UKRI
Science and
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Facilities Council

Next Generation XFEL: Options Analysis for the UK

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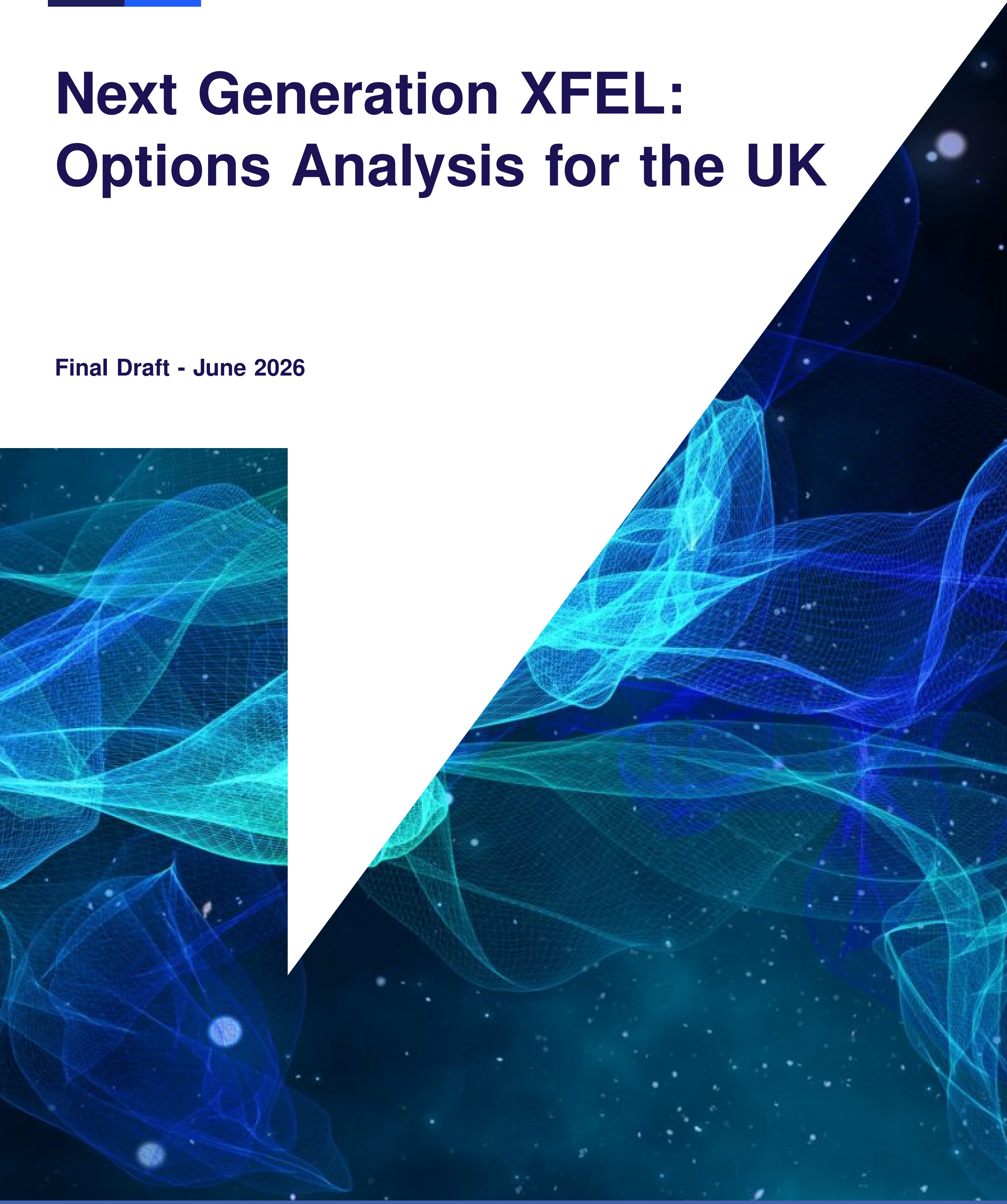

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1 Executive summary

The advent of X-ray free-electron lasers (XFELs) is one of the major technological achievements for the 21st century. They allow us to understand and control how matter behaves by resolving ultrafast processes at the quantum scale. XFELs are entering a bold new era characterised by substantial maturation of the technology and unprecedented new capability. Major developments have been recently initiated by international facilities which will cement the status of XFELs as the successor to synchrotron light sources.

The scientific mission need for UK access to such 'Next-Generation' XFEL capability has been clearly established through a robust, peer-reviewed process, captured in the 'UK XFEL Science Case' published 2020. This consultation has identified that future UK community requirements – highly stable, transform-limited pulses; evenly spaced repetition rates at $\sim$100 kHz; and high throughput via simultaneous multi-beamline operation – diverge sharply from today's facilities and are expected to define the global scientific frontier from the 2030s onward.

No current facility meets all these criteria, and demand for access to existing capability exceeds supply. The UK is the largest non-domestic user of the two largest existing XFEL facilities – European XFEL (Hamburg, Germany) and LCLS (Stanford, US) – which demonstrates the influence of the UK scientific community, but exposes potential vulnerabilities: dependence on oversubscribed overseas infrastructure, limited influence on upgrade planning, and no ability to conduct sovereign or secure research.

In response to the UK XFEL Science Case, the UKRI Infrastructure Advisory Committee (IAC) has recommended action be taken in the form of a Conceptual Design and Options Analysis (CDOA). This document is an options analysis of the question: **how can the UK best enable its researchers to explore ultrafast dynamics at the quantum scale - and what would the broader socioeconomic impact be.** It evaluates three possible configurations through which the UK can secure access to next-generation XFEL capability by the 2040s, examining: (1) maintaining the status quo, (2) investing to upgrade one or more existing international XFELs, and (3) constructing a new UK-based facility.

Publication of this CDOA is a key moment for STFC and UKRI. It represents the culmination of over a decade of coordinated scientific and strategic activity focused on XFEL technology. The research community requires clarity and confidence in the future of XFEL provision. This will enable long-term planning, help structure forward investment, and maximise the scientific, economic, and societal returns from this transformative technology.

A brief summary of the outcomes of the options analysis is provided below:

Option 1: Status Quo

Under this scenario, the UK remains dependent on overseas XFELs. While international upgrades are planned, their delivery depends on external funding and the strategic priorities as identified by those facilities. This option is not without financial risk: the UK is a member of European XFEL and contributes a percentage of the facilities overall running costs through an annual subscription.

Future upgrades as pursued by European XFEL may invoke increased operating costs, and/or requests for UK funding support.

The Strengths, Weaknesses, Opportunities and Threats (SWOT) associated with the status quo option are summarised in Table 1.1.

Strengths	**Weaknesses**
■ The UK avoids major project, technical and financial risks by leveraging international efforts to develop next-generation XFEL capabilities, while still benefiting from access to that capability (should it be successfully realised). ■ The UK can optimise returns from its European XFEL membership while retaining flexibility to respond to (e.g.) cost changes.	■ UK strategic influence over international XFEL facilities is limited. ■ UK users are reliant on these international facilities and are limited to the capability provided, which may not fully meet their requirements. ■ UK is unable to achieve a guaranteed higher level of access and is constrained in user numbers. This will limit the ability of the community to deliver impact in the short-term, and will hinder the growth of the community, both in number and intellectually, in the long-term. ■ Skills development and associated pipeline benefits are primarily realised local to the host and not within the UK. Activities may promote a 'brain drain' of UK talent to the host. ■ Sovereign research applications including defence requiring ultrafast X-ray capability cannot be fulfilled without domestic infrastructure. ■ Maintaining the status quo forfeits opportunities to stimulate UK science and technology growth through strategic investment.
Opportunities	**Threats**
■ Potential funding could be allocated against other UK national priorities. This could be positively received, based on projected public spending pressures and public appetite for large-scale investment in UK science and scientific infrastructure. ■ UKRI can focus limited resources on strengthening UK user skills and access to existing international facilities through training, travel and other funding support mechanisms.	■ Limited access and influence concerning next-generation XFEL capability may erode the UK's global competitiveness in science and technology. ■ Without protected access, UK science and technology enabled by XFELs is vulnerable to external political and regulatory shifts. ■ UK-prioritised next-generation capabilities may not materialise due to external funding or strategic constraints. ■ Lack of investment reduces UK influence over strategic decisions shaping future XFEL capabilities. ■ Delaying a decision on a UK-based XFEL could result in a 10-15 year capability gap, undermining future strategic needs.

