Department for Business Innovation & Skills

INNOVATION FROM BIG SCIENCE: ENHANCING BIG SCIENCE IMPACT AGENDA

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Executive Summary

The views expressed in this report are that of the authors and not necessarily those of the Department for Business, Innovation & Skills.

Aims of the Study

This report examines the potential of shared, large-scale scientific facilities to contribute to innovation above and beyond their immediate scientific mission. Based on a systematic review of research into this area, we:

1. Build a conceptual model that outlines the elements of Big-Science Impact Agenda (see Figure 3, page 36).

2. Build a framework that illustrates the technological innovation potential opened up by big-science facilities over their life cycle (see Figure 1, page 29).

3. Build a framework that illustrates pertinent issues of the management and operation of big-science facilities over their life cycle (see Figure 2, page 35).

4. Using the above models, explore seven case studies of large-scale scientific facilities in the UK.

5. Draft a research agenda for the study of the Big-Science Impact Agenda (see text from page 52).

Findings

1. There exists a good number of reports documenting cases of impact generation in big-science contexts[1]. However, relative to the importance of the big-science mode of scientific research, and relative to the volume of research into 'little science[2]', there exists an acute lack of research into the societal, economic and innovation impact of

[1] See, e.g., www.stfc.ac.uk/2428.aspx for STFC's listing and copies of impact reports.

[2] By 'little science' we refer to scientific research conducted outside the sphere of shared, large-scale scientific research facilities. Much of the academic research conducted in universities would fall into this category, for example.

Big Science. Given the potential magnitude of this impact, it is important to understand better how this impact is created.

2. The Big-Science Impact Agenda is broad and extends far beyond the immediate scientific agenda. However, we are still lacking comprehensive frameworks to explore this agenda; one attempt to develop such a framework is presented in this report (see Figure 1, page 29)

3. The missions of big-science facilities can be usefully categorised into research-oriented and service-oriented missions, on the one hand, and fundamental research oriented and solutions-oriented missions, on the other. In practice, many big-science facilities exhibit elements of each, and the emphasis on different missions is likely to vary along the life span of the big-science facility (see Figure 4, page 51).

4. The impact potential of big-science facilities evolves during their life cycle, with different impact mechanisms dominating in different phases. In order to maximise this impact it is important to understand how this potential changes along the life cycle and what the key impact drivers are in each stage.

Big-Science Impact Agenda: Recommendations

The Big-Science Impact Agenda outlined in this report (Figure 3, page 36) covers four major areas:

1 **Scientific Mission**. The core of big-science impact delivery is their contribution towards a specific scientific mission. In this report we distinguished between fundamental and solutions-oriented missions, each being equally important. An important, often neglected aspect of this mission is the influence of a given big-science facility on adjacent fields of science and industry – e.g., through the provision of research and R&D services.

2 **Facility creation and maintenance**. An important aspect of the Big-Science Impact Agenda is the specification, design, planning, implementation, extension and upgrade of large-scale scientific facilities. Especially when the scientific mission necessitates the implementation of frontier-pushing technological performance requirements, there is major scope for providing innovation push for industrial suppliers through big-science procurement activity.

3 **Management and operation**. Through their management and operation, big-science facilities generate a major, on-going impact on their adjacent scientific communities.

Big-science facilities also operate important ‘Third Mission’ activities, e.g., in the form of community engagement and technology transfer.

4 **Broader societal impact**. Perhaps the least well understood, yet potentially the most significant aspect of big-science facilities operates through their broader contributions to society and culture. Big-science facilities not only operate as important platform for human resource and research capability development; they are often also major contributors to culture and important societal conversations on, e.g., global warming. This is a crucial, yet hard-to-measure impact, similar to the economic impact of Big Science.

In order to more efficiently advance Big-Science Impact Agenda, systematic research on the various impact mechanisms is urgently needed. We therefore propose a research agenda for the systematic exploration of these issues. Suggestions to this effect are made from page 54 onwards.

Summary for Innovation Policy-Makers

This report examines the potential of shared, large-scale scientific facilities to contribute to innovation above and beyond their immediate scientific mission. It starts with a literature review and discussion of the received evidence on the economic impacts from scientific research and in particular from Big Science facilities. **The report notes the lack of evidence on Big Science impact but provides a conceptual framework for thinking about the impact.** It also notes some of the management and governance challenges around Big Science facilities and the relevance of these to facilities' impact. Using the framework it then explores seven case studies of large-scale scientific facilities in the UK. Finally, it recommends directions for further research.

Economic Impact of Big Science

Received evidence on the economic impact of science divides impact into four broad categories:

- Creating new general purpose scientific knowledge and intellectual property
- Developing the human capital of students and researchers
- Providing research services or carrying out joint projects with external partners
- Creating spinout firms to commercially exploit new knowledge

Developed thinking in terms of **what separates out Big Science from 'small' scientific research** can be divided into the following themes:

- **infrastructure building and maintenance**: the unique frontier-pushing infrastructure demanded by many Big Science projects can lead to major knowledge generation opportunities for the high tech firms which supply the facility;
- **international collaboration:** Big Science facilities provide a platform for global research networks; this social capital has been shown to provide an excellent setting for combining ideas leading to innovations such as the world wide web;
- **service provision:** Big Science facilities often provide research services which would otherwise simply not be available to firms; and
- **more training intensity:** due to the fact that Big Science facilities are usually mission-led rather than researcher-led.

The report **notes two dimensions on which Big Science projects can be placed, and the consequent implications for innovation potential:**

- Facilities can be fundamental research (discovery) or solutions oriented; the former are more likely to generate innovation advances which stem from the design and creation of the facility, the latter directly from knowledge generated in the mission.

- Facilities can be service or research oriented; the former have better innovation potential as firms can use the equipment for specific bits of R&D.

The report notes three further factors which determine the innovation potential arising out of the design and build of big science facilities:

- **The physical and technological requirements and specifications:** the more technologically frontier-pushing projects, and those with a wider range of technological requirements, have greater innovation potential.
- **Organisation of R&D:** the effectiveness of, say, the collaborations with universities and industry impact upon the potential for innovation.
- **Policy:** procurement rules and the level of support to suppliers will determine how much innovation can actually materialise.

Management and Governance Issues

Big science facilities pose project management challenges owing to their size, their length, their exceptionally demanding and frontier-pushing specifications, and the highly political internationally collaborative environment in which the projects take place. The technology frontier pushing nature of many Big Science projects means that often they are “non-linear”, i.e. it is not possible to predict the precise steps and progress of a project ex ante.

These management decisions can be broken down between the different stages of a project. In the early mission-defining stage, decisions have to be made around the following areas:

- principles of procurement policies;
- rules governing university collaborations;
- emphasis on possible alternative missions (discovery vs. solutions etc); and
- emphasis given to different impact delivery mechanisms (as discussed above).

At the second stage, the specification of physical and technological requirements, decisions have to be made around the following areas:

- practical organisation of exploratory R&D projects;
- the distribution of work between the facility and collaborating universities; and
- the level and balance of engineering skills needing to be maintained by the facility and collaborating universities (and the balance of skills across these two).

The length and iterative nature of many of these projects allows for within project learning. According to the (sparse, unsystematic) evidence, within-project learning is an important determinant of success for Big Science projects.

Case Study Evidence

Using the above framework, the study looked at seven projects[3] funded by the Large Facilities Capital Fund (LFCF). The first observation is that most Big Science facilities are introduced not with a big bang, but with gradual expansion and diversification of functionality. Advantages of this include the speedier introduction of the 'earlier' functionalities, the technological learning that can be used, and the verification of demand for and scientific 'ability' of the facility. Big Science facilities have the potential to be hubs of innovation; hence it is important that impact strategies are long-term and evolving.

Overall, the case studies show that the scientific impact is most determined (unsurprisingly) by the service and scientific missions of big facilities, whilst technological innovation potential is determined largely by the phase of the project life cycle. The facilities were in general trying to a) increase scale, b) increase scientific scope, or c) enhance performance. The nature of technological innovation potential follows from this. Finally, evidence of more hard to measure societal impact, such as Halley VI's contribution to the data underlying the public debate on climate change, was present in all cases.

Research Agenda Going Forward

The proposed research agenda going forward (Section 5) is divided into four sets of questions. The first set of questions surrounds the scientific impact as well as high-level governance issues. Questions suggested for further research include:

- How is international consensus on research agendas and on decisions such as the location of facilities reached?
- What are the motivations of governments to support Big Science?
- How do Big Science research agendas influence research in other fields?

Second, on the core issue of technological innovation coming out of the design creation of Big Science facilities, research questions suggested include the following:

- How are the technological specifications formed and what factors determine the associated potential for technological innovation?
- How do different ways of organising the design of technological specification influence technological innovation?
- How does the potential for innovation vary over the life cycle of a facility?
- How and why do Big Science facilities differ in terms of their technological innovation potential?

[3] These are the Diamond Synchrotron, the Royal Research Ship James Cook, ISIS Neutron Source, Accelerators and Lasers in Combined Experiments (ALICE), Halley VI Antarctic Research Station, High End Computing Terascale Resource (HECToR), and the Muon Ionisation Cooling Experiment (MICE)

Third, the report proposes further research into the management issues faced by Big Science facilities. Research questions suggested include:

- How are the one-off projects of Big Science managed, and what are the lessons for project management?
- What are the different governance and administrative structures for Big Science and what are the implications of these in terms of innovation potential?
- What are the direct services facilities offer to firms and what firms' needs are thus addressed?

Finally, proposed research questions for the remaining mechanisms for impact include:

- What are the mechanisms through which Big Science generates societal impact?
- Is it possible to track the impact of Big Science on macroeconomic indicators?
- How do Big Science impact mechanisms vary across participating countries?

Introduction

During the past century, scientific progress has become increasingly reliant on large-scale collaborative efforts that involve shared facilities and other resources, a form of scientific endeavour popularly known as 'Big Science[4]' (Weinberg, 1967). Big-science research typically involves capital-intensive shared facilities, a large number of often geographically distributed researchers, a host of participating organisations and their interactions (Galison & Hevly, 1992). In contrast with investigator-driven research, which typically characterises university research, big-science research is mission-driven and seeks to accomplish a demanding, widely agreed scientific mission (Esparza and Yamada, 2007). Initially confined to astronomy and nuclear physics, this mode of scientific research is becoming increasingly common in other branches of science, such as molecular biology and even social sciences, where researchers are learning to tap into 'big data' resources to monitor human behaviour even on a real-time basis and in large populations (Meyer, 2013; Meyer, 2009; Thanos, 2013).

The influence of the big-science trend extends beyond shaping how an increasing proportion of scientific research is conducted, as big-science initiatives often shape and even dictate research agendas in related branches of science. As an example, astrophysics research can have direct implications for climate science (STFC, 2009), and the frontier-pushing information processing needs have provided a major impetus for advancing both information technology infrastructures as well as related information science (COST, 2010; STFC, 2011).

As big-science projects transcend national borders and economic blocks, they also have an important cross-national harmonising influence over science funding. While promoting concentration of effort, the indirect influence on the allocation of science funding underscores the importance of better understanding the role the big-science mode of research plays in the overall palette of scientific activity. For example, because of the effort-concentrating and harmonising effect, big-science projects are an increasingly important part of the training of new researchers and the shaping of national research cultures (Galison & Hevly, 1992; STFC, 2011). These trends are highlighted by the predominant focus of science communicators on Big Science (Coppola & Elliot, 2005), the increasingly significant discoveries from big-science facilities (Ekers, 2009) and the ambitious long term plans by leading nations (Malakoff & Cho, 2003; RCUK, 2010; STFC, 2011; Xin & Yidong, 2006).

In spite of the increasing importance of big-science endeavours to scientific and societal progress, not enough is known about the impact of big-science on innovation and economic development (Zuijdam et al., 2011). This is in contrast with 'little science', the impact of which has been the focus of major and solid research tradition (Merton, 1979). In our systematic literature review, for example, we uncovered only a handful of articles and

[4] We use first-letter capitalisation when referring to Big Science as a noun. We do not use first-letter capitalisation when using the term as an adjective (e.g., 'big-science projects').

reports that directly addressed the economic impact of big-science projects (Streit-Bianchi et al., 1984; Autio et al., 2003; Zuijdam et al., 2011). This is an important gap, since, in contrast to the ‘carte blanche’ approach that prevailed during the early big-science endeavours (e.g., the Lawrence Berkeley National Laboratory and Manhattan projects), big-science projects face increasing pressure to justify themselves not only with scientific arguments, but also with their societal and economic impact (Autio, Bianchi-Streit, & Hameri, 2003). Although such assessments are regularly applied to ’little science‘ programmes (Hare, 2002), big-science projects have much less empirical evidence, benchmarks and conceptual frameworks to draw upon when making their case.

As science budgets face increasing strain due to persistent pressure to downsize government budgets, the capital-intensive investments called for by big-science budgets are particularly exposed. This exposure is exacerbated by the challenges big-science centres face in building and operating their facilities in a cost-effective manner (Zuijdam et al., 2011; “RAMIRI Handbook,” 2013). For example, the cancellation of the Superconducting Super Collider project was in part due to the quadrupling of the projected cost estimates from $4bn to $12bn from 1987 to 1993, exposing it to criticism(Riordan, 2000). This is in contrast to Lawrence Berkeley lab, which was mobilised in 1931 at the height of the great depression with generous support from the Rockefeller Foundation (Galison & Hevly, 1992; Price, 1986). As capital-intensive projects with often uncertain future payoffs are increasingly vulnerable in an environment of tight budget constraints and competing demands, it is important for big-science facilities and infrastructures to learn to argue their case not only in scientific terms, but also in terms of the corollary benefits that investments in big-science infrastructures can generate for the economy and society as a whole (Zuijdam et al., 2011).

In summary, while the big-science mode of doing science appears to be increasingly important, and while there exists a fair number of case studies detailing individual impact mechanisms, much of the received literature is fragmented and lacks a coherent underlying framework. More needs to be known about how big-science research generates societal and economic impact, and also, about how to best build and operate these facilities so as to maximise the technological, economic and broader societal impact that such facilities offer. It is our objective in this report to carry out a systematic literature review to summarise received research and empirical evidence on these issues. In so doing we seek several contributions for research in this domain: First, drawing on the systematic literature review, we create an organising framework of the mechanisms through which big-science research creates societal and economic impacts. Second, we summarise key managerial challenges associated with big-science facility construction and operation, from the perspective of maximising the economic and societal impact of big-science endeavours, alongside their scientific impact. Third, we lay out a research agenda for future research on big-science project management, operation, and associated economic and innovation outcomes.

This report proceeds as follows. First we provide an overview of the big-science research landscape. Then, we conduct the systematic literature review using the critical synthesis method. After this, we draw on case evidence from CERN to propose an organising framework of the mechanisms through which big-science creates societal and economic impacts. We conclude by proposing a research agenda for big-science impact monitoring and research.

Big-Science Context

The term ‘Big Science’ is used to refer to large-scale, often capital-intensive scientific collaborations that are underpinned by shared scientific resources, such as measurement and observation facilities, experimentation and research facilities, shared data resources, and supporting infrastructure. Although initiated in particle physics and astrophysical research, large-scale scientific facilities are employed also in other branches of science, such as life sciences (molecular biology in particular) and even in social sciences. As the collaborative mode of organising scientific efforts around shared resources has proliferated, also the definitional boundaries of ‘Big Science’ research have become somewhat blurred. For the purposes of this review, we define our focus as being on collaborative scientific endeavours that have an overarching research agenda, share capital-intensive facilities, data resources and infrastructure, and involve a large number of organisational stakeholders. We do not limit our focus on transnational collaborations, however. Although the great majority of big-science collaborations are international and even global by nature, there are also important domestic facilities, whose impact is equally important to understand.

