Eisler 2013; Johnson 2004; Hallonsten 2013b).

The effects of the globalized knowledge economy and the increasing competition between groups, units and organizations in science have not spared Big Science – quite the opposite, there is a growing competition between these facilities that motivates systematic measuring of performance and comparison between labs that emulate the advanced appraisal and ranking exercises that have taken a hold on the academic sectors in most countries (Hazelkorn 2011; Wildavsky 2010). Large scientific facilities that provide cutting edge experimental resources to those scientists passing the peer review-based selection process measure their performance and make comparisons with their contenders on principally three accounts: reliability and technical performance, demand for access from scientific communities, and publications (Hallonsten 2013a). While the two former are fairly straightforward measures of the level of performance of facilities that take several relevant factors into account, there is overwhelming evidence in bibliometric study that the third – measuring output in the shape of publications based on experiments at the facility in question – is a problematic measure almost regardless of how it is applied.

As will be shown in this article, the counting of publications is not just problematic as a measure of productivity and/or quality, but becomes a truly mind-boggling exercise once it is combined with figures of expenditure of these facilities, i.e. used to calculate figures of productivity, that is, output related to cost. The article presents three cases, for which complete figures of both cost and output are available, and presents calculations of the average cost per publication in the first few years of operation of the respective facilities. The purpose is to highlight the (rather absurd) consequences of using these simple bibliometrics as a performance measurement for Big Science labs, which can be taken as evidence that in principle, any attempt to use simple publication counts as measures of performance on such aggregated level is flawed.

The cases are the European Organization for Nuclear Research (CERN) in Geneva, the European Synchrotron Radiation Facility (ESRF) in Grenoble, and the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory in Menlo Park, California. They are scientifically and technically dissimilar, and their spread of ages also essentially precludes square comparison. However, availability of data put limits on the choice of cases, but for supporting the argument of this article, the cases are nonetheless quite adequately chosen, because at their respective times of opening, all three were advertised as state-of-the-art Big Science installations built to facilitate absolute spearhead science in the fields they serve.

Square comparison of the three cases is hence not the purpose of this article, and not part of the argument of the article, but square comparison of the (severely deficient) quantitative data is nonetheless used a key piece in the discussion that underpins the argument: Exploring the similarities and differences between the cases in detail, on basis of this comparison of data, the article shows that their dissimilarities indeed drive the exercise of measuring their productivity in relation to their cost by simple counting of publications further into absurdity. This result is put in proper context by a systematic discussion on what the publication counts actually represent in terms of scientific productivity and the role of the labs in the science system.

Three main conclusions are drawn, which possess a descending degree of triviality. First, the realization that Big Science is *very expensive*. Second, a reassertion, on basis of a new type of empirical material, that publication counts *per se* are highly misleading as a measure of performance at the level of institutions in science, most of all because the caveats surrounding such counts are many and complex, which the article and its analysis manages to display in a partly new way. Third, and related, the implication that even if these oversimplified publication counts would be adequate measures of scientific quality, they should probably not be used as the only measure by which investments in Big Science are motivated, perhaps especially not when different possible investments are weighed against each other.

The article proceeds as follows. First, the competition between Big Science facilities and their systematic performance assessment and comparison with other labs are presented as a background under the headline 'facilitymetrics', derived from Hallonsten (2013a). Second, the three cases are presented, highlighting their histories and their scientific and sociological context. Third, the figures on costs and publication counts are presented and used for comparison and analysis, with the aid of contextual information, of what they represent. The article concludes with a discussion and reiteration of the above argument of the (absurd) consequences of using simple publication counts for performance assessment of large scientific facilities.