Table 1.1: SWOT analysis: no additional investment

Option 2: Investment to Upgrade One or More International XFEL Facilities

A moderate UK investment (<100 MGBP) could strategically support upgrades at European XFEL and/or LCLS, ideally through in-kind contributions. This would enhance UK influence and strengthen international technical collaborations. Such contributions may also influence improved access for UK researchers.

The SWOT analysis of this external investment option is summarised in Table 1.2.

Strengths	**Weaknesses**
■ Enhances strategic influence over international XFEL upgrades. ■ Leverages areas of strength within UK national laboratories, academia and industry, including that developed through the UK XFEL conceptual design project. ■ Offers direct benefits to UK institutions charged with in-kind delivery, particularly during any construction phase. ■ Facilitates and strengthens international collaboration. ■ Delivery risk is owned primarily by the host facility.	■ No guaranteed access despite investment (c.f. UK shareholding in European XFEL). ■ Uncertainty in the realisation of proposed international upgrades, which may not fully meet UK requirements. ■ Engagement of UK industry potentially limited due to external project delivery frameworks. ■ Sovereign research applications including defence requiring ultrafast X-ray capability cannot be fulfilled without domestic infrastructure. ■ Complexity in negotiating access agreements and alignment with external timelines.
Opportunities	**Threats**
■ Potential to enable user access which exceeds the financial value of any investment. ■ Potential for long-term knowledge transfer and capability building between the UK and international partners. ■ Potential to increase likelihood and accelerate international projects through UK support including funding. ■ Improved UK reputation as a trusted partner may lead to invited contributions to other international activities. ■ Investment could be made a component of a broader bilateral agreement or strategic international partnership.	■ Internal and external political factors may affect feasibility or timing of investment. ■ Risk of residual misalignment with UK next-generation needs despite influence. ■ Dependence on external project success and timelines. ■ Financial value of investment currently unknown and to be subject to future negotiation, impacting planning processes. ■ Investment possibly associated with long-term operational cost commitments not yet clarified.

Table 1.2: SWOT analysis: investment to upgrade an existing international XFEL facility

Option 3: Construction of a new UK-Based facility

A UK-based facility would deliver the full suite of next-generation XFEL capabilities through a dedicated, ‘ground-up’ design process. Although a multi-billion-pound investment, international partner contributions would be approached to substantially offset UK costs. The delivery of the new facility would be phased to reduce delivery risks and generate flexibility for future capability to be aligned with emergent UK social and defence priorities.

The results of the SWOT analysis for a UK-based facility are summarised in Table 1.3.

Combined approaches

Greater benefits could be potentially achieved through an investment approach which combines the options above. For example, the UK could seek to initially build a low energy next-generation national XFEL while investing in an existing high energy facility such as European XFEL or LCLS. This could potentially accelerate UK access to next-generation capability while a UK-based facility is under construction. Formalised collaboration would de-risk technical challenges through joint research developments and knowledge exchange.

Summary of the Options Analysis

This document is structured as follows:

Chapter 2: Background Provides an introduction to the processes and decisions to date which have motivated and directed this options analysis.

Chapter 3: Objectives We define the objectives for the options analysis. These will be used to identify compatible options and structure their analysis.

Chapter 4: Essential criteria To ensure that the options identified are feasible and fully aligned with Mission Need, we define a series of essential criteria to be used in shortlisting. The rationale for these conditions is outlined in detail.

Chapter 5: Landscape analysis We review the XFEL landscape, including existing capability accessible to the UK and planned developments of relevance to the project objectives.

Chapter 6: Socioeconomic analysis An executive summary of a report detailing the socioeconomic impact of an XFEL is presented. The full report is attached to this volume as an addendum.

Chapter 7: Options analysis We outline and compare possible investment options compatible with the project objectives.

Strengths	**Weaknesses**
■ The UK would retain majority control over the facility's capability, delivery, operations and user access models. ■ The capability of the facility would be fully aligned against all UK science and technology requirements, including the essential criteria listed. ■ A UK-based facility would host sovereign research activities in support of defence and national security interests, for which secure access – which cannot be guaranteed at overseas facilities – is essential. ■ The socioeconomic return to the UK would be maximised as compared to other investment options, by giving the UK full control over strategic inputs and activities during project delivery. ■ Impact would be realised across diverse pathways, including in non-research driven domains (e.g. financial management, workforce development, business innovation, public engagement) of relevance to the UK's Modern Industrial Strategy. ■ The construction and operation of the new facility are likely to attract global talent to the UK, enhancing its reputation as a scientific superpower. ■ Data produced by a new national facility – which would be one of the largest data 'factories' in the world – could be leveraged as an asset in support of economic growth.	■ A new facility would be a multi-billion pound investment and committent running over multiple government terms. ■ The UK would bear the majority of delivery risk and need to navigate complex UK legal, environmental and planning frameworks to ensure construction of the facility. ■ Coordination of international partner contributions to the facility (including construction and user operations) will be complex and involve significant stakeholder engagement. ■ The UK would be responsible for resolving major technical challenges associated with next-generation capability (Table 7.4).
Opportunities	**Threats**
■ Global partners can be engaged against technical, financial and in-kind contributions, strengthening UK-international scientific collaboration. ■ Strategic coordination of investment across impact pathways could amplify socioeconomic benefits, with site selection offering a targeted means to augment regional growth. ■ A phased delivery model as proposed would allow the facility to adapt to evolving national priorities and incorporate technology advances in XFEL capability. ■ Rates of return on investment are likely higher for UK-based infrastructure as compared to international investments, however further investigation is required to confirm this. ■ A new facility would be of the scale of a national laboratory and represent an opportunity to stimulate science, technology and innovation developments around a new hub.	■ Public spending pressures and political shifts throughout decade-spanning delivery may impact project continuity and support. ■ While international partnerships are expected, the scale and timing of their contributions is not known and may result in delays or higher costs to the UK. ■ A Phased delivery model introduces cost inefficiencies due to inflation, staff retention and focus, along with potential disruptions to user operations. ■ Advances at international facilities such as European XFEL, LCLS (LCLS-X) and SHINE may compete for UK users and diminish the strategic relevance of a UK facility. ■ Successful delivery would require complex coordination of contributions from across academia, industry and government. ■ Varying environmental factors could emerge and impact construction and operations phases, including regulations determining greenfield site development and energy sourcing.

Table 1.3: SWOT analysis: investment to create a new national XFEL facility

2 Background

STFC began the formal process to develop the scientific case for a UK-based X-ray Free Electron Laser (XFEL) in 2019. The goal of this process was to address, via comprehensive peer-review, the following questions:

- Over the coming decades, how will the technological and scientific opportunities enabled by XFELs develop?
- What specific impact might there be from a UK machine at offering new capabilities beyond those that exist today, that might exist from 2030 and forward?

The process began with a broad community consultation, gathering data and ideas through workshops with key national and international stakeholders. A science case was subsequently developed by a team comprising ∼25 experts from a wide range of fields, led by Prof. Jon Marangos (Imperial College). A further ∼80 authors provided additional contributions.

This science case was reviewed by a panel of external experts, with the objective of establishing if there was a scientific "Mission Need" for a UK facility. If established, a conceptual study would be performed to identify how best to achieve it.

The UK XFEL Science Case [1] was published in 2020 and endorsed by peer review. The review recommended the project proceed to the next phase, stating there was a clear case for UK XFEL from a scientific mission need perspective. It requested the development of "...a conceptual design that will allow the identification of a self-consistent technical and scientific case that can provide the information needed to assess overall value-for-money and comparison of design options."