By definition, then, big-science facilities tend to be large and capital intensive. In Europe alone, EU member countries together spend around €10 billion annually on running shared research facilities (Barker, Sveinsdottir, & Cox, 2013). Big science refers to large scale scientific research facilities funded by governments, often on a project by project or year by year basis. Several scientific goals of national or international importance are pursued, defined and managed by a committee of administrators. It occupies a distinct space within the global research portfolio. These projects are different from large flagship projects, as the budget of big-science projects costs exceeds $500M, and they have broad participation and lead times of up to 10 to 15 years from early concepts to “first light” (OECD, 2004).

The big-science mode of research tends to be more common physical science, astronomy, space exploration and life sciences, where large shared infrastructures sometimes need to be created to pursue scientific missions. However, the big-science mode of conducting research is by no means confined to these sectors: In fact, 10 out of the 31 existing large facilities listed by Research Councils UK (RCUK) are in the social science domain (RCUK, 2010). Many of these facilities are not capital intensive, however, and therefore not included in the present review. Examples of large international facilities include the European Southern Observatory (ESO), Institut Laue Langevin (ILL), European Laboratory for Particle Physics (CERN), European Synchrotron Radiation Facility (ESRF), Joint European Torus (JET), European Molecular Biology Laboratory (EMBL), International Thermonuclear Experimental Reactor (ITER) and the now completed Human Genome project. Examples of national facilities include: Australia Telescope National Facility; Canada: TRI-University Meson Facility (TRIUMF); France: Grand Accélérateur National d’Ions Lourds (GANIL); Germany: Deutsches Elektronen-Synchrotron (DESY); Japan: Super Photon Ring 8 GeV. (SPring-8); United States: Stanford Linear Accelerator Centre (SLAC).

Although big-science projects share many similarities, the knowledge and innovation dynamics may vary considerably across sectors and institutions. The most important dimensions along which big-science projects differ include the dynamic of knowledge creation in the relevant scientific field; the way the shared infrastructure is built and operated; the associated potential for innovation effects; and the way these facilities are governed ("RAMIRI Handbook," 2013). Different fields have varied experiences with large scale research activities, even in closely related fields such as physics and astronomy (Boisot, Nordberg, Yami, & Nicquevert, 2011; COST, 2010). For example, Ekers and White have highlighted differences between 'Big Physics' and 'Big Astronomy[5]' in terms of experiment orientation vs observation orientation, number of core questions asked, team structure and structural formalisation (Ekers, 2009; White, 2007). Such differences may influence the dynamic of scientific knowledge creation in the consortium and may be associated with the nature of research questions pursued and the empirical and experimental designs required to pursue them.

In another important dimension, big-science facilities can also differ in terms of how they are built. Particularly in physical science (e.g., particle physics and fusion energy), astronomy and space exploration the facilities required to conduct experiments and carry out missions are large, complex and often require frontier-pushing performance in many technologies. Considerable potential is thus created for technological learning and innovation (Autio, Streit-Bianchi, Hameri, & Boisot, 2011). Unlocking this potential will depend on two related issues: first, how the technological specifications of big-science procurement projects are produced; and, second, how the procurement process itself is organised. CERN, for example, operated as a 'specification factory', often undertaking significant technological research to create exact specifications for how individual deliveries should be designed (Autio, Hameri, & Vuola, 2004). This preparatory research (i.e., research that preceded the issuance of tenders) was often undertaken in collaboration with industrial suppliers and member countries' universities. This approach provided the opportunity for member countries' universities and industrial companies to leverage CERN's R&D resources for technological competence development. As another approach, the European Space Agency ESA only issues tenders for required performance specifications without providing detail on how this performance is to be produced. This 'grand challenge' approach would support innovation by providing aspirational stretch and fostering the creation of novel combinations rather than through R&D assistance and guided search.

In addition to knowledge creation and build-up, a third important aspect of big-science projects concerns governance and the management of the shared infrastructure. The annual operating costs of big-science facilities can be high, and sometimes the cost of operation can exceed the initial investment within a decade (although this significantly depends on the type of big-science facility) (Jiménez, 2010). The implication is that the governance of big-science infrastructures is a non-trivial issue, and some studies point to potentially important efficiencies that could be achieved in this area (*Cost control and management issues of global research infrastructures: Report of the European expert group on cost control and management issues of global research infrastructures*, 2010) (Jiménez, 2010). Some of such arguments may be outdated, however, as member

[5] While astronomy is a sub-field of physics, it also has a distinct identity of its own.

countries have become increasingly conscious of operations-related cost saving potential and apply increasingly tight demands on this aspect (“RAMIRI Handbook,” 2013). This emphasis on cost saving is also partly balanced by the benefits individual countries received from supporting and engaging with big-science collaborations. For example, the US bears only 1/11th of the cost of ITER project, but it is expected to receive a much larger share of the scientific findings produced by the collaboration, in terms of both scientific advances and industrial benefits. Nevertheless, the operation of big-science facilities represents a distinct area of interest that merits attention in its own right.

Despite the increasing importance of a big-science mode of scientific research, there is a dearth of academic research that assesses the innovation potential offered by big-science experiments – particularly when compared against the volume of research focusing on ‘Small Science’; e.g., on university-industry links (Autio et al., 2004; Boisot et al., 2011; Zuijdam et al., 2011). In particular, there is a major gap in management and policy understanding of the various mechanisms through which Big Science contributes to society and economy beyond the immediate scientific agenda. Given the scale of investment in big-science, it is important to review received evidence of the innovation potential associated with big-science experiments, and also, the best approaches to nurture and exploit this potential. This report reviews and summarises received literature on this topic. Drawing on a systematic literature review, we then create a conceptual model that elaborates on salient aspects of the innovation potential associated with big-science research. This model is further extended and elaborated upon by means of case studies of a representative set of big-science experiments.

We next outline our systematic literature review methodology. We then review received research and literature on big-science innovation. A conceptual model is then developed, which will be used as a guiding template for selected case studies.

Methodology

The development of systematic approaches to reviewing received literature was prompted by the trend towards evidence-based policy – i.e., the requirement that policy decisions be grounded in and informed by a synthesis of research findings on a given topic or domain. Originated in medicine and healthcare, systematic literature reviews have become an increasingly often used device to systematically collect and analyse received research also in other academic disciplines, including management research and innovation studies (Tranfield, Denyer, & Smart, 2003). In essence, systematic literature reviews provide a systematic approach to reviewing a received body of knowledge in a given domain in a way that leaves a documented trail and is independently replicable. Whereas in medicine and healthcare, most systematic literature reviews take the form of meta-analysis, the nature of research knowledge (especially the frequent use of qualitative constructs and the case study method) limits the utility of this technique in management research. Instead, systematic literature reviews in this domain most often take the form of a qualitative synthesis, such as a meta synthesis, critical review or a thematic synthesis. In the current review, we adopt the thematic synthesis approach (as defined below) and organise our review along central themes, as they currently exist in the big-science innovation literature.

The literature search was conducted using Google Scholar, Google Web and ISI Web of Knowledge. The keywords used in the search included but were not limited to “Big Science”, “mega science”, “science project management”, “science management”, “Big Science outcomes”, “large science + facilities”, “large/big research”, “science collaboration”, “science policy”, “basic science”, “benefits of basic science research”, “science funding”, “economics of science” and “research infrastructure”. References in these literatures were checked for relevant subject matter. Further search was carried out during a separate citation gathering exercise, where each title was used as a keyword, which yielded further relevant references that might have been missed during the first round of search. It is noteworthy that forward citations were in all but a few cases not focussed on Big Science. Specific search of big-science facilities were then conducted such as Genome Project, NASA, CERN, ITER, cyclotron, particle accelerator, space shuttle, ISS, Very Large Array, ESS, PARC. Keywords obtained from articles and news items were also explored. For example, projects such as CERN’s CoDisCo and TuoviWDM have been documented as reports that were not captured in the core search. Institutional websites were also scanned for reports, impact studies and news items on big-science projects.

Among the documents surveyed, only those with a genuine big-science emphasis were included in this review and synthesis. There was quite a large number of documents evoking the ‘Big Science’ term that nevertheless were not relevant for the purposes of the present review. During the course of reviewing the studies we found, we also developed other heuristics for excluding irrelevant documents. For example, several articles used Big Science or large research synonymous with, e.g., national flagship projects that nevertheless did not meet the scale and scope criteria we had developed to define Big Science. As noted above, our review was not limited to academic journals only, as much of the documentation of big-science innovation takes the form of case studies and other such documents, and also, because the literature is generally quite fragmented. One reason for this fragmentation could be that the study of big-science innovation is not very well established within management disciplines, but rather, has been contributed by big-science domain researchers such as physicists and astronomers and often published outside the mainstream management and innovation journals. There is also a stream of work focusing on supportive technologies such as distributed computing, grids and data processing.

Given the sparse, non-cumulative and fragmented nature of extant literature on big-science innovation and operation, there was no basis for conducting a full realist synthesis, a form of systematic literature review that seeks to develop meso-level theory from a fragmented base. Due to lack of guiding theory and the infrequent application of sophisticated social science research methods and designs in this literature, the criteria for conducting a meta-study – i.e., a construction using analysis of findings, methods and theories (Paterson, Canam, & Jillings, 2001) was also not fulfilled. Therefore we chose to apply a thematic synthesis approach – a technique that organises the literature into thematic streams and summarises received findings and insights without necessarily organising them according to the strength of the underlying evidence base. The thematic synthesis was using free codes of descriptive themes to yield analytical themes (Thomas & Harden, 2008). In organising the literature, we also used approaches informed by the ‘deductive framework synthesis’ approach (Pope, Ziebland, & Mays, 2000).

A critical interpretive process was used to inform the development of the conceptual framework. This involved an iterative approach to refine the research questions by applying codes to the selected literature (Dixon-Woods et al., 2006). This process helped deconstruct research streams and contextualise findings. As opposed to aggregative methods (which summarise well-specified data and stable concepts), the interpretive approach uses induction and interpretation to develop concepts and integrate them with theories. This is ideally suited to a literature that is diverse, complex and interdisciplinary, as was the case in this review.

Finally, a two-stage interpretive framework development approach was adopted in this report. In this method, a preliminary taxonomy of the literature informs an initial static high level framework. An attempt to consolidate the observations gives rise to a number of research questions which are then used as a lens for the next stage of induction and interpretation. This enables a deeper synthesis to yield a more detailed dynamic framework that can encompass big-science phenomena. This method is particularly useful in case where a synthesis is attempted in a field whose literature is sparse, fragmented, non-accumulative and lacking in theory and rigorous methods. Since the same literature is subject to this process, the initial taxonomy is essentially a simple review and the rest is considered synthesis. Another feature of this method is that the framework highlights research gaps which can be used to set up a coherent research agenda.

Review and Synthesis

Normally, thematic streams can be identified in terms of scholarly tradition, academic discipline, or, for example, theoretical perspective. In the big-science space, well-delineated streams are yet to emerge due to the scarcity of dedicated research attention in this space thus far. Fragmented work could nevertheless be identified within six main scholarly perspectives: sociology; assessment (including scientometrics); history; economics; policy; project management (including procedural reports) and innovation. Table 1 lists the literature organised along this taxonomy.

Table 1 Taxonomy of Scholarly Traditions in Research on Big-Science Dynamics

	Research areas	Academic Papers
Sociological **(including) Collaboration**	Rate of increase of scientists; discourse, power and science; social context and science; junior investigators; age; cooperation of academic and corporate; managing differences; co-authorship patterns.	(e.g., Cole & Meyer, 1985; Kinsella, 1999; Ness, 2007; Price, 1986; Remington, 1988) (e.g., Bammer, 2008; Berger & Cozzens, 2009; EC, 2009; Hand, 2010; Havemann, Wagner-Döbler, & Kretschmer, 2000; Knorr-Cetina, 1999; Leydesdorff & Wagner, 2008; Meyer, 2008; OECD, 1998; Thompson, 2009; Welsh, Jirotka, & Gavaghan, 2006)
Assessment **(including) Scientometrics**	Benefits from spin-offs and manpower training; comparing quantity of output and scientific performance from accelerators; meeting construction requirements; potential; evaluation techniques; citation; impact vs. quality;	(e.g., Alred & Siegfried, 1992; Ekers, 2009; Martin & Irvine, 1984; Martin & Irvine, 1981; Martin & Irvine, 1984; NRC, 1994; Quinlan, Kane, & Trochim, 2008; Stokols et al., 2003) (e.g., Collazo-Reyes, Luna-Morales, & Russell, 2004; González-Albo, Gorria, & Bordons, 2010; Krige & Pestre, 1985; Martin & Irvine, 1985; Shearer & Moravscik, 1979)
History	History of big-science research; evolution of big-science facilities; emergence and evolution of research communities in big-science sectors; historical trends in science evolution	(e.g., Collins, Morgan, & Patrinos, 2003; Collins, 2003; Furner, 2003; Galison & Hevly, 1992; Graham, 1992; Hoover, 2007; Kojevnikov, 2002; Kulkarni, 2007; Logsdon, 1989; Rasmussen, 2002; Riordan, 2000; Wang, 1995; Westfall, 2003)
Economics	Market failures in knowledge production; information asymmetries; economic effects from knowledge spill-overs	(Dasgupta & David, 1994; Diamond, 1996; Nelson, 1959; Stephan, 1996; Williams, Lemkau Jr, & Burrows, 1988)
Policy	Management of international research collaborations; knowledge creation effects of big-science experiments;	(e.g., Chubin, 1987; Collins, 1985; Kaysen, 1966; Kennedy, 1985; Lambright, 1998; MacMillan, 2004; Madison, 2000; Millett, 1966; Pavitt, 1991; Weinberg, 1967; Weinberg, 1961)

	Research areas	Academic Papers
	management of big science	
Project management **(including) Reports**	Management of big-science facilities; management of complex projects; complex product systems; learning in one-off projects	(e.g., Acedo, Andersen, Langlo, & Rødne, 2001; DIUS, 2007; NSF, 2009; Tuertscher, 2008; Van den Eynden & Ninin, 1997) (CPA, 2007; DTI, 2004, 2005; Fontana, 2008; Lambright, 2002; NSB, 2005; OECD, 2004, 2008; OIG, 2004; RCUK, 2010)
Innovation **(including) Potential**	Case studies of innovation in big-science contexts; mechanisms driving innovation in big-science facilities; documentation of knowledge spill-overs; studies of industry engagement; organisation of big-science procurement activity	(e.g., Autio, Bianchi-Streit, & Hameri, 2003; Autio, Hameri, & Vuola, 2004; Autio et al., 2011; Boisot et al., 2011; Bressan et al., 2009; Byckling, Hameri, Pettersson, & Wenninger, 2000; COST, 2010; Hameri, 1997; Heilbron, 1992; Schmied, 1987; STFC, 2009; Vuola & Hameri, 2006; White, Sullivan, & Barboni, 1979; White, 2007; Wilkinson, Kellermann, Ekers, & Cordes, 2004) (e.g., Autio, Hameri, & Nordberg, 1996; Esparza & Yamada, 2007; Irvine & Martin, 1985; Wilsdon, Wynne, & Stilgoe, 2005)

The breadth of scholarly perspectives applied to research on Big Science, as well as the general fragmentation of the literature, underscore the need to develop a coherent conceptual framework for the study of this phenomenon, and also, a coherent agenda for further research. The taxonomy shown in Table 2 suggests that such a research agenda does not yet exist. Similarly, the lack of robust social science methodologies and theoretical frameworks has inhibited the creation of overarching insights. For example, thus far, there have been no attempts to organise and classify big-science experiments and infrastructures according to shared underlying parameters describing, e.g., knowledge creation dynamics; aspects and associated mechanisms of innovation potential; and operation. Therefore, although there exists a number of case studies of individual innovations and technological developments from big-science contexts, the absence of organising theoretical frameworks has limited the ability of such studies to inform policy (e.g., Byckling, Hameri, Pettersson, & Wenninger, 2000; Hameri & Nordberg, 1998; STFC, 2009).