2. Facilitymetrics

The enormous growth in importance of nuclear and particle physics during the second half of the 20th century was halted with the end of the Cold War, as the geopolitical regime that sustained the growth of accelerator complexes for particle physics was replaced and new priorities in science policy took over (Johnson 2004; Kevles 1997; Elzinga 2012). Most noticeably, the cancelling of the Superconducting Super Collider (SSC) project in 1993 signaled a shift in priorities that was later confirmed by the fact that investments in large scientific projects continued, but expanded into other areas. Space exploration apparently still had attraction enough to be worth billions of dollars (McCray 2000) and the frontier of particle physics is indeed still pushed further (Giudice 2012), but importantly, accelerator complexes built for utilization in a wide range of disciplines, including materials science and the life sciences, took over as flagship facilities of many national Big Science labs, in the United States, Europe and eventually also in other parts of the world (Hallonsten and Heinze 2012, 2014; Westfall 2010, 2012; Lohrmann and Söding 2013). Widespread rearrangement of priorities in science and technology policy from the early 1980s and on had also put new demands on publicly sponsored science to contribute more directly to innovation and economic growth, and as fields significantly closer to applications than particle physics took over as the largest group of customers at accelerator-based Big Science facilities, the logic by which these facilities established their credibility and won necessary political support had made a radical turn from national security and superpower competition to sustainability and innovation for economic growth (Jacob and Hallonsten 2012; Johnson 2004; Guston 1999; Hallonsten and Heinze 2012).

As these development have been furthered into the 21st century and publicly funded R&D has come under heavy influence of managerialism, the audit society, and the use of quantitatively oriented evaluation of scientific excellence (Elzinga 2012; Wildavsky 2010; Hazelkorn 2011), Big Science facilities have come under increasing pressure of demands for demonstrable productivity, excellence and competitiveness. Globalization has increased mobility and expanded the market on which these facilities compete for the best users, and the broad experimental opportunities offered by synchrotron radiation, neutron spallation, and free-electron laser has turned many of the facilities into vital resources for breakthroughs in prestigious disciplines such as nanotechnology, proteomics, and drug development. Lab directors and policy-level advocates of particular facilities take every opportunity to present figures on technical reliability, user oversubscription, and not least publication counts which are used as proof of productivity and even quality, especially in comparison with other labs of similar size, scope and mission (Hallonsten 2013a).

The organizational, epistemological and political consequences of the use of these rather simple publication counts has so far drawn little attention by scholars of science policy, scientometrics and the sociology of science. This article can merely initiate the inquiry of what the ramifications of these publication counts will be if they are used in a consistent manner as an actual measure of productivity or scientific quality of a Big Science facility. Obviously, the straightforward counting of publications has advantages and disadvantages that have been the topic of several studies. A rudimentary and valid point of criticism is that quite obviously, quantity is a poor measure of quality. In the following analysis, however, this rather thorny discussion point is deliberately avoided and focus is kept on quantity. This has two reasons. First, the data used is entirely quantitative: publication counts and expenditure. Second, the facilities themselves use these quantitative measures rather one-sidedly, which is also (part of) the *raison d'être* for this article – we base the article solely on the information provided by figures of expenditure and publication lists/databases for the cases that are readily accessible in annual reports or online, and nothing else. Surely, annual reports of Big Science labs do highlight especially important scientific advances made at the facilities in a qualitative and rather nuanced fashion, but they also typically display graphs with rough and simple publication counts as a chief demonstration of productivity and quality.[1] Publication counts are considered very important markers of productivity for the facilities – one testament to this is that users are required to submit their publications to the facilities in order to be eligible for renewed access to the facility. The director of the ESRF, one of the cases here, is quoted in Hallonsten (2013a: 501*n*) stating that the facility strongly outperforms its main competitors in the United States and Japan in number of publications, which is taken as an indication of superiority over the competitors in scientific performance.

The point of this article is thus not to criticize or analyze the (lack of) correspondence between quantitative measures of publications and quality of scientific achievements, but to demonstrate the effects of a one-sided focus on those quantitative measures. Pure numbers of publications are apparently seen as valid representations of the productivity and scientific quality of Big Science facilities, sometimes to the extent that these publications appear as a type of commodity that the facilities are installed to produced. What, then, do these commodities cost? And, by extension, *how expensive is Big Science?*

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[1] See, e.g., the 'facts and figues' section of the annual reports of the European Synchrotron Radiation Facility (the 'ESRF Highlights'), available at http://www.esrf.eu/UsersAndScience/Publications/Highlights or the diagrams at the Publications page for LCLS, available at *https://portal.slac.stanford.edu/sites/lcls_public/Pages/Publications.aspx*