A proposal for a conceptual study was endorsed by STFC Science Board and UKRI Facilities Strategic Advisory Group (FSAG) in 2020, and subsequently the UKRI Infrastructure Advisory Committee (IAC) in 2021. The Committee was supportive of taking the conceptual study forward, but requested it address the following specific areas:

- The focus of the activity should be on the conceptual design
- Any future activities must demonstrate the role and activities of the European XFEL to give the Committee confidence of the impact and fit of a UK [based] XFEL in the wider landscape
- The project leads should consider having separate teams independently **develop, evaluate and make the case for each of the different options** in delivering the proposal
- There must be an independent **evaluation of options** which should include a majority of reviewers who are international, including the chair

Funding (3.2 MGBP, three years) for a Conceptual Design and Options Analysis (CDOA) was approved with activities beginning October 2022. Following the IAC recommendations, three project leads were appointed to explore three different investment options, including the conceptual design of a new facility, and exploration of upgrade options at two existing facilities, including European XFEL. This leadership group were charged with generating and publishing an Options Analysis, to be made available for external, independent review.

3 Objectives

3.1 Mission Need

The Mission Need for UK XFEL is **the requirement for UK access to an XFEL facility with new capabilities, beyond those which exist today, which could exist from 2030 and beyond.** For ease, this facility with "new capabilities" is referred herein as a 'next-generation' XFEL.

The capabilities of a next-generation XFEL are based upon the result of comprehensive stakeholder engagement, performed as part of the 2020 UK XFEL Science Case and updated as part of the UK XFEL CDOA. These capabilities have been fully endorsed by both external review (of the 2020 Science Case) and the UK XFEL international Advisory Board (IAB). These capabilities are summarised in Table 3.1. Moreover, several existing XFEL facilities have started to formulate their own vision of future light source capability.

3.2 Objectives

The primary objective of the Options Analysis is to **evaluate investment options which could enable UK user access to next-generation XFEL capability in the 2040s.** Although Mission Need refers to capability "...which could exist from 2030 and forward...", analysis performed during this project indicates that 2040 is a feasible timescale.

To achieve this objective, this Options Analysis considers:

- **Delivering the capability through a new facility based in the UK**
- **Delivering the capability through an upgrade to one or more existing international XFEL facilities**
- **Maintaining the status quo**, in which the UK does not make any additional[1] investment towards next-generation XFEL capability

A landscape analysis is required to establish future capability at existing XFEL facilities. The results of this analysis, performed in Chapter 5, help establish the placement of a new facility within the future landscape as requested by the UKRI IAC.

STFC and UKRI Environmental Sustainability Strategies specify a Net Zero estate by 2050. The Options Analysis therefore considers how best to **ensure new infrastructure is delivered and operated with minimal environmental impact.**

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[1] 'Additional' is emphasised to highlight the UK's current financial commitment to the ongoing operation of European XFEL ($\sim$7 MGBP in 2025).

Current capability	New capability (2030+)	Scientific and strategic benefit
Current XFEL pulses have a noisy temporal profile, and vary in time shot-to-shot	X-rays are generated with transform-limited properties and a smooth temporal profile, similar to an optical laser	Enables the XFEL to fully resolve subtle excitations in quantum materials, and generated X-ray pulses which can watch the fastest (electronic) processes in matter
User access is limited by number of experiments which can be performed at the same time at one facility	A high efficiency facility which can run significantly more multiple instruments and end stations at the same time, similar to a X-ray synchrotron	Expand access to researchers to perform many hundreds of unique experiments every year, and reduce the barrier to access to new users, promoting greater innovation. Reduces the cost per experiment in GBP and Carbon Dioxide emitted. Allows a greater number of instruments to be installed and for these to be optimised to specific purposes.
Current XFELs can generate 1000-10 000 pulses per second, with the fastest pulse rates delivered in a short burst which is challenging for detectors to follow	X-ray delivered at 100 000 pulses per second, evenly spaced apart	High repetition rate allows for small signal observables to be detected. Evenly spaced pulses are better matched to the delivery of optical lasers and detectors. High data rates provide opportunities to apply advances in artificial intelligence, digital twins, and real-time experiment optimisation to improve reliability, stability and efficiency.
Synchronisation of optical lasers with X-ray pulses is $\sim$50 fs, limiting temporal resolution and the range of physical processes which can be observed	Improved X-ray to laser synchronisation to $\sim$1 fs and combine with shot-by-shot time-stamping using X-ray photon arrival monitors to achieve $<$1 fs effective resolution.	Possibility to watch dynamics evolve across multiple timescales, from femtoseconds to attoseconds
X-ray/x-ray experiments can be performed, but with a small spacing in X-ray energy which limits the range of processes which can be resolved	Widely separated, multiple colour X-rays can be delivered to at least one station in the facility	Allows interrogation of multiple electronic, vibronic and excitonic (etc.) modes to completely uncover the complex paths and couplings in matter, as well as allowing access to the most extreme states of matter.
Optical lasers are a key component of each experiment, but have a limited range of wavelengths, pulse energies, and cannot be quickly reconfigured during an experiment.	Expanded laser capability from XUV to THz wavelengths, accessible to each instrument as standard, with a high level of technical reliability and support as would be delivered by a dedicated laser facility.	Expands the range of physical processes that can be investigated by each instrument, while improving experimental efficiency and up-time.

Table 3.1: Capabilities of a Next-Generation XFEL facility

4 Essential criteria

To ensure focus of the Options Analysis is placed on the most promising and feasible options that achieve its objectives, UK XFEL has established a series of “must have” capabilities – **essential criteria** – of a next-generation XFEL. These are listed below, including the rationale for each criterion in terms of benefits enabled and risks mitigated.

4.1 Evenly spaced pulses at high repetition rate

Description: UK users can access and perform experiments with evenly-spaced X-ray pulses at $\sim$100 kHz.

Critical benefits enabled: High repetition rate coupled with evenly spaced pulses is a clear demand of the Science and Technology Case. High data rates would allow deployment of data science techniques and open a new paradigm of user access, including AI-driven real-time experiment optimisation. Experiments that currently require hours of data collection could be performed in minutes. Multiple experiments based on the same machine configuration could be delivered within a block now lasting only a few days, allowing a greater number of configurations to be explored over a run period. These factors would collectively increase the number of users attending annually, reduce the barrier to access for new and smaller user groups, and in turn attract new communities to the facility.

Risks mitigated through inclusion: The XFEL landscape is already moving to evenly spaced, high repetition rate operation. It is a core capability at LCLS-II (2024) and SHINE (currently planned to finish commissioning in 2027), with both PAL-XFEL and European XFEL reviewing how to implement it via upgrade. There is a risk that, by not prioritising high repetition rate operation, the UK would not have access to what could constitute ‘standard’ capability in the 2040s.

4.2 Near transform-limited X-ray pulses delivered to end stations across a broad range of photon energies

Description: The facility can deliver near transform-limited[1], ‘laser-like’ X-ray pulses to users, across a broad range of X-ray photon energies. Transform-limited pulses have a smooth temporal profile, improved shot-to-shot stability, and enable ultrafast processes in matter to be resolved at the **combined** limits of temporal and energy resolution, for both the shortest ($\sim$100 as) and longest (up to $\sim$100 fs) pulse configurations requested by the Science and Technology case.

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[1] Transform-limited: shortest possible pulse duration for a given spectral bandwidth

Critical benefits enabled: Transform-limited capability is a clear demand of the Science and Technology Case. Achieving this capability will deliver significantly improved reproducibility and shot-to-shot stability, enable reliable data average during acquisition, and align operation with user expectations shaped by X-ray synchrotrons and ultrafast optical laser systems. It will increase the number of useful 'shots' in a single user experiment, increasing the number of successful user experiments performed annually. It also provides access to structural dynamics in the attosecond regime, exploration of which has been hindered by absence of a high brightness photon source. Access to a broad range of photon energies goes beyond existing provision which is limited to narrow and specific energy ranges only.