The above does not mean that no theoretical work would have been carried out in big-science contexts. For example, Autio et al (1996) created a framework of motivations for big-science collaboration from industry perspective; Knorr-Cetina has studied the sociology of knowledge creation in big-science contexts (Knorr-Cetina, 1999); Autio et al inducted a framework of social capital influences on knowledge spill-overs in big-science contexts (Autio et al., 2004); and more recently, Boisot et al applied Boisot's knowledge codification framework to model knowledge codification and learning in the context of CERN's Atlas experiment (Boisot et al., 2011). Thus far, these frameworks have not yet inspired a comprehensive framework to inform a coherent programme of research on innovation in big-science contexts, however.

Received Theorising on Big-Science Innovation

Although the potential of scientific research to contribute to innovation has been widely studied, the great bulk of this research has focused on higher educational institutions (HEIs; notably, universities), sector research organisations and contract research organisations (SROs and CROs). In these contexts, the potential for such institutions to contribute to innovation is mostly seen to be defined by:

- **Scientific research** – i.e., carrying out general-purpose scientific research consistent with the institution's research agenda and disseminating this research through, e.g., publications, conferences, and increasingly, also patents, licenses thereto, and, e.g., new software products and algorithms.

- **Human resource development** – i.e., teaching and training students, researchers and other stakeholders such as company personnel

- **Industry collaboration** – i.e., providing research and training services and carrying out joint research and development projects in collaboration with external stakeholders

- **Spin-off and spin-out companies** – i.e., the facilitated and non-facilitated creation of new companies to exploit knowledge advances created by the institution

Such mechanisms are well documented and subject to active promotion and facilitation by industrial and research policy-makers through generic and targeted policy measures. These may range from, e.g., mission definition (e.g., emphasis on ‘third mission’ activities) to resource provision (e.g., support for venture funds and science park facilities). However, as our focus is on the distinctive aspects of big-science centres, we do not elaborate on these mechanisms here.

Numerous authors have commented on the distinctive characteristics that set big-science research apart from ‘normal’, or ‘small’ scientific research (De Solla Price and Beaver, 1966; Price, 1986; Capshew and Rader, 1992; Heilbron, 1992; Autio et al., 1996; Knorr-Cetina, 1999). Given the considerable literature on the topic, the number of studies focusing on innovation in the context of big-science facilities is surprisingly small. Furthermore, most studies have not specifically sought to identify aspects where the innovation potential of big-science facilities is distinctly different from other research facilities. Nevertheless, a number of shared themes emerge from this literature. These themes point to distinctive differences between big-science facilities and other research facilities in terms of:

- **Infrastructure building and maintenance**. The distinctive aspect of big-science facilities is that they commission and build major chunks of scientific infrastructure (Hameri and Nordberg, 1998; Autio et al., 2011). Many of these commissions are one-off projects that often feature highly demanding, sometimes even frontier-pushing technological specifications. This means that big-science centres not only represent major markets for engineering supplies on their own right. They also provide stretch for industrial suppliers, and, depending on procurement policy, may provide technical and R&D assistance as these strive to meet their exacting demands (Hameri, 1997).

- **International collaboration**. Big-science centres host research infrastructures that are often shared by numerous universities across participating countries. Thus, they provide a platform for global research networks with shared research agendas. The social capital represented by such networks provides an excellent setting for facilitating the combination of ideas and breakthrough innovation (Autio et al., 2004). This aspect was well illustrated by, e.g., the creation of infrastructural technologies that presaged the World Wide Web (Hameri and Nordberg, 1998).

- **Service provision**. Although not the mandate of many big-science centres, many big-science centres host infrastructures whose mission features an important service aspect. In this role, big-science facilities such as the Diamond Light Source are able to offer industrial companies access to unique, capital-intensive facilities that these could not otherwise access for specific research purposes such as materials research.

Big-science facilities also carry distinctive properties in terms of the other drivers of innovation potential. In terms of scientific impact agendas of big-science facilities, a distinction is sometimes made between investigator-driven research (as is often the case in universities, for example) and more organised mission-driven research (Esparza and Yamada, 2007) – the latter being more characteristic of big-science facilities. Within the mission-driven research, a further distinction can be made between fundamental research and solutions-oriented research. While the former are characteristic of, e.g., astronomy and many physical science areas, big-science facilities can also pursue solutions-oriented research, as is the case of, e.g., biomedical sciences (Esparza and Yamada, 2007). Different missions imply different knowledge dynamics, and therefore, variation in the potential of different facilities to contribute to knowledge advances and innovation through knowledge spill-overs (Hameri, 1997).

In terms of human resource development, the mission of big-science centres focuses more on postgraduate and post-doctoral training, which can be a source of considerable impact as such (Bressan et al., 2009). This impact mechanism is accentuated by its international character, as by working with (or in) a big-science facility, researchers can build more international contact networks (a form of social capital) than they typically could by working at a domestic university (Autio et al., 2004). The cross-fertilisation of ideas resulting from the international and multi-disciplinary character of big-science collaborations endows many big-science facilities with potential to foster creativity and new knowledge combinations that is qualitatively and perhaps even quantitatively different from ‘ordinary’ scientific collaborations (Havemann et al., 2000; Autio et al., 2004; Leydesdorff and Wagner, 2008). Not only is there greater scope for creativity, sometimes the infrastructure required to support collaboration within a geographically dispersed scientific community can act as an inducement for innovation, as the case of World Wide Web suggests (Hameri and Nordberg, 1998). The on-going wave of corollary societal and economic impacts prompted by this innovation are global and are comparable to the industrial, economic and societal revolutions precipitated by the adoption of case iron, steel, coal, electricity and IT technologies.

In terms of industry collaboration, a distinctive aspect of big-science centres (in addition to the procurement activity discussed above) is the way the centres sometimes engage with industry in developing technical specifications for infrastructure installations (Vuola and Hameri, 2006). Depending on procurement policy, big-science centres sometimes engage with potential supplier companies to develop the technical specifications for calls for tenders issued to procure equipment and other pieces of infrastructure. In the case of CERN, for example, potential supplier companies were routinely engaged in the call specification phase to test alternative ways to deliver the required technological performance (Hameri and Nordberg, 1998; Bressan et al., 2009; Boisot et al., 2011). The European Space Agency, on the other hand, does not follow this practice, only issuing calls to delivered required technological performance without specifying how.

Summarising, the review of big-science innovation has highlighted the dimensions of industry interaction, international collaboration and service provision as the areas where big-science facilities exhibit the largest differences in terms of innovation potential relative to universities and other academic institutions. Distinctive features could also be identified in the other innovation impact areas relative to universities. Because big-science centres build and maintain capital-intensive research facilities, the core driver of innovation potential is created by this activity. We next take a closer look at this aspect, using the well-documented CERN case as our lens.

CERN, and particularly its Large Hadron Collider (LHC) represent perhaps the best documented case of industrial innovation potential (Streit-Bianchi et al., 1984; Autio et al., 2003, 2011; Bressan et al., 2009). Even among big-science centres, CERN, and LHC in particular, stand out in terms of scale, complexity and duration. In design since 1995, the LHC became operational in 2008, with actual operational launch in November 2009. By then, the budget of the LHC project had amounted to €7.5 Billion. With over 10 000 scientists and engineers from over 100 countries participating in the design and implementation of the LHC facility, and with a circumference of 27 kilometres, it is considered the largest and most complex scientific instrument ever built[6].

The CERN LHC was designed to test several theories, the most important of these being supersymmetry and the existence of a Higgs field and associated boson. Although first proposed by Peter Higgs and others in 1964-1965, the empirical case for the search of the Higgs boson only became compelling in 1983 with the announcement of the discovery of W and Z particles (Baggott, 2012).

The development of particle physics is a cumulative process within which evolving theory informs empirical experimentation, and empirical experimentation in turn constrains the scope of theoretical developments by disconfirming some hypotheses and reinforcing others. It is this dialogue between theoretical physics and fundamental research that drives the development of ideas and informs what discoveries to look for next and where. In particle physics, this translates into setting theoretical energy requirements for the discovery of the boson associated with the Higgs field.

In the case of LHC, experiments at Fermilab's Tevatron accelerators and CERN's LEP had ruled out discovery of the Higgs boson at collision energies less than 1 TeV, informing LHC's design proposition to target collision energies in the range of up to 14 TeV (TeV = Tera electron Volt or 10^{12} eV). This requirement, then, begins to inform physical performance requirements – i.e., how powerful magnetic fields would be needed to create the required energies. In other words, theoretical specifications are translated into physical performance requirements.

Once physical performance requirements are known, explorative R&D begins to identify the technologies that can meet physical performance requirements – i.e., physical performance requirements are translated into technological performance specifications. In the case of CERN, much of this work is carried out in-house, and also in collaboration with participating universities and prospective supplier companies. Explorative R&D activities may include, for example,

- Technology and trend analysis: Sometimes the performance requirements are so demanding that no existing technologies can meet them. Trend analysis helps predict when the required technological performance will be available (e.g., information processing standards)

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[6] Measures of instrument size can be debated, as some instruments in radioastronomy are made up of webs of interlinked antennas. The Square Kilometre Array, for example, will span two continents, Africa and Australia.

- Exploration and testing of alternative technologies

The goal of explorative R&D is to help choose between alternative technologies, particularly when there is considerable uncertainty with regard to alternative approaches to produce the required performance. Once the technological design choice has been made, the emphasis in explorative R&D shifts towards laying out the detailed specifications for a call (or calls) for tenders. In this phase, too, there may be collaboration with participating universities and prospective suppliers.

After a supplier has been selected through a competitive process, the emphasis shifts towards project delivery. Even in this phase there may be scope for substantial R&D investment, depending on how far ahead relative to existing performance frontiers the technological requirements are. In this phase, the supplier company may receive assistance and support either from CERN or from member universities, as it strives to meet the performance standards (Vuola and Hameri, 2006). This means that there can be scope for substantial technological learning among CERN suppliers, which may then lead to product and market diversification once the CERN delivery has been successfully accomplished (Streit-Bianchi et al., 1984; Autio et al., 2004, 2011).

The above discussion can be generalised into a life cycle model that illustrates the innovation potential opened up by the infrastructure design, procurement, construction and maintenance process created by big-science facilities. The life cycle model is illustrated in Figure 1. As noted above, the model distinguishes between stages in the big-science infrastructure design and procurement process, starting from the definition of the scientific mission of the big-science facility all the way to procurement and delivery. This process is demarcated by several transition points, during which the outcomes of the earlier stage are translated into problem formulations for subsequent stages. At the same time, interaction modes and patterns change, as the participation of different stakeholders evolves to reflect the new challenges.

On a general level, it can be noted that the scope for the introduction of scientific novelty is greatest during the early stages of the process, whereas the scope for technological innovation (notably, with industry partners) is greatest in the late stages of the procurement and installation process. The key drivers for these two kinds of outputs are: (1) definition (and subsequent execution) of the scientific mission; and (2) definition and implementation of the technological architecture required to deliver on this mission (Boisot et al., 2011). Whereas the scientific mission falls within the realm of ‘traditional’ innovation potential associated with scientific research, the distinctive aspect of big-science research is the significance of the mission itself. In order to justify the major capital expenditure, there has to be a broad consensus that the scientific mission is of major significance, and ideally, that the scientific impact pursued reverberates across several scientific fields. The mapping of the human genome is of obvious importance not only for genetics, but also for medicine, evolutionary studies, and anthropology, for example.

As for the scope of the potential technological innovation impact, it can take many forms. A crucial aspect in this regard is the extent to which the performance of the big-science infrastructure necessitates technological performance requirements that push performance frontiers. If so, there is scope for technological impact in terms of: (1) scoping between alternative technologies to deliver the required performance; (2) choosing between alternative technologies (thereby reinforcing some technological trajectories and not others); (3) performing explorative R&D to inform the above choice; and (4) performing focused R&D to deliver the required performance.

There has been some research to document the extent of technological learning and innovation that occurs during big-science deliveries and during the operation of big-science facilities (Streit-Bianchi et al., 1984; Autio et al., 2003; Vuola and Hameri, 2006). There has been less systematic research to document innovation occurring during the execution of the scientific mission, the extant studies focusing mostly on individual cases (Hameri and Nordberg, 1998; Byckling et al., 2000; STFC, 2009, 2011; Oxford Economics, 2012). In their survey of technological learning occurring among big-science supplier companies, Autio et al (2003) documented significant technological diversification and new product development occurring among the suppliers of the Large Hadron Collider due to the technological stretch created by the need to meet LHC's exacting performance standards. Their survey of 154 suppliers from the main European countries found that (Autio et al, 2003: iii):

- The various learning and innovation benefits (e.g.., technological learning, organisational capability development, market learning) tended to occur together – suggesting that the technological performance requirements were the ultimate driver of technological learning

- Learning and innovation benefits appeared regulated by the quality of the supplier's relationship with CERN: the greater the amount of social capital built into the relationship, the greater the learning and innovation benefits – suggesting that big-science centres can act as important networking hubs that can connect supplier companies with pockets of advanced engineering skills

- Regardless of relationship quality, virtually all suppliers had derived significant marketing reference benefits from CERN – suggesting an important legitimation effect derived from the prestige associated with the status of being a supplier to a big-science facility

- As a direct result of the supplier project, as many as 38% of the survey respondents had developed new products or services; 13% started new R&D activity; 14% started a new business unit; 17% opened a new market; 42% increased their international exposure; and 44% indicated general technological learning

Autio et al (2003) also found that technological learning benefits were present at approximately 10% of the supplier projects, where technological demands were genuinely frontier-pushing. Even at the case of CERN, the majority of the supplier projects were not of a frontier-pushing nature, consisting of, e.g., structural engineering projects; supplies of routine services and standard supplies (e.g., office equipment, furniture and such); and other similar procurements. However, although the share of genuinely frontier-pushing projects represented only 10% of all supplier projects, they nevertheless represented approximately 50% of the procurement budget allocations during the study period. This means that the scope for technological learning and innovation within big-science contexts can represent a considerable share of the capital expenditure associated with big-science infrastructures and should therefore be given close attention when designing policies to maximise innovation spill-over from big-science capital investment.

Another window to the technological learning and innovation potential is provided by an analysis of industrial companies to collaborate with big-science centres. Autio et al explored motivations for collaboration between industry and big-science facilities (Autio, Hameri, & Nordberg, 1996). Focusing on the context of high-energy particle physics and CERN, they used case and survey data to derive a model that identified major motivations for such collaboration from the perspectives of industry, academia and society at large. The motivations identified included technological, strategic, policy-related, and financial.