3. The cases

The *European Organization for Nuclear Research* (originally *Conseil Europeen pur la Recherche Nucleaire*, hence the acronym CERN) was founded in 1954 as the first multilateral European collaboration in Big Science. Its rationale was chiefly political; as part of the 'Marshall Plan for Science', i.e. the United States' efforts to assist the rebuilding of Western Europe in accordance with its geopolitical preferences (Krige 2006: 57-67). Nuclear physics had originally been only one alternative among others for the European collaborative project, but as the international status of nuclear energy grew, the choice became rather easy. The sensitive political climate in Europe in the first decade after the end of World War II could have killed the project already before its launch, but the fact that the laboratory mission was so firmly restricted to fundamental research enabled its realization, together with the realization that a joint scientific laboratory could be a favorable foundation for the tedious work to achieve political integration in Europe after the war, and create a competitive position not achievable by single countries (Pestre and Krige 1992: 83-84). Therefore, although CERN was created to complement national nuclear physics programs rather than replace them, its cost (if inflation-adjusted) was comparable to the level of similar investments today and so CERN was, undoubtedly, the flagship Big Science facility of (Western) Europe at the time. Run as an intergovernmental collaboration in science and utilizing collective capacity for the greater benefit, CERN could draw on a new and very powerful source of funding, namely the goodwill and collaborative spirit of Western European governments (Krige 2003: 897).

The CERN convention was ratified in 1953 and entered into force in the fall of 1954, and three years later, the lab opened (Pestre and Krige 1992: 80). Interestingly, despite the decisively drawn boundary to applied research, CERN had to prove its worth from day one and demonstrate productivity and quality of its research programs. The annual reports of CERN, specifying investment and running costs and otherwise reporting in great detail on the achievements of the lab, also contained publication lists of the very same type of present-day Big Science facilities pile together in their reports as well as online. That CERN was an international facility and based on an intergovernmental collaboration made it partly into a service facility reminiscent of today's Big Science labs (e.g. the other two cases treated here) since a significant part of its scientific program was carried out by temporarily visiting scientists from the member states. Competition was an institutionalized feature of nuclear and particle physics at the time, and CERN indeed made every effort to display its proficiency and scientific excellence (see Irvine and Martin 1984). In its six decades of existence, CERN has built and operated several accelerator facilities, the latest of which is the famous Large Hadron Collider (LHC) that opened in 2009. Use of scientific facilities at CERN, in the 1950s as well as today,[2] amounts to data taking at the interaction points of the accelerators where elementary particles are smashed together to disintegrate and reveal their constituent particles and energies.

The *European Synchrotron Radiation Facility* (*ESRF*) in Grenoble, France is a lab run as a French private company (*societé civilè*) owned and operated by 17 member countries as shareholders. The lab was constructed and operates on a budget of annual contributions from the member organizations decided in advance. Its origins date back to the experience of successful creation of a number of European intergovernmental collaborative projects in science in the 1950s and on, and a 1977 proposal by the European Science Foundation (ESF)

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[2] Although, obviously, the size of the teams doing such data taking have grown from a handful of scientists and engineers in the 50s and 60s to thousands today (e.g. Bodnarczuk and Hoddeson 2008). In this sense, the CERN facilities of the 1950s and 60s are clearly more apt for comparison with the ESRF and LCLS than today's CERN, where team size routinely exceeds a thousand people.