Risk mitigated through inclusion: Retrofitting equipment to generate transform-limited pulses is under consideration at LCLS, SHINE, European XFEL and SACLA. Efforts are complicated by existing constraints including tunnel size and beamline layout. Soft X-ray facilities including FLASH and FERMI have either implemented such capability, or are in the process of doing so. By not including this capability, the UK may not have access to what could constitute 'standard' capability in the 2040s.

4.3 Multiple FELs and end stations operated simultaneously

Description: The facility must have the capability to operate at least five FELs simultaneously from the same linear accelerator, and support the operation of at least fifteen end stations. This would effectively combine the outstanding X-ray properties delivered by an XFEL with the high throughput of a synchrotron. The facility should also have the capability to be upgraded in future to support additional FELs.

Critical benefits enabled: This is another defining feature of a next-generation XFEL and a step-change beyond the status quo. LCLS-II is capable of operating two FELs in parallel, with SHINE planning to do the same. European XFEL currently operates three FELs, however are exploring to plans to operate five. Fifteen end stations make the overall provision comparable (e.g., within a factor of $\sim$2) to current synchrotron facilities. The cost per experiment is expected to reduce almost linearly with the number of FELs and increase the number of hours made available to users. More end stations could be dedicated to specific science areas or applications, and would also allow 'standard configuration' stations optimised for high throughput and made readily accessible to first-time XFEL users.

Risks mitigated through inclusions: A large number of end stations and experiments running simultaneously provides greater flexibility for the XFEL facility to react to emerging scientific, technological or societal priorities. This flexibility is enhanced by reserving space for future upgrades in which additional FELs and end stations can be added. A high cost per experiment and limited number of user hours discourages diverse exploitation of the facility and increases the barrier to user access; this would have a disproportionate impact on new users and limit community growth. Inefficient operation of a high repetition rate linear accelerator, both in terms of financial and environmental cost, is a reputational risk.

4.4 Summary of essential criteria

The essential criteria are summarised in Table 4.1 for reference in future sections.

Ref	Essential attribute
EC-I	UK users can perform experiments with evenly spaced X-ray pulses at high ($\sim$100 kHz) repetition rate
EC-II	UK users can perform experiments with transform-limited X-ray pulses, across a broad range of photon energies including soft and hard X-rays
EC-III	UK users can access the benefits of a facility which operates at least five FELs simultaneously from the same accelerator, and supports at least fifteen end stations.

Table 4.1: Essential criteria (EC) for the Options Analysis

5 Landscape analysis

UK XFEL next-generation requirements go beyond current XFEL capabilities by definition. The international XFEL landscape continues to grow at a fast pace, with new XFEL facilities planned or under construction, and upgrades underway to expand the capabilities of existing facilities.

A review of international XFEL capability provides the context of the landscape in which a new next-generation UK facility might sit. It has also been to evaluate the possibility of UK investment in one or more existing XFEL facilities, which could deliver access to comparable capability. The international XFEL landscape is introduced in Section 5.1, and a summary of the UK strategic context with respect to XFELs provided in Section 5.2.

Focus has been placed on European XFEL and LCLS based on their projected future capability, which (as will be discussed) aligns closely with the criteria describing a next-generation XFEL. Both facilities continue to benefit from strong UK engagement within their user communities, and it is clear that such engagement has helped to shape the future plans of those facilities. There are also longstanding collaborative relationships between STFC and the relevant host organisations. Further information on these facilities and their strategic relevance to UK XFEL is provided in Section 5.3 and Section 5.4.

5.1 Introduction

A key step in the global journey of XFELs began in 2005 with the launch of FLASH (DESY, Hamburg), which was the first FEL facility to deliver XUV and (later) soft X-ray photons [2] to users. The world's first hard X-ray XFEL at LCLS (SLAC, Stanford) [3] began user operations in 2009. Since then the field has expanded rapidly; in just fifteen years, six more XFEL facilities have come online, each pushing the boundaries of ultrafast science, with a further facility – SHINE (CAS, Shanghai) [4] – currently under construction and expected to complete commissioning in 2027. These nine facilities, shown in Figure 5.1 and summarised in Table 5.1, constitute the current XFEL international landscape.

With more facilities coming online, the unique capabilities and X-ray modalities offered to users has increased rapidly:

- FERMI have pioneered seeded FEL techniques providing a route to full 3D-coherent – 'laser-like' – X-ray pulses [5]
- SACLA has achieved focussing of hard X-rays to 7 nm × 7 nm [6]
- Sub-femtosecond, terawatt peak power X-ray pulses have been demonstrated at LCLS [7]
- LCLS-II has demonstrated the acceleration of evenly spaced, high repetition rate hard X-rays [8] using superconducting RF technology with SHINE set to follow with similar capability [4]

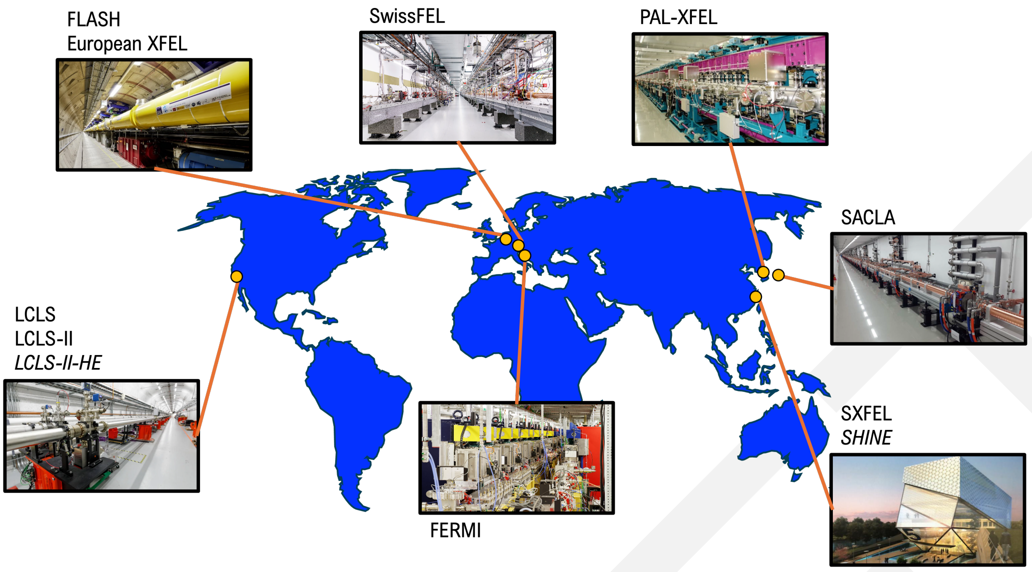

Figure 5.1: Map of international XFEL facilities.

The scale of these developments not only demonstrate that the XFEL landscape is entering a new era of capability and exploitation [9], but may look fundamentally different in the 2030s and 2040s if the pace of development continues.

Facility	**Location**	**Year**	**Beam energy [GeV]**	**Photon energy [eV]**	**Repetition rate [Hz]**
FLASH	Germany	2005	0.35–1.35	14–400	5000*
LCLS**	US	2009	2.5–16.9	280–12,800	120
SACLA	Japan	2012	5.1–8.5	4000–20,000	60
FERMI	Italy	2012	1–1.67	20–310	50
PAL-XFEL	Korea	2017	3.5–10	275–20,000	60
European XFEL	Germany	2017	8.5–17.5	260–25,000	2.7×10^4*
SwissFEL	Switzerland	2017	2.1–5.8	250–12,000	100
SXFEL	China	2021	1.0–1.5	50–600	50
LCLS-II**	US	2024	4	200–5000	1×10^6
SHINE	China	*2027*	8	200–15,000	1×10^6
LCLS-II-HE**	US	*2028*	8	200–13,000	1×10^6

Table 5.1: Comparison of international XFEL facilities based on [10] and updated. SHINE and LCLS-II-HE under construction and commissioning. Years correspond to first operation for users.
*Burst mode structure, averaged over 1 s.
**LCLS-II and LCLS-II-HE are listed separately from LCLS to highlight their distinct parameter ranges.