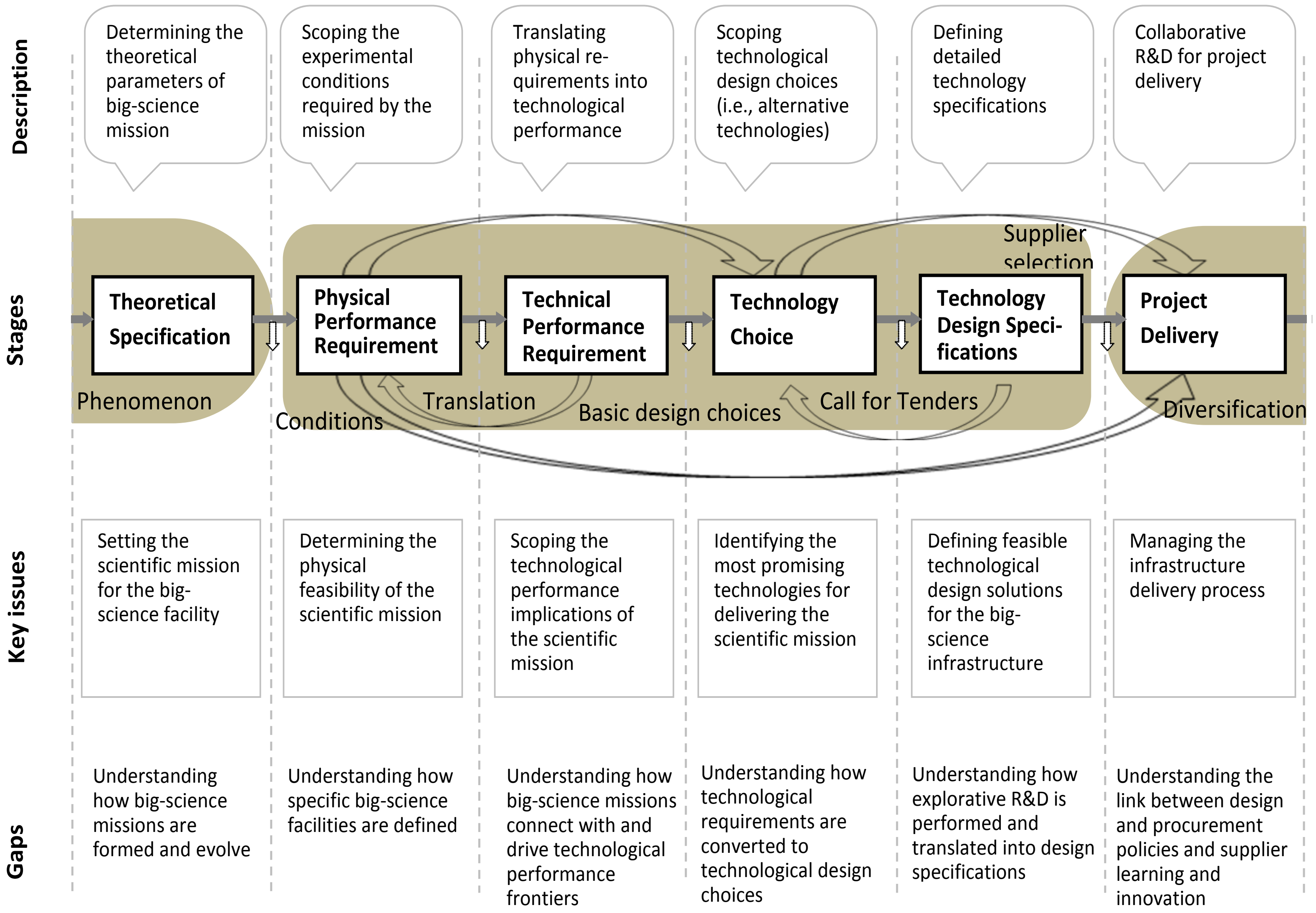
In their framework, technological motivations included benefits such as the technological stretch provided by the frontier-pushing performance requirements often associated with big-science procurements; the ability to tap into complementary knowledge and expertise available in big-science experiments; and development support often available in big-science contexts. An additional benefit is that many big-science facilities provide detailed technological specifications in their calls for tenders, often produced by means of experimental research, which can be used to boost the supplier's development effort.

Strategic motivations included access to new markets, support for internationalisation and the status of being recognised as a supplier to a large scientific facility such as CERN. Large-scale scientific facilities can represent a sizeable market in their own right, and being recognised as a big-science supplier can provide an edge in this market that is often difficult to enter. There are also brand benefits in being associated with a large-scale scientific facility, as these are known for their exacting demands in terms of technological performance and instrument quality.

Industrial and economic policy motivations are associated with strategic motivations and arise from the active support and assistance member countries of big-science facilities often offer for domestic companies bidding for big-science procurement projects. Many governments have recognised the market potential opened by large scientific installations and seek to maximise the national return from such projects in terms of industrial procurement. In such activity, the emphasis is placed on the procurement of technology-intensive supplies in the hope that these will create R&D benefits for the supplier companies. As some estimates put the share of technology-intensive supplies at around 50% of all procurements in large-scale particle physics installations, dedicated procurement facilitation becomes justifiable (Autio, Streit-Bianchi, & Hameri, 2003).

Financial motivations studied by Autio et al (1996) fall into three major categories: (1) direct commercial benefits; (2) operational benefits; and (3) immaterial benefits. Direct commercial benefits arise from the provision of supplies and services to big-science facilities – which thus acts as a source of income – and from marketing benefits. Marketing benefits include, e.g., access to new customers through the big-science facility. Operational benefits include cost savings achievable by employing services offered by the big-science facility; and also, efficiency gains achieved through, e.g., improved purchasing and contract control practices that big-science suppliers can gain through their collaboration with a big-science centre. Immaterial benefits include branding benefits achievable through the status of being recognised as a supplier to big-science facilities; and through technological learning gains derived from collaboration with big-science facilities. The enhanced status can be leveraged for branding, marketing and legitimacy-enhancing purposes.

Figure 1 Life Cycle Model of Innovation Potential Created by Big-Science Procurement



Finally, Figure 1 also summarises key characteristics that define big-science innovation potential, as revealed through our review of received research. First, the definition of the **scientific mission** of the big-science facility sets up its scope for contributing towards knowledge advances and spill-overs. As noted above, the distinction between fundamental and solutions-oriented scientific missions is important – yet, little is known about how the different modes contribute to innovation (Esparza and Yamada, 2007). One obvious difference is that whereas fundamental research is pursued for the sake of advancing knowledge without immediate or even medium-term prospect of practical application (e.g., hunt for the Higgs boson or mapping variation in the background microwave radiation), solutions-oriented research pursues defined contributions with potential application (e.g., mapping the human genome). This implies that solutions-oriented scientific missions are more likely to generate corollary innovation benefits that directly result from advances achieved in the pursuit of the scientific mission. In contrast, fundamental research mission may well be better positioned to generate indirect innovation benefits resulting from the design and implementation of the often extreme experimental conditions that the scientific mission necessitates.

Another important distinction is between service orientation and research orientation. Some big-science facilities maintain infrastructure that is mainly designed to offer services to others – e.g., the Diamond Light Source facility. Other big-science facilities are more specific to the experiment for which they have been designed, thereby offering less scope for facilitating innovation through offering facilities for, e.g., industrial companies to access for specific R&D tasks.

A third important regulator of the innovation potential derived from the facility's scientific mission relates to the extent the scientific outputs are applicable across a broad range of sectors. Clearly, the greater the potential for cross-fertilisation across several knowledge domains, the greater will be the potential of the scientific mission to contribute to innovation.

As regards the definition of **physical and implied technological performance requirements**, a number of key characteristics emerge as important determinants of associated innovation potential. First, as noted above, the degree to which the performance requirements push performance frontiers will regulate the stretch created by the scientific mission, and therefore, the extent to which technological learning is achievable through explorative R&D. Typically, experiments requiring extreme physical conditions (e.g., particle accelerators, fusion reactors) tend to exhibit greater potential in this regard, whereas more applied missions may be achievable even with relatively modest engineering advances.

The second important dimension concerns the range of physical and technological performance categories covered. This dimension is closely associated with the systemic complexity of the big-science facility. The broader the range of performance categories required for executing the scientific mission, the broader will be the associated learning potential, and also, the more numerous will be the opportunities for innovation through technology combination. Highly complex facilities such as CERN's LHC will offer broader scope for innovation than will, e.g., Europe's Very Large Telescope.

As regards the **technology choice**, the same technological performance can sometimes be produced with alternative technological architectures (e.g., alternative methods of particle acceleration). As noted above, these choices necessitate the exploration of alternative technologies and their development trajectories. This means that innovation potential in this stage is regulated by the choice of a given trajectory, as well as the relationship of the performance requirements relative to the chosen trajectory. Indirectly, choices between alternative technological architectures may reinforce some trajectories (e.g., through advancing real or de facto standards) and not others. In doing so, this may create a path-dependent effect on the chosen architectures.

As regards **technology design specifications**, key regulators of the associated innovation potential include the extent of exploratory R&D required to define the design specifications, the organisation of this R&D activity, as well as the policies used in specifying resulting Calls for Tenders (CFTs). Clearly, if major exploratory R&D is required to establish the design specifications of individual procurements, this activity in itself supports technological learning. Whether and to what extent such learning materialises and where depends on how the exploratory R&D is organised in terms of, e.g., university and industry participation. Given that there is considerable latitude in deciding how the design specification is organised, there is also considerable room to facilitate technological innovation. Unfortunately, systematic explorations of the effect of design policies on technological innovation do not exist.

Finally, the project **delivery phase** can offer major potential for technological innovation in its own right. As in the design specification phase, a major determinant of this potential is provided by the extent of project-specific R&D required by the project delivery, the way this R&D is organised (notably, the organisation of support provided to the supplier), as well as choices enshrined in the procurement policy of the big-science facility. Relevant policy choices include, for example, the emphasis on price in determining prospective suppliers, choices regulating who can act as a supplier, and assistance provided for the supplier during the supplier project.

Design, Building and Operation of Big-Science Infrastructures

The distinctive aspects in the creation and management of big-science facilities are similar to those affecting big-science innovation. Big-science projects are large, complex, one-off projects with extensive international collaboration with participating governments, universities and industry (“RAMIRI Handbook,” 2013). This creates distinctive management and governance challenges that arguably have not been sufficiently addressed until recently. According to the “Ramiri” project funded by the European Commission, distinctive challenges are related to finance, legal issues, human resources issues and management of the day-to-day operations in a big-science facility. All of the distinctive aspects derive from the international and shared character of big-science infrastructures. The focus of this study is innovation and, therefore, this report concentrates on project management and day-to-day operations rather than the legal and financial aspects of big science facilities. For information on financial and legal issues, the reader is advised to consult the RAMIRI website (www.ramiri.eu).

As noted previously, big-science infrastructure projects are large and complex, incorporating design, procurement, construction, and operation of high-technology and capital-intensive facilities. The management of big-science projects refers to the management and organisation of the process of planning, building and operating facilities and infrastructures to generate technological and scientific innovation benefits. As such, traditional project management principles such as setting up project goals, matching resources, and carrying out project plans are well applicable to big-science projects. However, there also exists considerable variation in terms of project management practices across scientific, engineering and national contexts (NSF 2013).

The big challenge in managing big-science facilities is that these are one-off, large-scale projects that have their own lifecycle. The scale and complexity of big-science infrastructures places important challenges for project management, and there traditionally has been fairly little transfer of learning across projects[7]. Unfortunately, relatively little is known about the management of one-off 'megaprojects' (Davies et al., 2013). Therefore, this is largely uncharted territory. From a project management lens, most big-science projects can be categorised into one of the two types or a combination of the two: "Linear" projects and "non-linear" projects.

From the National Science Foundation's (NSF) perspective, "linear" big-science projects are characterised by a reasonably predictable, linear and phased project lifecycle approach (NSF 2013). The scientific requirements of linear big-science projects are reasonably well defined ex ante, and the technical requirements for facilities and infrastructures are well specified at the outset. Most medium-size big-science facilities, as well as service-oriented big-science facilities probably would fall into this category, as their technological designs are reasonably well established. In such projects, goals and targets are clear, project deliverables can be planned at an early stage, and project schedules are reasonably predictable. Project managers track project performance and integrate resources to execute project plans. In short, in linear big-science projects, traditional project management approaches are feasible, with a clear structure, deliverables and schedules. Project managers are expected to manage and control time, scope and cost, so as to deliver projects with good quality, on schedule and on budget. Examples of "linear" projects include, for example, many smaller-scale synchrotron facilities. In general, relatively small-scale, standardised infrastructures tend to fall into this category.

"Non-linear" big-science projects are characterised by a high degree of innovativeness, low standardisation and often frontier-pushing scientific and technological requirements. In such projects, the elements of novelty and uncertainty are high. Whereas the general scientific vision is fixed during the mission statement phase, specific project targets may not be available at the outset, and unforeseeable uncertainties are present at each stage of the project delivery lifecycle. Managing non-linear big-science projects to explore scientific initiatives presents theoretical and practical challenges in multiple domains. To identify and settle clear scientific requirements, non-linear projects normally require trial-and-error iterations supported by project teams with varied backgrounds in multiple scientific and engineering disciplines. Therefore, the project has to be able to accommodate sometimes considerable exploration with uncertain outcomes (Lenfle and Loch 2010). This means that for the successful execution of the project, the creation of built-in buffers in the project organisation is critical. Because budgets are constrained,

[7] Systematic efforts have started to address this challenge only recently, notably, with the Ramiri project initiated by the European Strategy Forum of Research Infrastructures.

buffers can be built by establishing collaborative arrangements with, e.g., universities of the participating countries to carry out collaborative R&D funded in part from domestic sources within the member country. Given the high level of uncertainty in each stage of project delivery, a variety of collaborative arrangements are possible, such as: (1) Loosely coupled structures composed of a distributed network of project teams emphasising improvisation and organisational learning; (2) System integration approach with a network of contractors orchestrated by a system integrator; and (3) Distributed R&D networks. As an example of “non-linear” projects we may mention the LHC project of CERN.

Thus, different governance modes are required for “linear” and “non-linear” projects. The main point is that non-linear big-science projects often exhibit extraordinary complexity not only in terms of scientific missions and technological installations, but also in terms of the organisational and governance arrangements created to implement the projects. Because the projects are carried out in international networks consisting of research institutions and industrial suppliers that exhibit different emphasis over different stages of the project lifecycle, the resulting potential for innovation is similarly complex. During the early, mission-defining stages of a big-science project, fundamental and theoretical research dominate, often informed by empirical findings achieved in previous installations. This stage is important for subsequent innovation potential, because during this stage the project is sold to participating governments and its governance and funding structure is set up. Important decisions at this stage include, for example: (1) principles of procurement policies (including the design of the tendering process; possible countries-of-origin requirements; rules governing the choice between competing); (2) rules governing university collaborations; (3) emphasis laid on alternative missions (e.g., discovery orientation vs solution orientation; emphasis on service mission; etc); and (4) emphasis given to different impact delivery mechanisms (e.g., spin-outs and technology transfer activities; human resource development; support and services provided to universities and industry; and so on).

During the specification of physical and technological requirements, the emphasis shifts towards accommodating exploratory R&D activities, and project management challenges evolve accordingly. Important questions that may arise at this stage include, for example: (1) the practical organisation of explorative R&D projects; (2) the distribution of work between the big-science facility and collaborating universities; and (3) the level, quality and balance of engineering skills and competencies maintained by the big-science facility and participating universities. Such choices have important consequences for capacity building in terms of where adjacent scientific and technological capabilities are built and how they are maintained.