to create a collaborative European synchrotron radiation source to satisfy the growing demand of European scientists of high quality synchrotron radiation (Hallonsten 2014a: 229). The high-level ambitions written into the planning documents made the ESRF a constant contender for the prize as the world's leading synchrotron radiation facility, although such a title is hard to award on any grounds that withstand rudimentary criticism (Hallonsten 2013a: 508-512). This ambition of world leadership was, however, decisive in the process of making the plans for the lab reality in an unremittingly cluttered international European policy field (Hallonsten 2014a) and was hence built into the organization of the lab, both in formal terms, by its comparably very generous financial endowment from the member states, and informally, by the lab culture which is very much characterized by unceasing comparison with other facilities elsewhere, especially the siblings and direct competitors in Japan and the United States, respectively, the SPring-8 and the APS (Hallonsten 2013a: 501). The ESRF convention was signed in 1988 and construction work started in January 1989. In 1994, the facility opened to users. An important detail, often mentioned as a major reason for the continuously strong performance of the ESRF on various parameters (Hallonsten 2013a: 509), is that the founding documents stipulated that new investments and refurbishments of instruments should be an annual budget post, using 20 % of the annual operations cost. This is highly unusual (or, conceivably, even unique) among synchrotron radiation laboratories worldwide, and it has allowed the facility to maintain a rather aggressive refurbishment and maintenance program which has enabled continuous renewal to keep up with technological development and shifting expectations in user communities. In the context of this article, this has the important implication that the ESRF annual budget thus is higher than the typical case, but also that the facility's performance can be expected to be higher than its immediate competitors. The ESRF is essentially a service facility for outside users, who apply for access in competition and conduct experiments on a temporary basis (usually for a couple of days). The number of annual users (individuals) has gradually increased from 1,149 in 1995 (the first full year of operation) to 6,318 in 2010 (Hallonsten 2013a: 506). The facility is built around a circular accelerator that emits synchrotron radiation to 41 so-called beamlines, a the end of which experimental stations are located, which means that in principle 41 experiments are running, and 41 external research groups served, simultaneously at the facility.

The *Linac Coherent Light Source* (*LCLS*) is one of two main user facilities at the *SLAC National Accelerator Laboratory* (formerly known as the *Stanford Linear Accelerator Center*, with the acronym *SLAC*), a dual-mission United States National Laboratory for particle physics/particle astrophysics and so called photon science. SLAC was founded in 1962 as a single-mission, single-machine National Laboratory for particle physics, and started operation of its first experimental facilities (a linear accelerator, linac) in 1966. Since then, it has built and run several machines for particle physics, and importantly, undergone a gradual transformation from a single-mission particle physics lab to a dual-mission and multi-purpose center nowadays dominated by its service to the scientific communities utilizing synchrotron radiation and free electron laser for atomistic studies of matter (Hallonsten and Heinze 2013). The LCLS is a *free electron laser (FEL) facility* built on a recent (21st century) extension of the original SLAC linac. Free electron lasers are often described as a next generation light sources that produce extremely bright radiation of the same type as synchrotron radiation sources (such as the ESRF), but with performance enhancements of several orders of magnitude on some specific accounts and by the use of linear accelerators instead of circular ones. The idea to turn the original SLAC linac into a free electron laser first emerged in the early 1990s, but the novelty of the technology and the fact that SLAC was still a single-mission particle physics lab with the synchrotron radiation activities still "parasites" on site (Hallonsten 2014b), made it take several years until the concept won necessary support. In 2002, after a design had been detailed and scientific and political support had been mobilized, funding for the LCLS commenced. It is widely assumed that the federal government's decision to fund a comparably risky project was made possible by the fact that that the fully operational SLAC linac along with expertise and staff could be utilized as part of the project, which is estimated to have saved "hundreds of millions of dollars" (Woods 2006: 12). In the context of this article, this is important because it means that the cost for LCLS construction (and, conceivably, operation) was lowered significantly compared to a situation where it would have been constructed on green field elsewhere. Another important point concerns the physical infrastructure of a FEL. Synchrotron radiation laboratories like the ESRF are built with experimental stations spread evenly around a circular accelerator, which means that in principle, the number of experimental stations (and, hence, the number of experiments possible to run simultaneously) can be increased by originally designing and constructing a larger accelerator. FELs are built with linear accelerators as centerpiece and thus have a physical limit on the number of experimental stations they can accommodate (because the beam of radiation only emerges in one direction), and furthermore, the LCLS design is such that the six experimental stations are located serially and only can be operated one at a time. Importantly, this means that in (the unfair) comparison with the ESRF, the LCLS is approximately 41 times less productive in purely quantitative terms, since the ESRF can (in principle) support 41 simultaneous experiments while the LCLS supports only one at a time. The LCLS started operation in 2009, and its status as one of the flagship projects of the US National Laboratories system has been manifest ever since, not least perhaps because the opening of the facility in effect meant that the transition of SLAC from particle physics lab to 'photon science' lab now is completed (Hallonsten and Heinze 2013). The LCLS is indeed advertised as a facility providing experimental resources unavailable elsewhere and, hence, a facility where unique experimental work is done by teams of researchers competing for access in intense competition.