Table 5.1 (based on an equivalent table in [10]) compares the key X-ray and accelerator parameters of each international XFEL facility. The values provided are illustrative only, with many of the parameters for a single facility coupled by operating mode. It excludes consideration of novel FEL modalities (e.g., harmonic lasing, self-seeding, external seeding).

There is no current facility worldwide which meets all of the UK XFEL essential criteria; indeed, only one facility – LCLS-II – has capability currently compatible with any of the criteria (EC-I). The XFEL landscape is however expected to evolve and existing facilities to upgrade their capability.

5.2 UK strategic context

An excellent history of UK development and engagement with FELs (including XFELs) is provided in the recollection *“The origins and development of free-electron lasers in the UK”* by E. Seddon and M. Poole [11]. It covers 45 years of UK activity from the 1970s through to 2022 including the background and technical detail of UK projects. It also describes the influence and benefit of those projects within the UK and abroad.

STFC’s strategic position on FELs has evolved in recent years. A summary of recent exercises (2016-2021) relevant to FEL developments is provided below.

5.2.1 2016: STFC FEL Strategic Review

STFC undertook an exercise to consider the future of large facility provision for the UK in 2015. A coherent strategy was considered necessary to match rapid changes in the national and international landscape. It was recognised that FELs were a key area and that both the UK and STFC needed to develop a strategic position on their provision. A FEL review report was commissioned which aimed to identify the key science areas enabled by access to FELs, requirements for both capability and capacity, and from this develop a roadmap for UK community engagement and development. The report was to be considered a basis in shaping future support for FEL science, facility provision, and underpinning developments in accelerators and instrumentation.

The report was published in 2016 [12] and includes the following recommendations:

- Increased engagement (particularly for enhanced scientific exploitation) with international XFEL facilities; in particular, European XFEL, but also including LCLS-II, SACLA, PAL-XFEL and SwissFEL.
- Coordinated development of the UK FEL user community via national laboratories, international photon institutes and UK higher education institutions.
- Exploration of constructing a UK national XFEL facility, to address a projected increase in national demand which would outstrip existing availability. This included recommendations for a ‘SwissFEL-like’ XFEL (∼500 MGBP), deemed an appropriate compromise between requirements and affordability. It was suggested that such a facility would compliment higher repetition rate developments at European XFEL and LCLS-II – projected to meet the needs of only a minority of users – and would benefit from co-location with the high performance laser capability of STFC’s Central Laser Facility (CLF).

5.2.2 2017: Accelerator Strategic Review

In 2017 STFC published the outcomes of a strategic review of its accelerator programme. [13] The expectation of the review was UKRI (set to begin operation as a new non-departmental government body in 2018) would place greater focus on industrial applications, and STFC should take a strategic approach to cross-cutting activities. An international panel was formed to develop recommendations for both cross-cutting and theme-specific areas. a topic on ‘Light Sources’, encompassing both synchrotron and FEL activities, was considered.

The 2017 strategic review report did not make any recommendations specific to the light sources theme; however, the concept of “UK XFEL” – building upon the idea of a UK FEL facility as described in the 2016 review report – is referenced throughout as a potential focus of activity. It recommended research into superconducting RF (SRF), noting the preferred option for a UK XFEL in the absence of funding constraints would be a “...dedicated [SRF], high rep-rate ($\sim$1 MHz) facility based in the UK...” A “UK XFEL accelerator underpinning technology programme” was presented within the report as funding developments in this area, including examination of an energy recovery linac (ERL) option which would build upon experience gained with the ALICE ERL at Daresbury Laboratory [14].

A launch meeting was held 2017 at Daresbury Laboratory, with members from ASTeC, Cockcroft Institute, Diamond Light Source and John Adams Institute in attendance [15]. This technology programme did not receive external funding but was progressed at a low level using core funding from the contributing departments and institutes.

5.2.3 2020: UK XFEL Science Case

In recognition of the progress made in the aforementioned strategic exercises and the growing experience of the UK science community exploiting FELs, STFC commissioned an activity to update the science case for a UK-based FEL in 2019. The case was to focus on transformative scientific opportunities enabled by a “UK [X]FEL” and place them in context of UKRI and government priorities. It would also seek to identify the performance gap between capabilities required by UK users as compared with current and planned developments.

The UK XFEL Science Case, led by Prof. Jon Marangos (Imperial College) was subsequently published in 2020 [1], taking assistance from a large science team assembled from UK universities and institutes. An update to the 2020 Science Case – now a Science *and Technology* Case – has been performed as part of the UK XFEL CDOA project.

5.2.4 2020: UKRI Infrastructure Roadmap

UKRI published *“The UK’s research and innovation infrastructure: opportunities to grow our capability”* in 2020 [16]; this followed a landscape analysis of the UK’s research and innovation infrastructure in 2018-19 [17]. The goal of the report was to assess the future research and innovation infrastructure landscape, and identify “...potential opportunities to create a step-change in the next-generation of infrastructure capability...”, using 2030 as a target timescale.

The infrastructure roadmap was intended as a strategic guide to inform future investment decisions and help achieve the UK goal of at least 2.4 % of GDP invested in research and development by 2027. UKRI established the Infrastructure Fund as a means of delivering funding against these strategic goals.

The report highlighted the potential for the UK to host a new international (large-scale, multi-sector) facility, along with upgrades to existing facilities, in order to achieve step changes in capability. It acknowledged both “UK-FEL” and the successor to ISIS (ISIS-II) as subjects of potential long-term focus. It also highlighted that, while the construction of those facilities would not take place before 2030, consideration should be given to the timescale for evaluation of technical options; this drew upon the experience of DLS-II, for which technical assessment started ten years before start of construction.

The report highlighted the outcomes of the UK XFEL Science Case (which was in preparation during production of the roadmap) as determining the steps to be taken. Mid-2020 was cited as a possible date for a decision on constructing a national UK [X]FEL facility with a conceptual design phase and potential establishment of an FEL test-bed linked to this.

5.2.5 2021: A Strategic Vision for the UK's Large-Scale Light Source User Facilities

In 2021 STFC published a strategic vision for light sources, outlining the potential impact of significant upgrades to existing facilities and options for new developments [18]. The role of FELs within the UK light source provision was explicitly evaluated. This included consideration of "...an emerging case for increasing access to a new type of national facility, an [XFEL] source, that would bring significant new capabilities not accessible through existing national sources."

The report outlined multiple development options for each light source sector, reviewing these by time-to-implement and capital cost. Three options were outlined for XFELs:

- Building a UK test facility ($\leq$3 years, $\leq$100 MGBP), to reduce the risk associated with building a full future user facility but with limited opportunities for new science.
- Building a full-scale facility (10-20 years, $>$750 MGBP), with unique capabilities to enable dramatic science gains and create UK leadership in FEL science, founded on proven technologies.
- Engagement (unspecified) with European XFEL ($\sim$100 MGBP), enhancing science gains through international partnership/collaboration, but acknowledging that capped capacity would mean the facility could not serve all UK needs.

Other overseas XFELs were highlighted as potential options, but (unlike European XFEL) would be subject to making suitable access agreements with those facilities, accounting for available capacity.

A forward strategic plan was proposed, including a review of future European XFEL participation (2025-2035), and the design and construction of new sources (2025-2035). The FEL source plan as presented is shown in Table 5.2.

The report also highlighted the need to support the FEL user base; in particular, expanding skills to allow uptake beyond a small group of expert users. It also highlighted the challenge of data management faced by the current generation of light sources, including the need for efficient data extraction, storage and analysis. Future light sources were perceived as requiring a step change in technology, including implementation of artificial intelligence capabilities.