The choice between alternative technological designs to implement the required performance standards also has non-trivial management and governance challenges, as the choice between alternative technologies will reinforce some development trajectories and not others. Politically more challenging in the context of international big-science centres, the technology trajectories may reside in different countries and play to the strengths of different participating universities, for example. This is a delicate balance to manage, as sometimes design and supplier choices may be distorted by political considerations such as country-of-origin preferences. There are anecdotal examples where design failures have been attributed (rightly or wrongly) to preferred supplier policies.

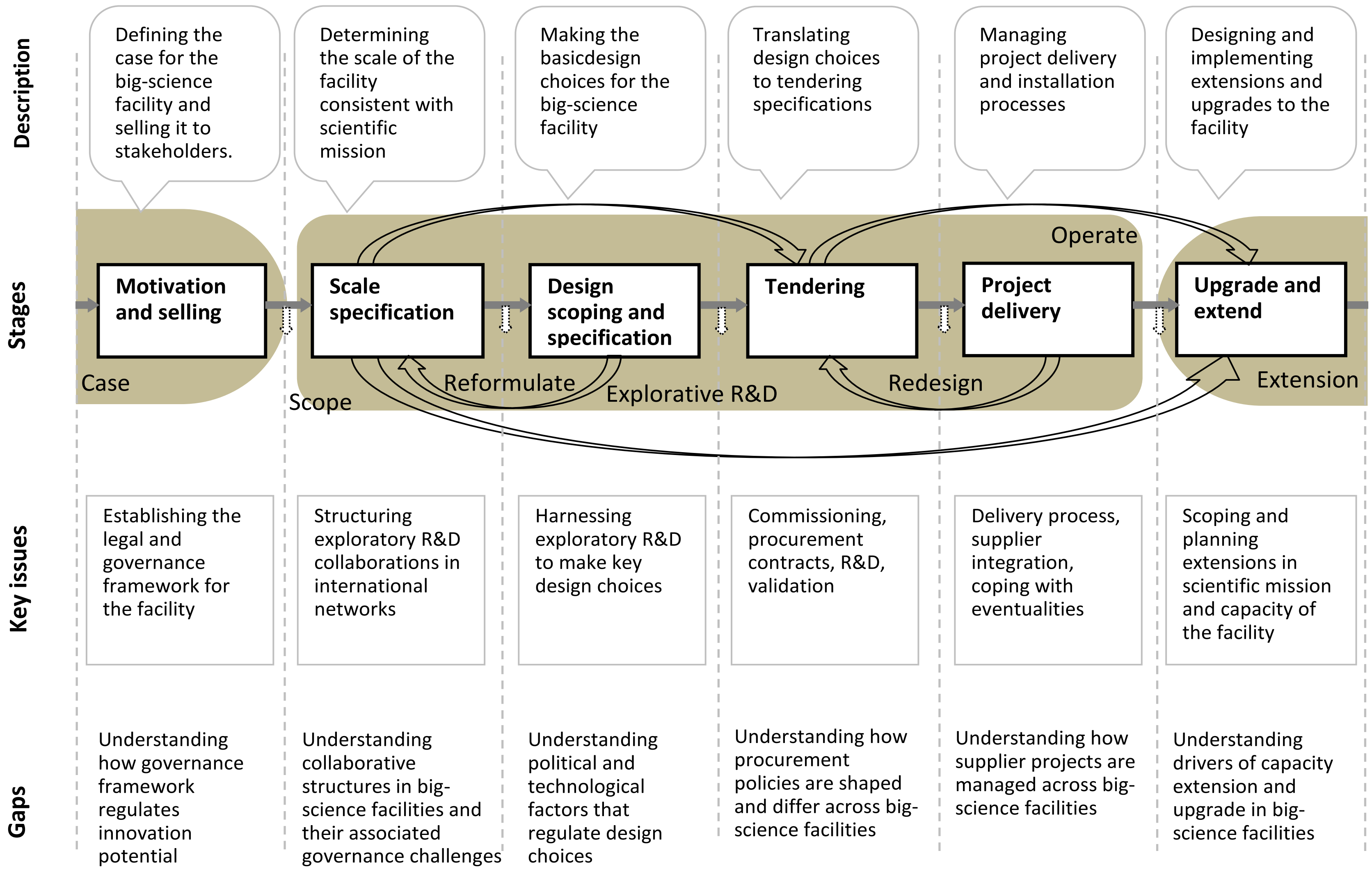
When the focus shifts on tendering and project delivery, the project management mode moves toward 'traditional' project management. From a project management perspective, a salient aspect of this phase relates to the actual management of the tendering and procurement process and of the resulting collaboration with industry partners. Different configurations are possible, but the implications of these for innovation have not been widely explored.

During the actual operational phase, the emphasis of innovation is dictated by the characteristics of the mission of the big-science facility, as well as the emphasis put on different aspects of the impact agenda. These issues were discussed in the previous chapter.

Finally, big-science facilities stand out because of the way their life cycles may be extended because of the upgrading of established facilities and the implementation of new facilities within an existing location. Here, opportunities are opened for within-project learning. According to what little is known about the management of mega-projects, an important determinant of success is within-project learning and the systematic identification and codification of successful practices throughout the project (Davies et al., 2013). However, apart from the RAMIRI project, there has been little systematic effort to inform this aspect of big-science facilities management.

Summarising, the above review has highlighted distinctive aspects when it comes to project management and operational aspects of big-science facilities. These are highlighted in Figure 2. At the level of individual big-science facilities, the questions raised by the big-science impact framework can be best captured through a process framework, which describes both the interaction of the four components and the dynamics in the form of stages in the big-science life cycle. A systems approach is ideally suited to frame how the components influence each other, as it views problems as part of the overall system (Checkland, 1999). By necessity, we have sidestepped the detailed discussion of legal and governance aspects of big-science facilities. Even the discussion of project management aspects has been limited to the bare minimum, the main purpose having been to highlight distinctive aspects to provide some background for our case studies, to which we turn next.

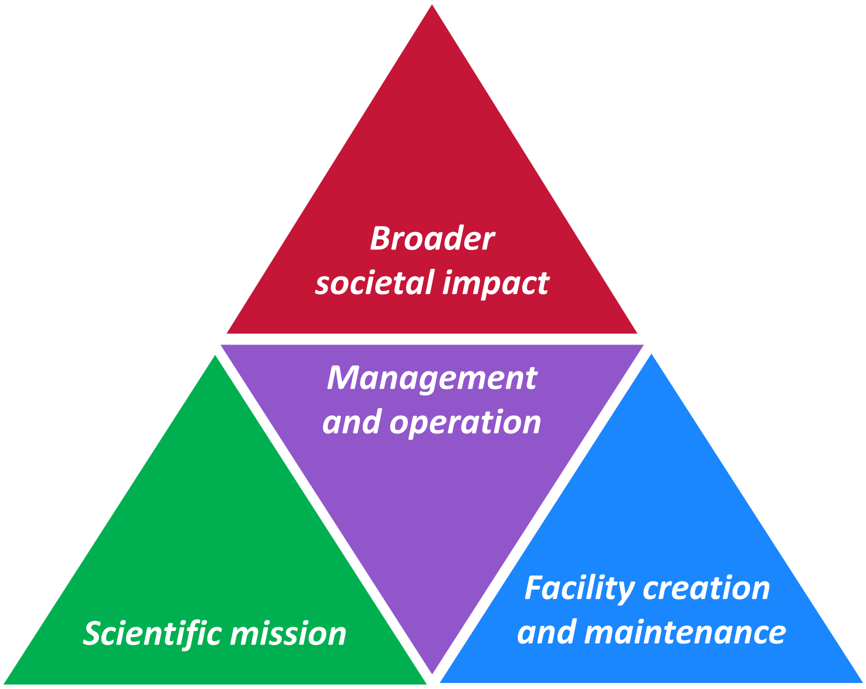
Figure 2 Summary of Key Management Challenges Over the Big-Science Lifecycle



Big-Science Impact Agenda: Case Studies of Big-Science Facilities

In order to examine innovation impact generated from real big-science projects, we selected seven big-science projects sponsored by the Large Facilities Capital Fund [8] for case studies. We conducted cross-case comparisons to identify factors that regulate innovation potential over the project lifecycle and across sectors. Drawing on the review presented above, we developed an organising framework to study big-science impact through the lens provided by individual cases. The big-science impact agenda is presented in Figure 3.

Figure 3 Big-Science Impact Agenda



We started by gathering general information of each project, including science mission, facility location, affiliated laboratory (if any), development history and financial support. For each project, we focused on scientific initiatives and supporting technological infrastructures to understand their inter-relationships and event histories. We explored practices of operating and managing big-science facilities, as well as self-reported scientific, technological innovation and societal impacts. Lastly, we created flowcharts illustrating each project's lifecycle and compared them with received theorising (Figure 1, Figure 2). Using these organising frameworks, we next examine how big-science projects are incentivised, managed and operated along the life cycle of big-science experiments.

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8 National Audit Office Report (2007), *Big Science: Public investment in large scientific facilities[Online] Available from:* http://www.nao.org.uk/wp-content/uploads/2007/01/0607153.pdf

According to National Audit Office's report published in 2007, the seven selected projects were included in a significant programme that the UK government aimed to deliver. The Large Facilities Capital Fund was introduced to help fund these projects in need of investment in large scientific facilities.

The seven case studies of big-science projects were:

- Diamond Synchrotron (Diamond Light Source Ltd, funded by STFC at 86% and by the Wellcome Trust at 14%)
- Royal Research Ship James Cook (Natural Environment Research Council)
- ISIS Neutron Source, Second Target Station (STFC)
- Accelerators and Lasers In Combined Experiments (ALICE), formerly known as Energy Recovery Linac Prototype (STFC)
- Halley VI Antarctic Research Station (Natural Environment Research Council)
- High End Computing Terascale Resource (HECToR) (Engineering and Physical Sciences Research Council, operated by STFC Daresbury Laboratory)
- Muon Ionisation Cooling Experiment (MICE) (hosted by STFC)

Table 2 illustrates the general information, scientific mission and supporting technologies and infrastructures in the seven cases.

Table 2 Illustration of the Seven Big-Science Cases[9]

Case	General information / Scientific mission / Supporting technologies and infrastructures
Diamond Synchrotron	***General introduction*** Diamond Synchrotron is a third-generation light source (3GLS) producing intense x-rays and shorter wavelength emissions. Diamond replaced the Synchrotron Radiation Source (SRS) at Daresbury in Cheshire. ***Scientific mission*** Diamond Synchrotron supports research in biological, physical, environmental and engineering sciences by, e.g., examining the structure of materials at molecular and atomic level. ***Supporting technologies and infrastructures*** Diamond Synchrotron contains the storage ring and a number of beamlines with the linear accelerator and booster synchrotron housed in the centre of the ring. These beamlines are the experimental stations where the synchrotron light's interaction with

[9] Note: Most of the text in Table 2 has been taken as such from the projects' own descriptions (as shown in their websites) so as to maintain fidelity in technical descriptions.

	matter is used for research purposes (e.g., drug discovery)[10]. The main techniques available at Diamond are:[11] - X-ray Diffraction and Scattering - X-ray Imaging - Spectroscopy
Royal Research Ship (RRS) James Cook	***General information*** The James Cook is a British Royal Research Ship operated by the Natural Environment Research Council (NERC). ***Scientific mission*** RRS conducts oceanographic and marine studies and is equipped to launch and recover heavy marine equipment such as submersible or towable sensing or monitoring devices[12]. ***Supporting technologies and infrastructures*** RRS has a dynamic positioning system, on-board laboratory space, data analysis facilities and berths for 32 scientists. It is one of two such vessels in the NERC fleet, the other being RRS Discovery[13].
ISIS Neutron Source, Second Target Station	***General information*** ISIS is the world's most powerful spallation neutron source. It supports research in physical and life sciences, particularly for condensed matter research. ISIS Neutron Source's suite of neutron and muon instruments allows the properties of materials to be understood at the atomic scale.[14] ***Scientific mission*** ISIS Neutron and Muon Scattering Facility supports a national and international community of more than 2000 scientists for research into subjects ranging from clean energy and the environment, pharmaceuticals and health care, through to nanotechnology, materials engineering and IT.[15] The newly built Second Taget Station enables the ISIS science

[10] STFC (2010): *New Light on Science. The Social and Economic Impact of the Daresbury Synchrotron Radiation Source (1981-2008)*: https://www.stfc.ac.uk/resources/PDF/SRSImpact.pdf

[11] Diamond webpage http://www.diamond.ac.uk/Home/Beamlines/Techniques

[12] NERC webpage http://www.nerc.ac.uk/research/sites/facilities/marine/jamescook.asp

[13] NERC webpage http://www.nerc.ac.uk/research/sites/facilities/marine/jamescook.asp?cookieConsent=A

[14] ISIS home webpage http://www.isis.stfc.ac.uk/ nned to update these references as the home page dosen't tell you all of this in references 13 - 15

[15] ISIS home webpage http://www.isis.stfc.ac.uk/

	programme to attract new users predominately from three key research areas of science: Soft Condensed Matter, Bio-Molecular Sciences and Advanced Materials. ***Supporting technologies and infrastructures*** ISIS Neutron and Muon Scattering Facility is the world's most powerful neutron source of its kind (a pulsed source rather than a continuous reactor). [16]
Accelerators and Lasers In Combined Experiments (ALICE)	***General information*** Formerly known as ERLP (Energy Recovery Linac Prototype), ALICE serves as a test facility for novel accelerator and photon science applications. The project uses free electron lasers and synchrotron radiation covering the terahertz to soft X-ray energy frequencies for studying matter[17]. ***Scientific mission*** ALICE is used to investigate and overcome the challenges presented to scientists in designing and building future generations of accelerators like the UK's proposed new light source. It provides all the features of a 4GLS facility, thereby supporting cutting edge research in ultra-fast, high-frequency phenomena. High-intensity x-rays provide new research capabilities from, e.g., nuclear physics to biosciences. ***Supporting technologies and infrastructures*** The ALICE accelerator is an Energy Recovery Linac (ERL) that incorporates all the features of the 4th generation light source albeit at smaller scale. An ERL can attain an unprecedented electron beam brightness limited only by the electron gun. Energy recovery also allows a significant increase in an average power of the light sources without the need to build a dedicated power station nearby. The ability to produce ultra-short electron bunches well below 1ps and an availability of several light sources of different colours open up numerous possibilities for conducting investigations of fast processes on a femtosecond scale in molecular and solid state physics among others.