4. Data and analysis

In the following, publication counts and figures for expenditure (both construction and operation costs) for the three cases will be presented in a manner that facilitates the presentation of comparative data. Since the three facilities under study are all user resources, meaning that their collected infrastructure complexes are provided to external scientists on temporary basis, any calculation of output in relation to cost must account for the full amount of investments made in the facilities. Scientific experimentation conducted at a facility several years after its opening still benefits from investments made at the very beginning of the construction of the facility, as well as from all other investments made until the experimentation takes place. Scientific work conducted at e.g. CERN and published today can therefore not be said to benefit only from investments made at CERN in the current year, but need to be assessed in comparison with the full amount of investments made in the facility up until today.

To achieve symmetry in the presentation of costs and output in the analysis below, we have therefore chosen to use figures on accumulated investments and accumulated number of publications, and to identify of a 'Year 0' for each facility, which denotes the year of start of operation of the facility, i.e. the year during which scientific productivity of the respective labs can be expected to have taken off. At this point, since the LCLS has only been in operation for little more than three years, we are forced to cut the data off at year three in order to achieve the desired comparability in the presentation of figures.

Basic information on the cases, and on the type of data used, is presented in table 1. After collection of the data and conversion of currencies and adjustment for inflation,[3] construction costs and operations costs for the three cases were added together and figures on the accumulated costs (construction plus operation) for 'year 0' of the three labs and the following three years of operation were calculated, along with accumulated numbers of publications. The result of this exercise can be seen in tables 2 and 3, which lists the data obtained. In order to account for errors, the final figures on cost per publication (annual as well as accumulated) have been rounded to the closest hundred USD.

Table 1: Basic information on the cases plus summary of data sources and data types

	CERN	**ESRF**	**LCLS**
Facility type	nuclear/particle physics accelerator	synchrotron radiation source	x-ray free electron laser
Start of construction	1954	1988	2002
opening year ('year 0')	1957	1994	2009
Data source on expenditures	CERN Annual Report 1965	Annual reports ('ESRF Highlights') 1994-1997	DOE budgets[4]
Unit noted in source	1958 CHF	1987 FF (1988-1993), yearly nominal FF (1994-1997)	yearly nominal USD
Publication data source	CERN Annual Reports 1954-1960	ESRF publications database	LCLS publications database

Studying tables 2 and 3, some obvious differences between the three cases can of course immediately be noted, that has great significance for the (limited) prospects for comparison. At their respective starts of operation, counting all costs (for construction as well as operations), the LCLS had cost approximately three times as much as CERN, and the ESRF had cost almost four times as much as CERN. These higher construction costs for ESRF and LCLS (in the 1990s and 2000s, respectively) than for CERN (in the 1950s) are the first (and probably least significant) of several instances where the comparison is imbalanced. The ESRF and LCLS were both, at their respective times of opening, state-of-the art facilities in photon science, and their construction costs are consequently also roughly comparable – perhaps the somewhat lower construction costs of the LCLS are indeed explained by the money that was allegedly saved by using an existing and fully operational linac as technical centerpiece in the