5.2.6 Summary of UK users at international facilities

A comprehensive analysis of UK user access to existing XFEL facilities has been performed as part of the UK XFEL project. Data was requested from user offices, with responses received

Source	**Strategic Plan**	**Anticipated timing**
UK XFEL	Whilst building a small-scale facility would add some increase to capacity, building an internationally competitive UK facility will provide the greatest gain in capabilities and opportunities for research benefits. The UK FEL specification should: ▪ Build on world-wide experience so that research gains can be maximised ▪ Take account of Diamond upgrade and EPAC capabilities to maximise complementarity The existing FEL test facilities should be used to support development of the optimal design and minimise the technical risks.	Year 0: finalise design Years 1-4: initiate detailed design planning and test programme Years 4-5: finalise design and secure funding Years 5-8: begin construction Years 9-10: begin commissioning Year 10: begin operation
European XFEL	Maintain European XFEL membership but review regularly. Investment in any future upgrades needs to be considered against UK XFEL specification.	Review every five years.
Other	Maintain active links with the world-wide network of FELs so that: ▪ Ad hoc arrangements for mutual access are maintained ▪ Opportunities for collaborative partnership research programmes can be identified ▪ UK is engaged in, and can benefit from, international advances in FEL science and technology.	Ongoing

Table 5.2: Strategic plan, FEL sources: as presented in STFC's "A Strategic vision for the UK's Large-Scale Light Source User Facilities", published 2021 [18]

from European XFEL[1], FLASH, LCLS[2], SACLA[3] and SwissFEL. (FERMI[4] and PAL-XFEL were contacted but did not provide a response).

A summary of the data received is shown in Figure 5.2. Total user visits by individual (not institution) are presented as a function of year in Figure 5.2a. The data potentially encompasses return visits by users to the same facility, and users who may have visited multiple facilities within the same year. Each facility uses a different definition of reporting year (over which data is collected and recorded, e.g., calendar, financial); the data shown should be interpreted accordingly, e.g. as illustrative only, and showing trends rather than accurate statistics for a calendar year.

Figure 5.2a shows that UK visits have steadily increased from 2015, increasing by over a factor of two from 2018 through to 2024. UK user visits to LCLS exceeded 100 in 2021, and exceeded 100 again for European XFEL in 2024. Access to all facilities in 2020 was compromised by the COVID-19 pandemic, and access hours to LCLS in 2023 and 2024 were impacted by both planned upgrade work (LCLS-II) and unexpected power loss from major storms. The growth of the UK community was highlighted as a strategic objective within the 2016 STFC FEL Strategic Review report [12] – this objective appears to have been achieved.

The total number of user visits for all nations to the same five facilities is shown in Figure 5.2b, increasing from ∼3500 to ∼4500 between 2015 and 2024. In comparison, UK user visits as a percentage of all visits increased from ∼2.5 % in 2015 to ∼6 % in 2024 (right axis). This illustrates that the growth in UK access exceeded the rate of change in total visits and that UK user groups were taking a larger share of available access. The data reflects UK groups that successfully secured beam time; figures on total requests including unsuccessful applications and rejection rates were not available across all facilities.

The data provided does not include a breakdown of all users by nation. Select data is however available for European XFEL and LCLS in 2024; UK visits as a percentage of non-domestic users is shown in Figure 5.3. In both years UK users were the second largest non-domestic user of the facilities shown, and *the largest from a nation without access to domestic XFEL capability*. This emphasises the significance (and potential influence) of UK users within the global XFEL community. Figure 5.3 also demonstrates that the largest non-domestic users for European XFEL and LCLS came from each other's host nations (US and Germany respectively).

UK visits as a percentage of all visits following COVID-19 have remained between 5–6 %, despite the increase in visits to European XFEL. Access to XFELs remains challenging, with beam time scarce and highly oversubscribed. UK groups informally report that ∼25 % of all experiment proposals are successfully awarded beam time. Data from European XFEL indicates that 42 % of proposals with UK participation were successful between 2021 and 2024.

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[1] Data excludes UK contributors to the HED-HIBEF consortium, which receives access separate to public beam time and pays for operation costs of provided instrumentation, including personnel. This impacts figures for 2023 and 2024, which will underestimate total UK users.

[2] User data between 2009 and 2013 was not available.

[3] SACLA data for 2024 was not available at the point of survey; to allow analysis of other facilities and not exclude SACLA, data for user visits for 2024 are based on the average of the period 2021-2023.

[4] According to their website, FERMI supported 7 user visits from the UK in 2024 [19]; this is a small fraction of all UK visits and is therefore would not significantly impact UK access trends.

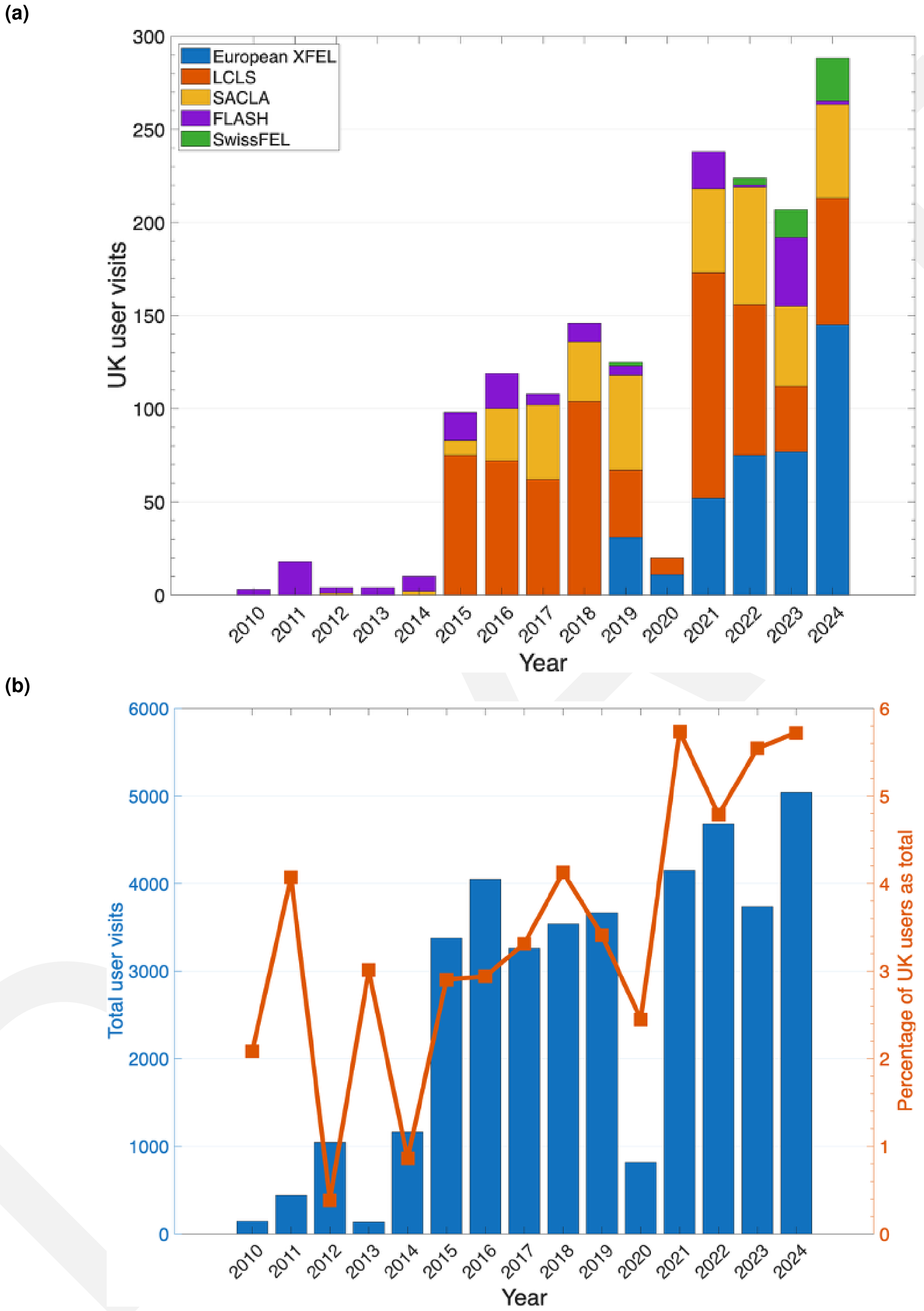
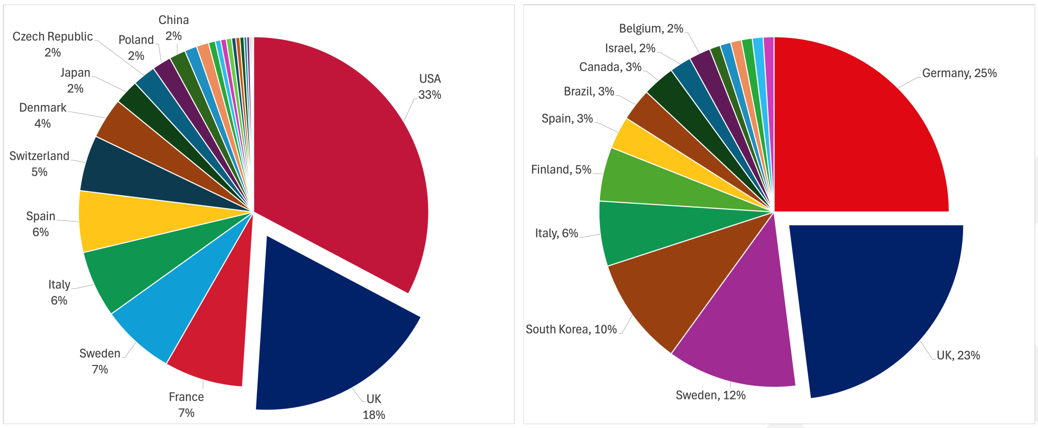