[16] ISIS home webpage http://www.isis.stfc.ac.uk/

[17] Science and Technology Facilities Council http://www.stfc.ac.uk/Roadmap/obj1320.aspx

Halley VI Antarctica Research Station	***General information*** The project involves the building of a new re-locatable Halley VI Antarctic research station and the removal of the existing station, Halley V. [18] ***Scientific mission*** The scientific programmes carried out at the Halley base include atmospheric sciences, geology and glaciology. Studies at Halley are important for a global perspective on ozone reduction, atmospheric pollution, sea level rise, and climate change. Halley, lying within the aurora zone, is ideally situated for aerospace research.[19] ***Supporting technologies and infrastructures*** Halley VI provides a unique facility for monitoring climate, ozone and space weather and forms a key part of the UK's regional presence. Unlike Halley V, the building rests on skis, which allows the building to be relocated periodically. Occupation of Halley V would become increasingly unsafe after 2010.[20]
High End Computing Terascale Resource (HECToR)	***General information*** HECToR is a next-generation of high-performance computer (currently a Cray XE6). Users span several fields of science including computational chemistry, physics and climate modelling. [21] ***Scientific mission*** To advance the frontiers of UK-based research activities that rely on modern high end computing tools and techniques, such as forecasting climate change, designing new life-saving drugs, constructing safer aircrafts, predicting natural disasters, and understanding how complex biological systems work and develop.[22] ***Supporting technologies and infrastructures*** HECToR is UK's newest national supercomputing facility, operated by STFC Daresbury Laboratories. After successful launch of phase

[18] British Antarctic Survey http://www.antarctica.ac.uk/living_and_working/research_stations/halley/

[19] British Antarctic Survey http://www.antarctica.ac.uk/living_and_working/research_stations/halley/

[20] British Antarctic Survey http://www.antarctica.ac.uk/living_and_working/research_stations/halley/halleyvi/?page_id=13

[21] HECToR Official webpage http://www.hector.ac.uk/abouthector/hectorbasics/

[22] HECToR Report (2004), High End Computing Terascale Resource Capability Challenge

	1, 2a, and 2b, HECToR phase 3 uses the latest "Bulldozer" multicore processor architecture from AMD which theoretically allows twice the performance over the old architecture used in phase 2b.[23]
Muon Ionisation Cooling Experiment (MICE)	***General information*** The Muon Ionisation Cooling Experiment (MICE) is a step towards the possible creation of a neutrino factory which would aid the understanding of the properties of neutrinos. ***Scientific mission*** MICE seeks to demonstrate that "muon cooling"—making a tightly focused muon beam—is possible through a process of ionisation. ***Supporting technologies and infrastructures*** A neutrino factory based on a muon storage ring is used for studies of neutrino oscillations, including possibly leptonic CP violation. It is also the first step towards μ+μ- colliders. The performance of this new and promising line of accelerators relies heavily on the concept of ionisation cooling of minimum ionising muons, for which much R&D is required.[24]

Most of the above cases focus on advancing research in their own fields. However, projects such as Diamond Synchrotron, ISIS Neutron Source, and HECToR also feature an important service provision aspect. Hosting frontier-pushing technological infrastructures, the three big-science projects provide access for a large inter-disciplinary scientific community and industrial partners. For example, Diamond Synchrotron centre provides researchers from the UK and elsewhere with access to synchrotron-based techniques, supporting life, physical and environmental sciences. Diamond Synchrotron facilitates experimental research and R&D in a wide range of scientific and industrial sectors, including, e.g., Archaeological & Cultural Heritage, Digital Economy, Security, Energy, Engineering, Environment, Earth & Planetary Science, Food Science, Health & Wellbeing, Nanoscience Applications, and Technique Development[25]. This facility has been able to either meet or exceed initial projections in terms of industrial engagement and academic output. Similarly, the ISIS Neutron Source provides a national and international community of over 2000 scientists with facilities to conduct research into subjects ranging from clean energy and the environment, pharmaceuticals and health care, through to nanotechnology, materials engineering and IT[26]. The newly built Second Target Station at ISIS aims to attract new users from three key research areas: Soft Condensed Matter, Bio-

[23] HECToR Official webpage http://www.hector.ac.uk/abouthector/hectorbasics/

[24] Imperial College London webpage http://www3.imperial.ac.uk/highenergyphysics/research/experiments/mice

[25] Diamond Annual Review 2011

[26] ISIS home webpage http://www.isis.stfc.ac.uk/ check ISIS refs as I don't think these are right

Molecular Sciences and Advanced Materials[27]. Lastly, the High-End Computing Terascale Resource (HECToR) project also provides services for supercomputing users spanning across fields of computational chemistry, physics and climate modelling. HECToR aims to support and advance the frontiers of UK based research by utilising the capabilities of massive parallel computing architectures[28]. We also noted that the ALICE project not only facilities cutting-edge research in its field of ultra-fast physics but also provides facilities and services to a list of sub-projects. These include the construction of EMMA (a 19-cavity accelerating Non-Scaling FFAG ring) in March 2011 as an addition to the ALICE programme and VELA (Versatile Electron Linear Accelerator), which went online on the 5th of April 2013[29].

Six out of the seven cases plan to improve and extend their capabilities over time (Table 3). Although most of these projects have stretched industrial suppliers to provide frontier-pushing technologies and facilities, their learning impact is therefore not one-off but occurs incrementally, as the facility expands and improves its capabilities along its life cycle. One example is the recent Halley VI, which was completed in February 2013. The idea for building Valley VI arose from the lessons learnt from the previous five Halley bases. The previous Halley bases having experienced problems with snow accumulation – to the extent that structural damage had eventually occurred – Halley VI had the main buildings built on steel platforms that were raised annually to keep them above the snow. Extending the capabilities of the previous bases, it was built to become the first fully re-locatable antarctic research station in the world.

When considering the drivers of innovation potential, the seven cases represent both fundamental research and solution-oriented research missions. For example, the Muon Ionisation Cooling Experiment (MICE) explores and demonstrates the feasibility of ionisation cooling of muon beams. The fundamental research carried out by this experimental demonstration would provide input into the final design of the cooling channel for the Neutrino Factory. On the other hand, the Halley VI Antarctic research station conducts solution-oriented research such as ozone layer monitoring and exploration of the interaction of molecules between air and snow in unprecedented detail[30].

Table 3 Categorisation of the Case Studies According to their Scientific Mission

Case	Service mission	Nature of the project	Scientific mission

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[27] ISIS official webpage http://www.isis.stfc.ac.uk/about-isis/target-station-2/science/science-at-the-isis-second-target-station8200.html

[28] Report High End Computing Terascale Resource Capability Challenge

[29] http://www.stfc.ac.uk/2638.aspx

[30] British Antarctic Survey http://www.antarctica.ac.uk/living_and_working/research_stations/halley/halleyvi/?page_id=4

Diamond Synchrotron	Service oriented	Capacity expanding; related to another big-science project	Fundamental scientific research
Royal Research Ship (RRS) James Cook	Research oriented	One-off project	Solution-oriented research
ISIS Neutron Source, Second Target Station	Service oriented	Capacity expanding; related to another big-science project	Fundamental scientific research
Accelerators and Lasers In Combined Experiments (ALICE)	Both research and service oriented	Capacity building; evolution from an energy recovery prototype to a 4th generation light source to multifunctional facility hosting a range of projects	Fundamental scientific research
Halley VI Antarctica Research Station	Research oriented	Capacity expanding	Solution-oriented
High End Computing Terascale Resource (HECToR)	Service oriented	Capacity expanding	Fundamental scientific research
Muon Ionisation Cooling Experiment (MICE)	Research oriented	Capacity expanding; related to another big-science project	Fundamental scientific research

In each of the seven cases, we used the previously theorised life cycle model to examine the process of setting scientific mission, determining technological requirements, as well as designing, procuring, building and operating infrastructures (for the detailed project lifecycle of each case, see Appendix). Since most of the seven case facilities went into full service approximately three to five years ago, these projects are currently mostly in the second or third phase of their development and operations (Table 4). Having successfully demonstrated their ability to deliver on their scientific missions, these projects have moved into the next phase of their life cycles. The emphasis of the current stage differs somewhat across cases but can nevertheless be categorised into three main categories: (1) increasing the operational capacity of the facility; (2) adding new scientific capabilities into the facility; and (3) enhancing existing technological capabilities of the facility. This categorisation illuminates how scientific missions and organisational priorities evolve differently across big-science projects in terms of scientific, technological and operational aspects of the facility.

Service-oriented big-science projects are often introduced in a staged fashion, with gradual expansion and diversification of service capacity. Such an approach offers many benefits. First, capacity utilisation can start as soon as facilities are completed, thereby improving economic efficiency. Second, experience from facilities introduced earlier can be drawn upon to inform the construction of later phases, thereby reducing technological uncertainty. Third, through staging, it is also possible to verify that sufficient demand for the facility exists both within academia and industry, thereby reducing demand uncertainty. Fourth, gradual introduction of incremental capacity makes it possible to control that the scientific goals are being met, thereby reducing scientific uncertainty. In the Diamond Synchrotron, for example, has benefited from all four uncertainty reduction mechanisms when gradually introducing new beams for new purposes. However, such strategies are not limited to service-oriented facilities only. In the context of CERN's Large Hadron Collider, for example, power upgrades have been introduced gradually so as to keep the project more manageable and control technological risks. The cases also show that capacity expansions and enhancements within big-science projects can also be driven by technological advances. For example, both Halley VI, MICE and HECToR Phase 3 are actively constructing new facilities to enhance the technological capabilities required to implement their scientific missions.

Table 4 Current Life-Cycle Stage of the Cases

Case	Operational date	Current project phase	Motivation to move into the current phase
Diamond Synchrotron	October 2007 Phase I – 2007 Phase II – 2007-2012	Phase III (2013-2017)	- To further increase the capacity of the facility (to 32 beamlines) - To maximise return on original investment and extend the reach of Diamond to new areas and applications
Royal Research Ship (RRS) James Cook	Spring 2007	No project phase identified	To achieve the original scientific mission
ISIS Neutron Source, Second Target Station	2009	Phase 2	To add new scientific capabilities in new fields
Accelerators and Lasers In Combined Experiments (ALICE)	March 2011	Phase 1 but the ALICE project has a number of sub-projects	Continue to support sub-projects as per original plans
Halley VI Antarctica Research Station	January 1956	Phase 6	To enhance technological capabilities
High End Computing Terascale Resource (HECToR)	October 2007	Phase 3	To enhance technological capabilities
Muon Ionisation Cooling Experiment (MICE)	April 2007	Phase 2	To progress from construction stage (phase 1) to operational stage (phase 2)

Table 4 reinforces the point that big-science facilities typically are not one-off projects but evolve over time, as their missions extend and their user groups become more diverse.

Because of this, for example, the technological innovation potential is not realised in a one-off fashion, but rather, is extended gradually through recurring project commissions. This implies that many big-science facilities have the potential to evolve to become hubs of complex knowledge ecosystems consisting of researchers, scientific institutions, industrial suppliers and other stakeholders. This also implies that impact delivery strategies have to be long-term and evolving.

We next summarise scientific outputs and technological innovation potential of the case projects (Table 5). We also examine the impact of industrial collaboration in each project and how the projects deliver on their broader societal impact mission.

Table 5 Innovation Potential and Broader Societal Impact of the Cases

Case	Scientific outputs	Technological innovation potential	Industrial collaboration and societal impact
Diamond Synchrotron	Diamond Synchrotron users publish over one thousand papers each year in the field of life, physical and environmental sciences. Another indicator of Diamond's scientific performance can be measured by the number of protein structures solved on the Macromolecular Crystallography beamlines and deposited in the Protein Data Bank.	From Phase I, II to Phase III, the number of beamlines have been increased, with concomitant increase in their capabilities and the introduction of new beam technologies to reach new sectors.	20% of Diamond Synchrotron's beamtime was directly connected with industry in 2010/2011. Industrial research priorities help shape operational strategy of Diamond Synchrotron. The dialogue between the Diamond Synchrotron facility and its user community also informs the operation and future strategy of Diamond. As do most STFC facilities, also the Diamond Synchrotron operates as an important training platform for researchers in its domain.
Royal Research Ship (RRS) James Cook	The mission of RRS is to conduct oceanographic and marine studies heavy marine research equipment and instruments such as submersible or towable sensing or monitoring devices. In addition to supporting a host of multidisciplinary research missions, scientific output includes related discoveries, such as the discovery of the world's deepest undersea volcanic vents	The ship operates a mobile platform for oceanographic and marine research, carrying a range of dedicated research facilities. The upgraded vessel enables work in higher sea states than any other NERC's existing research vessels. As RRS operates as a research platform, its technological innovation potential is determined more by the research missions supported by the vessel than its own intrinsic capabilities.	Leading-edge multidisciplinary and international research. For example, NERC has an agreement with IFREMER (France), Institute of Marine Research (IMR) and the University of Bergen (UoB)(Norway), BMBF (Germany), NIOZ (the Netherlands) and CSIC (Spain) for barter exchange of a wide range of marine facilities including RRS James Cook. A similar bilateral arrangement exists with the US National Science Foundation (NSF).

ISIS Neutron Source, Second Target Station	ISIS is the world's most powerful spallation neutron source. The second target station extends the capabilities of ISIS in neutron beam generation and detection, further enabling high-resolution spectroscopy in, e.g., soft condensed matter, bio sciences and advanced materials. These facilities are used by universities and industry researchers within and outside the UK, and the scientific advances are typically published in academic journals.	The new instruments in the second phase of the ISIS project will add capabilities in, e.g., microchip screening, neutron imaging and small angle scattering, together with extending the time and length-scales of neutron experiments. In addition to advancing neutron beam generation and measurement technologies, the facility supports technological advances through services offered for R&D in a wide range of industry sectors.	ISIS supports a national and international community of more than 2000 scientists and industry for research into subjects ranging from clean energy and the environment, pharmaceuticals and health care, through to nanotechnology, materials engineering and IT. ISIS makes an important contribution in research capability development in accelerator technologies, materials research and computational modelling.
Accelerators and Lasers In Combined Experiments (ALICE)	The intense light produced from ALICE enables the study of physical processes at the atomic level. This capability has applications in a broad range of sectors including materials science, chemistry and bio sciences, e.g., in supporting drug development or the design of more efficient solar cells. ALICE's scientific agenda includes understanding of the mechanisms of molecular organisation. Like ISIS, ALICE supports experiments by a wide range of research teams, whose research is published in academic outlets.	As a facility, ALICE advances particle acceleration technologies by incorporating features of a 4th generation light source. ALICE teams also have strong capabilities high-speed computational modelling of a wide range of accelerator phenomena. The ALICE facility encompasses several light sources and offers a variety of scientific and industrial exploitation possibilities by supporting academic and industrial R&D across a wide range of sectors.	Like ISIS, ALICE supports a large community of scientists and industry researchers in a range of sectors. ALICE also makes an important contribution in research capability development in accelerator technologies, materials research and computational modelling.
Halley VI Antarctica Research Station	Halley research stations have collected meteorological and atmospheric data on the Antarctica	Halley VI is built to become the first fully re-locatable research station in the world. Halley VI is built on	Halley VI has attracted a wide range of media interests including BBC, Guardian, CIBSE careers, BAS

	since 1956 and provide a global perspective on ozone reduction, atmospheric pollution, sea level rise, and climate change. The stations provide a base for a range of research on these topics.	special legs so it is able to keep the buildings above the snow level, and the station can be periodically relocated across distances of many kilometres. This makes it possible for the station to remain a safe distance from the edge of the ice shelf.	press release, Faber Maunsell press release, and Channel 4.
High End Computing Terascale Resource (HECToR)	HECToR offers high-performance computing services to universities and industry in the UK and abroad. As a shared, generic computing resource, it can support computing- and modelling-intensive research in virtually domain. The scientific outputs facilitated by HECToR are published mostly through normal routes of scientific publication.	HECToR contributes to technological advances in two ways: first, by advancing supercomputing capabilities; and second, through the services it offers for industrial companies. The first help advance the rapidly advancing field of high-performance computing. The second materialise through enhanced R&D outputs.	HECToR provides services for academic and industrial users in the UK and Europe. HECToR is a part of the PRACE initiative giving leading scientific users access to a European pool of supercomputers. Industrial influences range widely, including, for example, forecasting climate change, designing new life-saving drugs, constructing safer aircrafts, predicting natural disasters, and understanding how complex biological systems work and develop.
Muon Ionisation Cooling Experiment (MICE)	The Muon Ionisation Cooling Experiment (MICE) is a particle accelerator facility that seeks to design, build and operate a muon ionisation cooling channel that meets the constraints imposed by muons’ short lifetimes (in the microsecond range). It is an international collaboration with active participation from Europe, US and Japan. Its mission is to	MICE’s technological innovation potential is closely related to its scientific mission. The demonstration of the feasibility of ionisation cooling of muon beams will represent a major technological advance towards the development of a "neutrino factory".	MICE is an international collaboration comprising some 140 physicists and engineers from Belgium, Italy, Japan, the Netherlands, Russia, Switzerland, the UK and the US. With the advances it is set to produce, it will pave the way for a wider implementation of muon beams within the particle physics community.

	demonstrate the feasibility of this technique (ionisation cooling) of muon beams. This demonstration will be an important milestone in R&D towards a Neutrino Factory. Aside with demonstrating the cooling technique, an important mission is also to learn how to build and operate a device that performs as desired. MICE also provides a number of important physics and methodological results. The measurements are expected to constitute a textbook contribution to experimental particle physics, and to be essential for reliable simulation of the performance of neutrino factory and muon collider.		