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[3] The figures for numbers of publications were obtained by manual counting. The figures for expenditure were recalculated to 2012 US dollars (USD) to ensure comparability. This recalculation proceeded in the following way. *First*, expenditures for CERN are originally reported in Swiss franc (CHF), 1958 prices, and we converted them to yearly nominal values by the use of inflation figures for Switzerland for the years 1958-1965 obtained from the Federal Statistics Office of Switzerland (www.bfs.ch). Each year's nominal values were converted to US-dollars (USD) with the aid of the year by year exchange rates CHF-USD as available through MeasuringWorth (www.measuringworth.com/exchangeglobal). It shall be noted that construction costs and operations costs are not separated in the data source for CERN. *Second*, construction and operations expenditures for ESRF are originally reported in current prices French franc (FF) for every year except expenditures for construction for the years 1988 to 1994, which were given in constant 1987 prices. The 1988-1994 expenditures were hence converted to yearly nominal values by the use of inflation rates for France 1988-1994 (obtained from www.inflation.eu). Thereafter, the nominal figures for every year were converted to USD with the aid of the year by year exchange rates FF-USD as available through MeasuringWorth (www.measuringworth.com/exchangeglobal). *Third*, construction and operations expenditures for LCLS are originally reported in USD, nominal values for every year. Having calculated all figures for all three cases to nominal USD, these were adjusted to 2012 prices by the use of the official Consumer Price Index data for the years 1954-1965, 1998-1997, and 2002-2012 from the US bureau of labor statistics (www.bls.gov).

[4] Note: The figures used are not budget requests but retrospectively noted appropriations (these are noted in budget documents for comparison), thus they represent actual expenditure and not projections/requests.

construction (see above). CERN, on the other hand, was a laboratory established in a completely different field (nuclear physics) in a completely different time (forty and fifty years before the ESRF and LCLS, respectively). The fact that the accumulated costs at start of operation of CERN are roughly comparable with those of ESRF and LCLS is what enables comparison but, it can well be argued, comparison ends there – the differences in political, organizational and scientific character of the cases are simply too big.

Table 2: Expenditure (all in 2012 USD)

	Year 0	*Year 1*	*Year 2*	*Year 3*
CERN	**1957**	**1958**	**1959**	**1960**
Accumulated expenditure before start of operation	120,942,153.3			
Annual expenditure	111,174,468.8	105,265,955.4	100,624,887.9	119,520,972.2
Accumulated total expenditure	232,116,622.1	337,382,577.5	438,007,465.4	557,528,437.6
ESRF	**1994**	**1995**	**1996**	**1997**
Accumulated construction expenditure	684,207,431.7	684,207,431.7	684,207,431.7	684,207,431.7
Annual operations expenditure	126,782,740.4	124,863,687.2	121,195,653.2	100,463,450.9
Accumulated total expenditure	810,990,172.0	935,853,859.2	1,057,049,512.0	1,157,512,963.0
LCLS	**2009**	**2010**	**2011**	**2012**
Accumulated construction expenditure	428,577,955.5	462,842,315.2	462,842,315.2	462,842,315.2
Annual operations expenditure	119,578,285.0	121,959,373.0	125,583,000.0	127,900,000.0
Accumulated total expenditure	686,204,410.1	842,428,142.8	968,011,142.8	1,095,911,143.0

Table 3: Accumulated number of publications for the three cases up until third full year of operation

	Year 0	**Year 1**	**Year 2**	**Year 3**
CERN	99	136	210	274
ESRF	486	694	1012	1499
LCLS	21	34	57	115

Note: CERN and the LCLS both note publications from year –2 (1955 and 2007, respectively), whereas the ESRF notes publications being produced already from its first year of construction (year –6; 1988).

Therefore, comparing numbers of publications produced at CERN in the 1950s and 60s with facilities in completely different scientific fields in the 1990s and 2000s is a difficult exercise, to say the least. Publication cultures and the whole pattern of dissemination of results was, quite obviously, very different back at the time of the launching of CERN, and further similar comparison is therefore hereby avoided and discouraged,[5] but as will be discussed later, this does not dismiss the choice of cases and/or the article's argument. Moving on to the comparison of publication numbers between the ESRF and LCLS, however, we note that the ESRF and the LCLS serve similar scientific communities, and they are furthermore closer in time. Nonetheless, the publication numbers are strikingly dissimilar. Some of the explanation for this might be the fact that the ESRF actually reports publications from 1988 on and in total 348 publications in the years up until 1993, which is one year before start of operation. The

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[5] An extension of the analysis conducted here, to citations and journal impacts, would not change this. Citation cultures are also severely different now than fifty years ago, and journal impacts are similarly impossible to compare.