Figure 5.2: a) UK user visits (including return visits) to five major international XFEL facilities (European XFEL, LCLS, SACLA, FLASH and SwissFEL, as legend top left), by year; b) Total visits to the same international XFEL facilities (bars, left axis) compared with UK user visits as a percentage of that total (line, right).



(a) European XFEL (Germany) **(b) LCLS (US)**

Figure 5.3: Users visits by nation in 2024, as a percentage of all non-domestic users, highlighting the UK's contribution.

5.3 European XFEL

5.3.1 Introduction

The European XFEL facility was conceived at DESY [20] and developed in detail by a large European collaboration [21]. The official realisation of the project as an international research infrastructure was made in 2009 with the founding of European XFEL GmbH.

The facility is based primarily underground and extends over 3.4 km. Construction began in 2009, with twelve participating member countries including the United Kingdom. European XFEL GmbH and its main stakeholder DESY collaborate on construction, commissioning and operation of the facility. Together with international partners, DESY constructed the 1.7 km long superconducting accelerator including the electron source and operates the accelerator on behalf of European XFEL GmbH.

The unique feature of the European XFEL is the capability of the superconducting linac – based on technology developed through the TESLA collaboration [22], led by DESY – to accelerate trains of up to 2700 electron bunches within one 600 μs long RF pulse, to very high beam energy (17.5 GeV). Using a 10 Hz RF pulse repetition rate, up to 27,000 electron bunches and photon pulses can be produced each second in a burst-mode structure.

The beam distribution fan, shown in Figure 5.4, provides space for five FEL undulators (three initially installed), each pointing into a separate tunnel. SASE 1 and SASE 2 deliver X-ray photons between 3–25 keV to five end stations; SASE 3 can be tuned from 260 eV to 3 keV and delivered to three end stations. To cover this photon energy range, the electron beam energy is varied from 8 GeV to 17.5 GeV.

European XFEL began operations in 2017, with accelerator uptime 6500 hours/year and 4500 hours/year X-rays for experiments. Fully parallel operation of all three FEL sources started in 2019, increasing X-ray delivery to 10,000 hours/year.

5.3.2 Status

European XFEL has emphasised reliable and sustainable operation through continuous improvement. The facility has a dedicated R&D programme against mid-term (2025-2029) and long-term

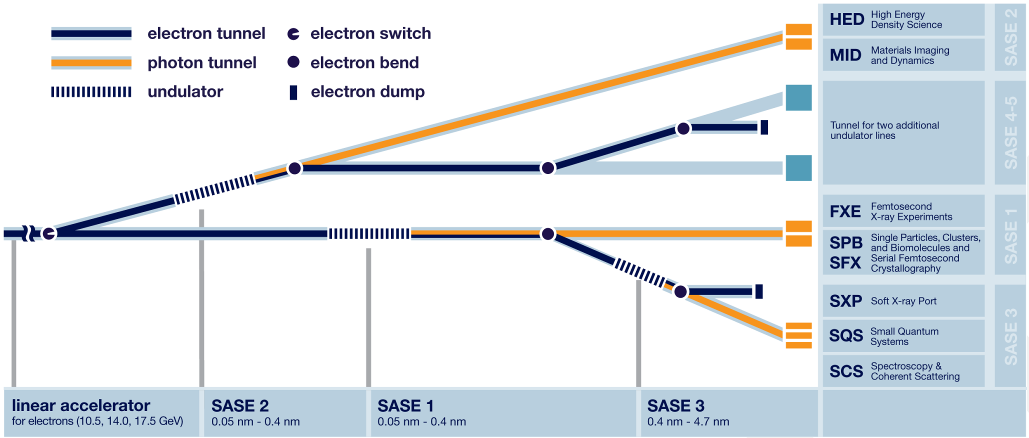


Figure 5.4: European XFEL beam spreader, FELs (SASE 1-3) and end stations (courtesy of European XFEL)

(2030+) strategic goals, which include:

- Facility improvement (e.g., diagnostics, feedbacks, components)
- Extending facility capabilities (photon energy range, pulse length, spectral brightness, novel sources)
- Superconducting undulators to reach higher X-ray photon energies
- Demonstration of cavity-based XFEL oscillator (XFELO) for transform-limited lasing
- Intelligent process control and robotics
- Advanced accelerator concepts
- SRF technology for high duty cycle (HDC) operation including a new superconducting gun

The facility entered into a Long Installation and Maintenance Period (LIMP) for six months starting June 2025. Along with routine checks, this period included various R&D activities to inform a future upgrade path for European XFEL expected to begin 2030+.

5.3.3 UK engagement

The UK agreed to become a full member of European XFEL in 2014, with the protocol to the convention signed in Berlin on March 19, 2018 in the presence of representatives from the UK government, the German federal government [23]. As part of its membership, the UK agreed to contribute 2 % to the facility construction costs ($\sim$26 MEUR, 2005 price) and 2 % of annual operating costs.

The UK is involved in various collaborations with European XFEL, including the High Energy Density (HED) end station: a collaborative facility developed with significant contributions delivered through the Engineering and Physical Sciences Research Council (EPSRC) and the Science and Technology Facilities Council (STFC). It is a key component of the Helmholtz International Beamlines for Extreme Fields (HIBEF) project which investigates matter under extreme conditions. UK researchers are expected to receive 140 days access to HED in the first five years of operation.

At the heart of the HED end station is the DiPOLE100-X (D100-X) laser: a high-energy, high-repetition-rate laser developed by the UK's Central Laser Facility (CLF) in collaboration with the

University of Oxford. Funded by STFC and EPSRC, the laser delivers up to 100 J of energy at 10 Hz repetition rate. It is used to compress materials to extreme pressures, simulating conditions found in planetary interiors. The laser's output is synchronized with the XFEL's X-ray pulses, enabling detailed analysis of the compressed matter. The first official user experiment utilizing the D100-X laser took place in May 2023. The experiment exceeded expectations, providing high-quality data to over 30 collaborating institutions and marking the successful integration of the laser into HIBEF [24].

The UK Hubs for the Physical Sciences and Life Sciences on XFELs support the UK academic community wishing to access the European XFEL and other international XFEL facilities. The UK's involvement in the HED end station is facilitated through the UK Hub for the Physical Sciences on XFELs, managed by the CLF with support from Diamond Light Source. The hub provides logistical support, funding for consumables, and opportunities for UK academics to engage with XFEL facilities including SwissFEL, SACLA, PAL-XFEL and LCLS, as well as European XFEL. The UK Life Sciences Hub at the European XFEL, operated by the Diamond Light Source, supports researchers in structural biology and related fields. This hub provides essential infrastructure and expertise to enable UK scientists to conduct cutting-edge experiments at the European XFEL. Both hubs provide travel assistance to participate in experiments.