As summarised in Table 5, the scientific outputs of the cases are closely related to the categories that they belong to, depending on whether the projects conduct fundamental or solution-oriented research as their scientific mission, and whether the projects are service-oriented or research-oriented in their service mission. However, although distinct categories can be identified, there is also wide overlap across the scientific and service missions of different facilities, and we also saw that these missions can evolve over the life time of the facility.

As illustrated in Figure 4, Diamond, HECToR and ISIS Neutron Source projects seek to advance fundamental scientific knowledge with potential practical applications across a broad range of sectors. Meanwhile, each of the three projects has facilitated the publication of an important number of scientific papers and reports as an output of their scientific missions. Some of the cases also report breakthrough progress in advancing knowledge, with applications exploiting these breakthrough expected later.

The RRS and Halley VI are categorised as research oriented and as conducting solution-oriented research. They operate primarily as platforms for scientific outputs, rather than offering facilities for the use by industrial R&D. Many of their scientific advances also have broader societal implications. By facilitating accurate research data on global warming, for example, the Halley IV advances evidence-based insight into the role of human activity in global warming, thereby informing societal debate on this question.

ALICE is categorised as conducting fundamental research and as being both research and service-oriented. The pattern of scientific outputs in this case was similar to those in the Diamond and HECToR project cases, but with additional scientific output associated with ALICE's sub-projects including FEL physics, THz studies and exploitation, EMMA, ERL-based accelerator physics. Such complementarity between the main project and sub-projects can sometimes heavily influence the profile of scientific and technological impact and therefore needs to be taken into account.

Finally, MICE has been categorised as a research oriented facility that conducts fundamental research (although it will also carry a service component in its mission). Since the MICE project remains at an early stage, scientific outputs are not available as yet but the desired outcome has been stated in its scientific mission – introducing new cooling methods to muon beams to facilitate more extensive take-up of muon beams in research. Thus, the scientific impact mission and technological mission of this project are closely intertwined.

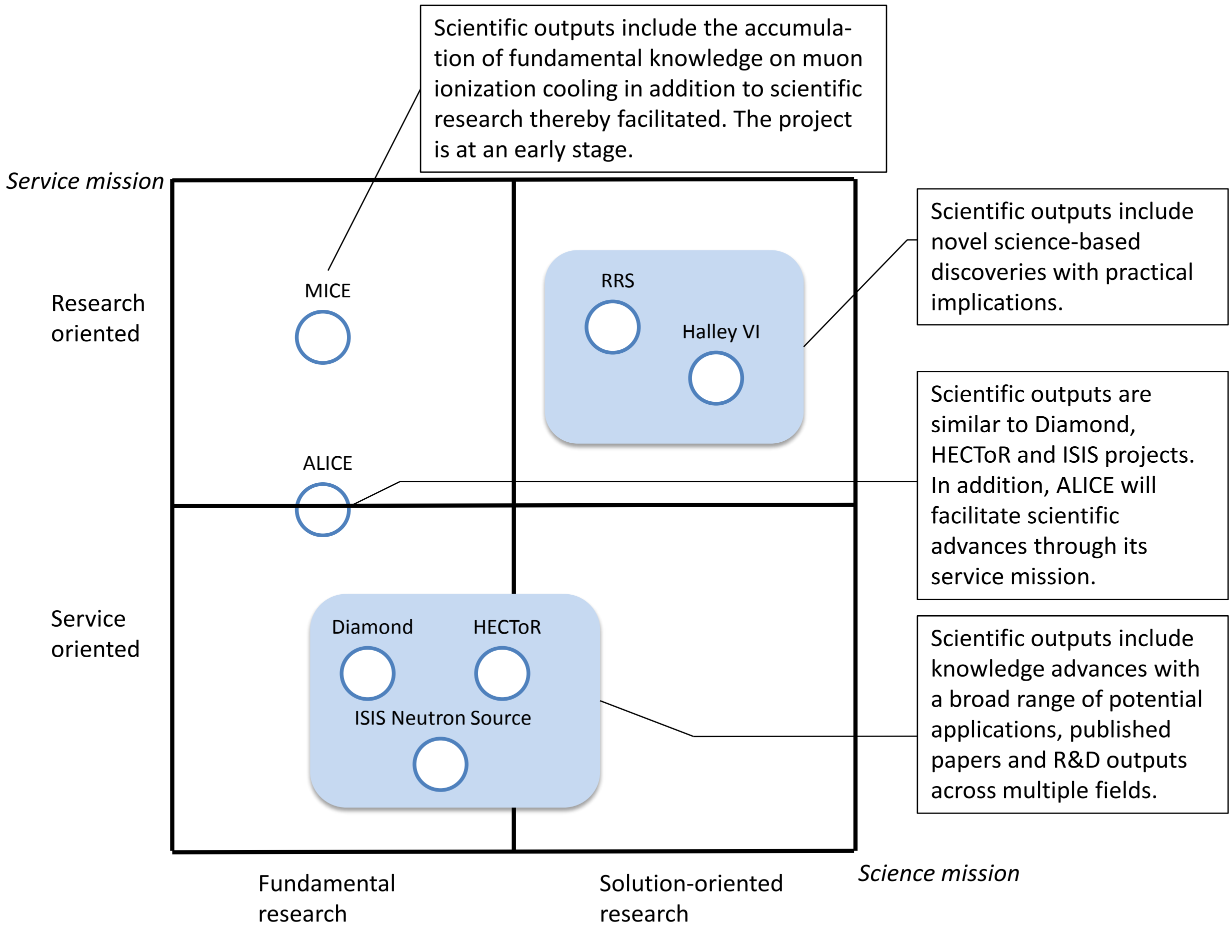

Figure 4 Categorisation of the Cases According to Service and Science Missions

The technological innovation potential in the cases takes a variety of forms (Table 6). Corresponding to the three categories of project motivations along the lifecycle (Table 4), technological innovation potential in the cases appeared to take three main forms: 1) increasing the scale of technological capacity (e.g., service capacity); 2) broadening the scope of technological capabilities; and 3) introducing frontier-pushing technological performance. Interestingly, the observed technological innovation potential of the projects did not appear fully defined by the scientific and service missions of the cases. Although the technological innovation potential was ultimately driven by the need to deliver on the scientific and service missions of the facilities, the form this potential took varied across cases.

Table 5 Technological Innovation Potential of the Cases

Case	Motivation to move into the current phase	Forms of technological Innovation
Diamond Synchrotron	To increase the capacity of facilities To satisfy increasing demand from a broader	Increasing the scale of technological capacity; broadening the scope of these; pushing performance

	range of sectors	frontiers in beam technologies
Royal Research Ship (RRS) James Cook	To service scientific mission	No significant technological innovation beyond vessel design and instrumentation
ISIS Neutron Source, Second Target Station	To add new scientific capabilities in new fields	Broadening the scale and scope of technological capabilities; advancing beam technologies
Accelerators and Lasers In Combined Experiments (ALICE)	To facilitate planned progress in ALICE's sub-projects	Pushing performance frontiers in muon spectrometer technologies
Halley VI Antarctica Research Station	To enhance operational capabilities of the research station	Mostly incremental enhancement of existing technological capabilities
High End Computing Terascale Resource (HECToR)	To enhance technological performance of the facility	Important degree of frontier-pushing technological performance
Muon Ionisation Cooling Experiment (MICE)	To progress from construction stage (phase 1) to operational stage (phase 2)	Introducing a technology breakthrough in muon ionisation cooling

Lastly, industrial collaboration and societal influence reflect the impact of the cases in a broader societal context. As noted, scientific advances and technological innovation was observed in all cases. Some of these also facilitated broader societal impacts. For example, all of the cases provided an important capability development impact by acting as training platforms for research students and junior researchers. Many of the facilities and their research missions are regularly featured in media, thereby enhancing their impact on public conversation and public awareness (e.g., climate change, advances across a range of scientific and industrial fields). In many cases, outreach activities such as industrial and social community collaboration and outreach played an important role alongside with their scientific missions. One example of these was the Diamond Synchrotron Light Source's engagement with its industrial partners and local communities – e.g., its contribution to the teaching programmes of local schools.

Summarising, the above case studies employed cross-sector and longitudinal analysis along the project life cycles to understand the impact mission of select big-science projects. The scientific impact potential of the case facilities was illustrated by categorising projects along their service mission and scientific missions. In contrast, the forms of technological innovation appeared to be regulated more by the stage of the project life cycle and by how it was organised. In addition to evidence of scientific and technological impact, evidence of more-difficult-to-measure, yet important societal impact was present in all cases.

The limitations of the case studies suggest opportunities for future research. The current case studies are based on archival reports and online media data, most of which are self-reported. The archived dataset provides valuable information for the past project development events, but available documentation only offers relatively limited insight into why and how events unfolded the way they did. To shed more insight into the big-science innovation dynamic, a more systematic research agenda is required, to which we turn next.

Research Agenda for Big-Science Impact Research

The systematic literature review and comparative case studies conducted above suggest a number of relevant themes for a research agenda that centres around big-science research and its impact on society. It seems that the big-science impact agenda is shaped by four elements. The first of these concerns the scientific impact: how are big-science research missions pursued, and how do they shape research agendas in core and adjacent fields? This is the primary and most visible element of big-science impact creation and one that is perhaps the most widely researched thus far (e.g., Knorr-Cetina, 1999). From an impact agenda perspective, a number of questions appear to merit further research attention:

- How are the core scientific research agendas shaped?
- What factors and dynamics shape international and inter-governmental consensus on big-science research agendas, and decisions such as the location of big-science facilities and infrastructures?
- How do big-science scientific research agendas shape and influence research agendas in adjacent fields of science?
- What are the motivations of governments to fund Big Science, and what are the factors that influence those motivations?
- What are the areas with most potential for cross-fertilisation across scientific fields, and how do cross-fertilisation effects materialise?

In addition to scale and capital intensity, the distinctive aspect of big-science research is that it involves international collaboration within the scientific community and between governments and science funding agencies. The processes of agenda shaping and international consensus creation are important, as these determine the location of big-science infrastructures and the configuration and dynamic of the scientific community organised around them. These, then, influence where the societal impact from big-science research materialises, what forms it is likely to take and who is likely to benefit from this impact.

The second major element of the big-science impact agenda involves the creation of big-science facilities and infrastructures. This is the element that offers the greatest potential for innovation benefits above and beyond those emanating from the core scientific research agenda. Depending on the scientific domain, the design and commissioning of big-science research facilities and infrastructures can be a hugely complex undertaking with important implications for the development of supporting technologies and for the strengthening of R&D capacities by big-science suppliers. Important questions for big-science impact research agenda include, for example:

- How are the technological specifications of big-science infrastructures created, and what factors determine the associated potential for technological innovation?

- How are big-science infrastructures commissioned, and how do innovation benefits materialise in this process?
- What are the technology fields most likely to receive a boost from the design and construction of big-science infrastructures? How do big-science infrastructures differ from one another in this respect?
- What are the different ways to organise the processes of technological specification, design and commissioning, and what are the consequent implications for technological innovation?
- How does the potential for technological innovation vary over the lifecycle of big-science infrastructures?
- What factors determine the participation of member countries' research and academic institutions in the technological specification process, and how do these translate into corollary benefits?
- What is the size of the industrial community specialised in servicing and supplying big-science facilities and infrastructures, and where are these suppliers located?
- How do big-science sectors and facilities differ in terms of their technological innovation potential, and what factors explain those differences?
- How can member countries maximise the industrial innovation benefits from the design and construction of big-science facilities and infrastructures?

Similar to the core scientific research agenda, the potential for technological innovation benefits is shaped in a complex process that involves a broad range of stakeholders with different motivations and agendas. The distribution of innovation benefits is likely to be different from the distribution of scientific benefits, with different stakeholders standing to gain from the implementation of big-science infrastructures. Although there is much anecdotal evidence describing innovation benefits in individual cases, overarching frameworks describing the technological innovation potential associated with big-science infrastructures over their lifecycles and across big-science sectors are missing. This inhibits the ability to maximise the innovation benefits from investment in big-science infrastructures.

The third element in the big-science impact agenda involves the management and operation of big-science research facilities and infrastructures. While many aspects of this element are closely related to the two previous elements, there are also distinctive questions that are relevant for the big-science impact agenda. Big-science infrastructures are capital intensive and often involve high operating costs. These are potentially influenced by the way these facilities are managed, which makes it necessary to address this aspect as a distinct domain of inquiry. For example, thus far, there has been relatively little systematic experience exchange across big-science facilities, although the RAMIRI initiative has begun to address this issue. Relevant questions in this domain include:

- How are the one-off projects of big-science facility building organised, and what are the lessons for project management?
- What are the different governance and administrative models in big-science facilities, and what are the consequent implications for, e.g., the cost efficiency of big-science infrastructures?
- How do big-science facilities shape and steer their adjacent scientific communities through their on-going interaction with these?

- Beyond the design and implementation activities discussed above, how do big-science facilities approach and implement their Third Mission?
- What are the different models to organise technology transfer from big-science research?
- How do big-science centres organise their outreach and societal engagement activities, and how do their outreach agendas differ?
- What are the direct services big-science facilities offer for industrial companies and what are the needs addressed?
- How do Third Mission activities vary across big-science facilities, and what are the appropriate metrics for monitoring the effectiveness of these activities?

Third Mission activities are an increasingly important aspect of scientific research, and big-science centres offer important and distinct potential for conducting these. In particular, through important discoveries such as the Higgs boson or the fluctuations in the Cosmic Microwave Background Radiation, big-science facilities have the potential to inspire popular imagination and motivate schoolchildren to pursue STEM studies (i.e., Science, Technology, Engineering and Mathematics; these subjects are commonly considered as critical for the continued development of countries' innovative capacity). There is, however, little systematic research on what the best models for organising Third Mission activities are and what determines their effectiveness. Experience accumulation in big-science infrastructure management and operation is important but also a rather neglected area of the big-science impact agenda, where significant improvements appear possible.

The final element in our model captures the remaining mechanisms of big-science impact delivery. These include, e.g., the training of researchers; increasing the popularity of STEM studies; the generation of patents and other forms of intellectual capital; and other such mechanisms. Relevant questions for the big-science impact agenda include:

- What are the other mechanisms through which Big Science generates societal impact?
- How does the relevance of different impact mechanisms vary across big-science facilities?
- What are the contributions of big-science research towards the accumulation of human capital in member countries?
- Is it possible to track the impact of big-science research on macroeconomic indicators such as, e.g., total factor productivity, GDP growth, or the Human Development Index?
- How do the big-science impact mechanisms vary across member countries?