LCLS, on its part, reports its first publication in 2007 and a total of five in the year before start of operation (2008). But also leaving this bias(?) in reporting aside, there is a naturally significant difference which we have touched upon in the presentation of the cases above: When operations started in Grenoble in 1994, a total of nine instruments serving parallel experiments were in operation, and the facility increased this number by six per year in 1995-97, so that when year 3 of operations was concluded, the facility could accommodate 27 simultaneous experiments.[6] The LCLS, on its part, runs a total of six instruments but only one at once, meaning that it can, by design, only accommodate a fraction of the number of experiments that the ESRF provides for. Achieving comparability by dividing the publication number of ESRF by a number (e.g. 27) won't do the trick since the two facilities obviously have different ways of counting which allowed the ESRF to report 348 publications even before start of operation of the facility.

These differences clearly assist in articulating the argument that the publication counts as such are problematic measures of productivity, and this can also be articulated in a structured fashion that is instrumental to the analysis here but will be saved for the concluding discussion. What remains is however the presentation of a calculation of the average cost of a single publication produced at a Big Science facility that can show what the results are of a one-sided focus on numbers of publications in the assessment of output, productivity or even quality of research of a Big Science facility. The result is shown in table 4.

Table 4: Cost per publication for the three cases (accumulated expenditures divided by accumulated number of publications, for each of the years, all in 2012 USD)

	Year 0	Year 1	Year 2	Year 3
CERN	2,344,600	2,480,800	2,085,700	2,034,800
ESRF	1,668,700	1,348,500	1,044,500	772,200
LCLS	32,676,400	24,777,300	16,982,700	9,529,700

From this table, it becomes obvious, once more, that the cases are not comparable, and this is indeed the chief conclusion of the article, which is hereby forestalled.

Big Science is expensive. At year three of operation, the cost of a single journal publication reporting on experimental work done at the LCLS is just below ten million USD, and although table 4 clearly shows that the marginal cost of publications is decreasing quite dramatically for both the ESRF and LCLS, the costs involved are still extremely high. With that rather mundane conclusion already drawn, we will now proceed to a concluding discussion where the implications of the whole material and especially the figures presented in table 4 are scrutinized, and a couple of other conclusions, hopefully of somewhat less trivial nature, are drawn.

5. Concluding discussion: How expensive is Big Science?

There are numerous methodological difficulties in the material presented above, some of which we have already touched upon and some which remain to be discussed. If the ambition would be to compare the performance of the facilities or otherwise display and analyze properties of the cases as such, the material would be condemned as unfit on the verge of uselessness. But since the point is the exact opposite, namely to prove the inaptness of the comparison and, by extension, the inaptness of the whole exercise of simply counting publications to measure scientific productivity or quality, these methodological flaws should

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[6] These figures have also been obtained from annual reports (ESRF Highlights) for the relevant years.

rather be used to forward the argument. We will now do this, systematically, beginning with the most basic objections to one-sided comparison of simple publication counts.

First, then, it is indeed highly expectable that publications are counted differently at different places, and this has expected reasons that do not necessarily indicate biased measuring but can also stem from seemingly inherent features of bibliometrics such as double counts, gift authorships, double affiliations, and so on. For the facilities under study here, and for the argument in this article, the main issue is to ask what element of the publication (result) in question, and to what extent, can be ascribed to the facility; in other words, would the piece of research that is communicated in a certain publication have been produced and published if it weren't for the facility that accounts for it in its Annual Reports and/or publication database? There are, quite possibly, as many answers to this question as there are publications in the data presented in table 3 above. For state-of-the-art experimental facilities like ESRF and LCLS (and, to some extent, also CERN) it is reasonable to believe that a large fraction of the publications report on truly unique data virtually impossible to obtain by any other mean than using these facilities, but that does not rule out that some publications in the sample are authored by staff members of the facility on basis of research that could have been done, or indeed has been done, elsewhere and/or with other means.

Second, the whole exercise of calculating the cost of the production units publications in this fashion is curtailed by the fact that the facilities under study essentially are service facilities, that is their contribution to the work of a research group is only partial, albeit perhaps crucial – the scientists using the facilities have their employment, lab spaces, etc., elsewhere. Which, in effect, means that the average cost per publication in table 4 is an underestimation.

Third, and not the least important, the character of Big Science facilities are vastly different, also within roughly the same fields, as the ESRF/LCLS comparison shows. A fair comparison could probably be made between two very similar facilities, and from the figures in Hallonsten (2013a), such a "fair" comparison can be deduced, in which the ESRF comes out as 1.5 times as productive as one of its direct competitors (the Advanced Photon Source, APS, in Illinois) and more than twice as productive as the other one of its direct competitors (the SPring-8 in Harima, Japan).[7] That the LCLS has a significantly higher average cost per publication is thus quite natural, given the differences between the facilities. Not only does the ESRF run several experimental stations at once, it can also be rightfully argued that the ESRF was the result of a rather long scientific, technical and organizational development and relied heavily on the field-wide settlement of a reliable and customary technological design concept for similar facilities, that could be optimized within the context of the European collaboration that created ESRF (Hallonsten and Heinze 2014). The LCLS, on its part, was truly groundbreaking and even surrounded with doubts on whether it would perform at the level envisioned, which arguably made the facility's service to the scientific community less of an off-the-shelf exercise which might have had an effect on productivity.

To reiterate, the article shows beyond all reasonable doubt that the caveats, exceptions and methodological flaws surrounding the approach of simply counting publications to measure scientific productivity and quality of Big Science facilities is overwhelming. An extension of the analysis to cover citations and/or journal impact factors, so as to calculate e.g. the average

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[7] The figures are averages for the years 2004-2010. What precludes the data from Hallonsten (2013a) to be used in this article is the lack of comprehensive figures on expenditures from the first instance of construction of the facilities and on. The difference between the ESRF and APS is erased when accounting for the fact that the ESRF has ten more experimental stations than does the APS, but in a similar exercise the SPring-8 comes out even worse, running twenty beamlines more than the ESRF. A thorough discussion on these differences is found in Hallonsten (2013a: 508-512).

cost of highly cited articles or articles in journals of high impact, would not change this conclusion – quite the opposite, as any count of e.g. highly cited papers also possess all the potential flaws noted, and most important of all, a high number of citations is still not a reliable enough measure of quality.

But nonetheless, publication counts are used to measure productivity and quality, also at extremely expensive Big Science labs. The main purpose here is also to inquire, at some depth, what is actually the result of consistent use of these measures. There we arrive at the figures in table 4; the exercise of following the simple counting of publications as a measure of productivity or quality will lead to the demonstration that the cost per publication, calculated as the accumulated cost (construction plus operation) divided on the accumulated number of publications is descending, year by year, in all three cases, but that in the first full year of operation, the results coming out of the LCLS facility cost almost 25 million USD per publication. While this is an astronomical amount of money for a single publication, the cost for an ESRF publication is also high in year 1, namely 1.3 million USD. One trivial conclusion is that Big Science is expensive. But how expensive? Or, to pose the question differently, how can its expenses be motivated?

We argue that if this question is answered by reference to scientific productivity as measured by publication counts, as so often is the case, the result is rather absurd. This is the main conclusion of the article, and it is methodological, in a wide sense, rather than empirical or theoretical: While publication counts might serve its purpose on the level of individual scientists or perhaps research groups, displaying general productivity at the level of one or a few people, it is irrelevant on higher levels of analysis. The use of the data in this article displays this by dealing with an extreme case where the consequences of such an exercise are truly absurd. Obviously, if the rationale for investing in a Big Science facility (be it CERN, the ESRF or the LCLS) is an expectation that it will produce or facilitate cutting-edge science, then any evaluation of their performance must focus on the *content* of this science and the publications it produces, and assess these qualitatively.

Acknowledgements
The author is grateful to Richard Heidler and Heiko Heiberger for their assistance in processing the quantitative material used in the article.

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