An overarching question in the frameworks created in this paper relate to the question of how the elements interact over the life cycle of big-science facilities and infrastructures. It is also important to compare the mechanisms of impact generation across big-science sectors so as to gain a better understanding of factors that regulate big-science impact generation. The development of an overarching framework that covers the life cycle of big-science facilities and infrastructures is important not only to better understand the determinants of big-science impact, but also, to provide a basis for forming reasonable and informed expectations for this impact. Laying the foundations for such a framework calls for research that systematically compares impact generation mechanisms across big-science facilities.

Concluding Remarks

Several researchers have noted the distinctive management challenges of big-science facilities (Cyranoski, 2006; Mervis, 2008; NSB, 2005). As the scale and complexity of these infrastructures increases, so do the associated managerial and policy challenges. For much of its history, the management of big-science facilities has tended to lag behind advances and insights gained in management disciplines, and there has been little systematic focus on the impact agenda in Big Science. This is an important gap, given the increasing importance of the big-science mode of scientific research and its evident – and increasingly well recorded – potential to contribute not only to scientific progress, but also, more widely in society and the economy.

In this review, we have assessed the received stock of studies and knowledge on the various ways Big Science impacts society. We have found the literature to be fragmented, lacking coherent underlying theoretical frameworks, mostly consisting of small-scale case studies, often lacking in the application of rigorous research methods, and generally lacking in its ability to generate a cumulative impact. Overarching frameworks are missing that would cover the lifecycle of big-science infrastructures and cut across fields of big-science research. The absence of such frameworks hinders impact delivery and the ability to design policies that are informed by the ‘big picture’ of big-science research.

A dedicated research agenda on Big Science is important because the big-science mode of research differs so much from other modes of scientific research, because of the scale of investment required, and also, because of the coordinating and agenda-shaping effect big-science facilities have on multiple branches of scientific research. Often, big-science facilities have a profound effect on shaping how entire scientific communities organise themselves. In this sense, big-science facilities and infrastructures and associated research activity constitute a cornerstone of science policy with wide-ranging effects beyond immediate scientific output. Long-term investment in scientific capability development in countries therefore requires detailed understanding of the impact potential of Big Science.

To help address some of these gaps, we have proposed life cycle models that could provide a guiding framework for a systematic research agenda exploring the varied impacts of Big Science on society and the economy. We also outlined a research agenda that comprises four major elements: Big-science research delivery; supporting technologies and infrastructures; management and organisation of big-science facilities and infrastructures; and broader societal impact. We have outlined some open questions for each element that help inform the creation of coherent research agendas in this field.

The breadth of the proposed research agenda implies that a dedicated research programme, perhaps even a dedicated research centre, is likely required to effectively pursue it. Given the scale of research into university-industry interactions, as well as the scale of investment in Big Science in general, such a research agenda appears well justified.

Table 6 Select review of 'motivation' and 'innovation' literatures

Author, year chronological	Research question / focus	Theory / Framework / Lens	Data / Method	Summary / Findings
(Autio et al., 1996)	A framework to justify, motivate and establish systematic technological interaction between big science centres and industry	A priori framework.	9 case studies, Likert scale questionnaire measuring 14 types of benefits of industrial collaboration with CERN.	Developed a framework of motivations for big-science collaboration, illustrated with case studies and survey data
(Autio et al., 2004)	A framework describing the distinctive mechanisms through which big-science centres generate industrial knowledge spill-overs in the economy	Grounded theory method drawing on social network, social capital, and inter-organisational learning theories to examine knowledge spill-overs accruing to industrial partner companies in big-science–industry dyads	CERN (LHC)	Demonstrates the distinctive potential that big-science centres offer as a source of knowledge spill-overs in national innovation systems
(Byckling et al., 2000)	The most effective modes of operation for big-science projects.	No theory or framework. The focus is on technological and organizational factors affecting the innovation process.	Chronological documentation of catalysing events, key obstacles and other influences in a software project at CERN from	Administrators in big-science organisations are not sufficiently supportive of industrial application. This is partly due to attempts to obtain funding for the research organisation. Recommendations include strong input from industry

Author, year chronological	Research question / focus	Theory / Framework / Lens	Data / Method	Summary / Findings
			initiation to launching of a spin-off company.	towards management, technology transfer and supporting spin-off companies in member countries.

Table 7 Select review of the ‘Project Management’ literature

Author, year (chronological)	Research question / focus	Theory / Framework / Lens	Data / Method	Summary / Findings
(Ninin and Van den Eynden 1998)	A framework to introduce the application of project-based management in big-science environments	Project-based management in practice in project-based organisations	A case study on CERN	Suggests a project-based management approach applied in CERN
(Tuertscher 2008)	An analysis of how a distributed collaboration based on a loosely structured organisational work achieved high level of coordination of work in Big Science	Theory of different types of project management approaches	A case study of ATLAS collaboration followed by initial case-comparison results	Identification of a decentralised structure through subgroups that form with in the collaboration in a self-organising process is helpful to develop a complex technological system in big-science projects
(Lenfle and Loch, 2010)	Discussion of the emphasis of project management: control or flexibility	Project management theory in the setting of novel strategic projects	Case studies on Manhattan and the first Ballistic Missile projects	Development of a flexible project management process to complement a linear phased project management approach
(NSF 2013)	Guidance for NSF	No theory or	General	Guidance for

Author, year (chronological)	Research question / focus	Theory / Framework / Lens	Data / Method	Summary / Findings
	staff and awardees to carry out effective project planning, management and oversight of large facilities	framework. It is a manual updated by NSF every year.	framework and detailed guidance	effective project planning, management and oversight of large facilities and statement for policies, requirements and recommended procedures pertinent at each stage of a facility's life cycle
(Acedo, Andersen et al. 2001)	Focus on the practices of managing distributed projects	Definition and categorisation of distributed projects	Benchmarking studies on five organisations in different professions using distributed projects	Four project management knowledge areas, five project phases, and ten critical success factors were identified for managing distributed projects
(OIG 2004)	Determine what progress the Large Facility Projects (LFP) Office has made in developing and implementing its project management guidelines	No theory or framework. It is a report with discussion and recommendation based on survey findings	Interviews and survey individuals involved at all levels in LFP	Call for a more structured management approach by recognising and formalising the oversight mission of the Large Facility Project Office in National Science Foundation
(Fontana 2008)	Study a compilation of roadmaps to examine general options for implementing research infrastructures	A framework of different types of roadmap implementation in research infrastructure	Compilation and comparison of roadmaps	Roadmapping as a process for strategic planning in research infrastructures

Appendix: Illustration of Big-Science Cases

Diamond Synchrotron Phase III – Process of motivation, design, build and operation

Scientific case	Diamond Synchrotron is a third generation light source (3GLS) that has replaced older facilities at Daresbury in Cheshire
Scientific requirements	Use synchrotron light interaction with matter for a range of scientific research purposes
Technical requirement	The design, procurement, construction and commissioning of more beamlines to satisfy increasing demand for scientific research from both academics and industrial partners
Facility specifications	An additional 10 beamlines to be constructed and become operational over the period 2013-2017/18
Motivation	1) Synchrotron users increasingly publish research of high quality, impact, and relevance for society 2) Synchronton users become more valuable to their host institutions 3) Increasing demand for beamtime at Diamond
Procurement	Construction has advanced in phases. The third phase was approved in 2010
Creation/Build	Phase III, additional 10 beamlines are currently under construction
Operation	Diamond Synchrotron is operated by a joint venture company Diamond Light Source Ltd, 86% owned by the new Public Accounts Facilities Council and 14% by the Wellcome Trust. Academic and industrial partners are closely involved in advising operations and management.

Royal Research Ship (RRS) James Cook – Process of motivation, design, build and operation

Scientific case	To conduct oceanographic and marine studies and be equipped to launch and recover heavy marine equipment such as submersible or towable sensing or monitoring devices
Scientific requirements	To facilitate leading-edge multidisciplinary research in oceangeography
Technical requirement	The research ship is required to conduct oceanographic and marine studies and be equipped to launch and recover heavy marine equipment such as submersible or towable sensing or monitoring devices
Facility specifications	Built to accommodate up to 31 scientists and 23 officers and crew, and without the need to dock for nearly two months
Motivation	To support a broad range of research in oceanographic and marine studies to address a broad range of issues and problems
Procurement	The construction of RRS James Cook was funded by the NERC and DTI's Large Scientific Facilities Fund
Creation/Build	The ship was built by the Norwegian shipbuilder, Flekkefjord & Maskinfabrikk AS to a design by Skipsteknisk AS. The ship was completed during the summer of 2006 and went into full service in spring 2007
Operation	Managed by Natural Environment Research Council's (NERC) National Marine Facilities Division, based at the National Oceanography Centre, Southampton

Halley VI Antarctica Research Station – Process of motivation, design, build and operation

Existing facilities	The project involves the building of a new re-locatable Halley VI Antarctic research station and the removal of the existing station, Halley V. Halley VI has been designed to be movable so it can be re-located to adjust to movement in the continental ice sheet
Scientific requirements	The Halley VI project operates as a base for scientific research experiments (e.g., atmospheric research, climate research)
Technical requirement	To overcome snow accumulation, become re-locatable and minimise the environmental footprint of the station
Facility specifications	Halley VI is built on legs so that it has the ability of keeping the buildings above the rising snow level, allowing the station to be periodically relocated across distances of many kilometres. If the station must be moved the individual modules are designed to be separated, towed across the ice shelf by bulldozer, then reconnected again at the new site. This makes it possible for the station to remain a safe distance from the edge of the continental ice sheet.
Motivation	The global scientific importance and value to be gained by the construction and operation of Halley VI and the continued operation of the research facility by BAS on the Brunt Ice Shelf outweighs the minor and transitory impact the station will have on the Antarctic environment and fully justifies the activity proceeding.
Procurement	Funded by the Large Facilities Capital Fund and Natural Environment Research Council (NERC)
Creation/Build	The project involves the building of a new re-locatable Halley VI Antarctic research station and the removal of the existing station, Halley V.
Operation	Operated by the British Antartctic Survey and funded primarily by Natural Environment Research Council

ISIS Neutron Source, Second Target Station – Process of motivation, design, build and operation

Existing facilities	The first phase of ISIS second target station project was completed in 2009. All 7 Phase One neutron instruments Inter, Let, Nimrod, Offspec, Polref, Sans2d, and Wish are operational
Scientific requirements	To add new scientific capabilities in research areas ranging from clean energy and the environment, pharmaceuticals and health care, soft matter, advanced materials, bio-science, microchip screening, neutron imaging and small angle scattering, together with extending the time and length-scales of neutron experiments
Technical requirements	1) To offer instrumentation and facilities for structural and dynamic studies of matter, using cold neutrons and high resolution spectroscopy 2) There is capacity for a total of 18 instruments in the future at Target Station 2 adding to the 20 instruments already available at Target Station 1
Facility specifications	1) The world's most powerful neutron producer of its kind 2) Offer instrumentation and potential for structural and dynamic studies of matter, using cold neutrons and high-resolution spectroscopy
Motivation	1) Mitigate the threat to the UK's position in spallation source technology from US and Japan 2) The second target station safeguards UK ISIS's competitiveness in the world for at least the next decade
Procurement	The science case presented to funding partners demonstrated that ISIS can continue to make significant contributions in three key areas of science. The success of the phase 1 unlocked a further trance of £21 million from the UK government to add four more instruments for phase 2.
Creation/Build	Four new facilities are under construction in the second phase of Second Target Station: CHIPHIR, Zoom, Larmor and Imat
Operation	ISIS is run by the Science and Technology Facilities Council (STFC)

Accelerators and Lasers in Combined Experiments (ALICE) – Process of motivation, design, build and operation

Existing facilities	The ALICE accelerator is an Energy Recovery Linac (ERL) that incorporates all the features of the 4th generation light source with an ability to produce ultra-short electron punches with an unprecedented electron beam brightness
Scientific requirements	The project uses free electron lasers and synchrotron radiation covering the terahertz to soft X-ray energy frequencies for studying matter. Two major objectives of the ERLP are the demonstration of energy recovery from a beam disrupted by an FEL interaction as supplied by an infrared oscillator system.
Technical requirement	Incorporates all the features of the 4th generation light source albeit at smaller scale.
Facility specifications	1) The phase one (first) of the 4th Generation Light Source (4GLS) project 2) An ERL can attain an unprecedented electron beam brightness limited only by the electron gun. Energy recovery allows also a significant increase in an average power of the light sources.
Motivation	1) To fulfil scientific and technical requirements
Procurement	£21.3 million, with £10.1 million from the Large Facilities Capital Fund, £2.9m from the North West Development Agency, £0.3m from the EU and the rest (£8.0m) from Council for the Central Laboratory of the Research Councils.
Creation/Build	The ALICE project was extended by addition of a 19-cavity accelerating Non-Scaling FFAG ring, known as the EMMA project. Construction of the EMMA machine began in September 2009. On March 31st 2011, full ring circumnavigation was completed to establish proof of principle
Operation	Owned and to be operated by the Science and Technology Facilities Council (STFC)

High End Computing Terascale Resource (HECToR) Phase 3 – Process of motivation, design, build and operation

Existing facilities	HECToR phase 1, 2a, 2b
Scientific requirements	HECToR phase 3 project facilitates scientific research that requires high-end computing, such as modelling and simulation
Technical requirement	HECToR phase 3 uses the latest "Bulldozer" multicore processor architecture from AMD which theoretically allows twice the performance over the old architecture used in phase 2b. Learning to exploit these new architectures will place the UK at the forefront of scientific software development.
Facility specifications	HECToR is the UK's largest, fastest and most powerful supercomputer. It is capable of over 800 million calculations a second and has a memory of 90 Terabytes.
Motivation	1) Provide a world-class supercomputer located and run in the UK. 2) Provide an invaluable resource for researchers who study problems relying on modern high end computing tools and techniques 3) HECToR is part of the PRACE initiative giving leading scientific users access to a European pool of supercomputers.
Procurement	A public project funded through Research Councils of UK including Large Facilities Capital Fund, and Engineering and Physical Sciences Research Council.
Creation/Build	In December 2011, the Phase 3 configuration was launched
Operation	Operated by EPCC, STFC Daresbury Laboratory and NAG Ltd.

Muon Ionisation Cooling Experiment (MICE) – Process of motivation, design, build and operation

Existing facilities	The first phase of the experiment, which will deliver the MICE Muon Beam and the instrumentation required to characterise was commissioned with beam in April 2007.
Scientific requirements	To demonstrate that "muon cooling"—making a tightly focused muon beam—is possible through a process of ionisation. In other words, realising ionisation cooling of muons at minimum ionising energy
Technical requirement	1) Design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory; 2) Place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling.
Facility specifications	A neutrino factory based on a muon storage ring is the ultimate tool for studies of neutrino oscillations, including possibly leptonic CP violation. It is also the first step towards $\mu+\mu-$ colliders.
Motivation	1) To observe ionisation cooling of muons; cooling is the aim of the experiment but the lessons learned extend beyond that. 2) The experience gained from this experimental demonstration will provide input to the final design of the cooling channel for the Neutrino Factory.
Procurement	For funding and science reasons MICE is executed in six steps which provide a number of important physics and methodological results. MICE is funded by Large Facilities Capital Fund and UK and international sources.
Creation/Build	The construction of MICE progresses in steps. Step IV is currently under progress, with MICE set to be completed in 2018.
Operation	Measurements with progressively more powerful muon cooling devices are currently under way to demonstrate ionisation cooling. Measurements of the beam cooling properties of different absorbers are planned for 2014-2016.

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