The European XFEL subscription model changed in 2024 from pure shareholding (2.1 %) to 50:50 shareholding to user access. 'User access' is defined here as the proportion of beam time hours (including those accumulated during user-assisted commissioning shifts and preparatory shifts) delivered to users affiliated with institutions in shareholder countries, with the decisive factor being the location of the laboratory/department the proposer is affiliated with (and not the nationality of the proposer). This differs from (e.g.) Figure 5.2a in which total users, as compared to number of associated user affiliations, is plotted. A weighted average of this metric is made over a preceding 3-year period, with values in 2024 and 2025 based on the ranges 2019-2021 and 2020-2022 respectively.

The UK's use of European XFEL as a function of year, calculated by affiliated institution (as above) is plotted in Figure 5.5. Visits increased from ∼6 % in 2018-2020 to ∼9 % 2023-2025, enhanced by a peak of ∼12 % in 2024. The same figure compares user visits with UK's financial contribution to European XFEL operating costs. This includes estimated UK costs for 2026 (based on 2021-2023) and 2027 (2022-2024) based on available data[5].

The 50:50 cost model helps to smooth out fluctuations in cost originating with variation in user visits. The UK's contribution to operating costs in 2024 was ∼7 MGBP. As shown, the UK has consistently paid for a lower fraction of overall operating costs as compared to the level of access received.

The UK has been a member of both the European XFEL Council and Machine Advisory Committee (MAC) for as long as they have been in place. Current UK representation on the MAC is provided by Prof. Deepa Angal-Kalinin; representation on European XFEL council is provided by Prof. Jon Marangos (Science Lead for UK XFEL and Imperial College London) and Helen Beadman (UKRI).

An impact evaluation report commissioned by STFC on UK use of European XFEL was published in 2023 [25]. This report highlighted:

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[5] Costs for 2026-2027 are estimated, as data on the absolute number of users by institution for the relevant date ranges was not available. For the purposes of the calculation, this has been substituted by the total number of individual users, not institution, with the assumption this is approximately proportional to the number of attending institutions.

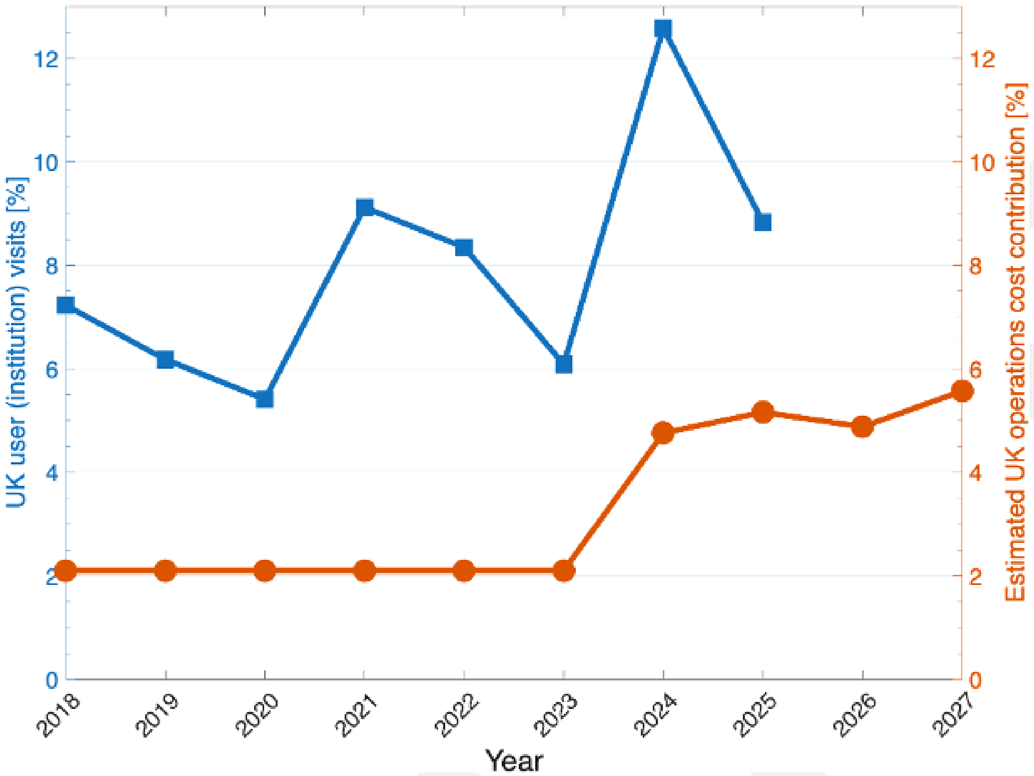

Figure 5.5: UK user visits to European XFEL (left axis, squares), based on number of affiliated institutes (not individual users), compared with estimated UK annual financial contributions as a percentage of total operating costs (right, circles).

- The unique experimental capabilities of the facility which allow UK researchers to conduct scientific investigations not possible elsewhere.
- The multidisciplinary nature of the research performed, which was primarily pure science in nature, but with examples of applied research in areas such as energy management and healthcare, and increase uptake by UK business (e.g., pharmaceutical research).
- The important contribution of the facility to the UK skills pipeline, including training for early-career researchers, and knowledge exchange with international groups.
- Supporting UK access to XFEL capability, which was oversubscribed elsewhere, and ensuring STFC and UKRI could meet their strategic goals on behalf of the UK's research and innovation community.
- Interactions which contributed to wider government policy priorities including alternative energy sources (e.g., nuclear fission), and improving health (e.g., helping to understand new drugs and treatment methods), helping to cement the UK's position as a scientific superpower.
- Increased UK standing via international collaboration opportunities, with all but one of the UK-authored publications including at least one international author.
- Opportunities for UK business, who had won contracts worth 700 KEUR, and further contracts outside of the commercial sector (including detector and laser developments).

The UK XFEL team was hosted by European XFEL management at the start of the project in December 2022, providing an opportunity to tour the facility and allow face-to-face meetings between technical experts. STFC staff have since engaged with several staff exchange opportunities working with DESY and European XFEL colleagues in Hamburg. These exchanges have proven invaluable learning opportunities, particularly regarding experience from European XFEL operations.

The European XFEL leadership team has been highly impressed by the process and the outcome of the science survey carried out by UK XFEL team. Project members Jon Marangos and David Dunning received an invitation to deliver a user seminar to the European XFEL team in October 2024. David Dunning was invited to take part in an internal (by invitation only) DESY/European XFEL High Duty Cycle/CW upgrade workshop, where he delivered a talk focussing on accelerator and XFEL technology, including next-generation requirements outlined by the science and technology case. **This engagement demonstrates UK XFEL is influencing European XFEL upgrade plans.**

As part of a broader collaboration initiated through the UK XFEL project, STFC and European XFEL/DESY are performing joint-research on multiple topics including high repetition rate, low emittance photoinjector & photocathode R&D, beam dynamics simulations, and activities supporting the design of a second fan as part of a potential future upgrade. There is already an active collaboration agreement between STFC and DESY on superconducting RF (underway from 2019) and recently an annex has been added for exchange of consumables to allow the photocathode collaboration on a superconducting RF gun. A generic XFEL R&D collaboration agreement between STFC, DESY and European XFEL is under discussion.

5.3.4 Strategic plans of relevance to UK XFEL

The European XFEL is actively pursuing several strategic upgrades to enhance its capabilities and maintain its position at the forefront of X-ray science. These upgrades span medium- to long-term initiatives aimed at expanding scientific reach and improving operational efficiency.

The facility management is actively planning the development of its two currently empty undulator tunnels, SASE 4 and SASE 5, as part of its medium-term upgrade strategy. These aim to expand the facility's capabilities and enhance its scientific output.

The European XFEL team is exploring the feasibility of High Duty Cycle (HDC)/continuous wave (CW) operation of the linear accelerator to enhance its experimental capabilities. This initiative aims to support a broader range of scientific experiments that require high repetition rates and stable beam characteristics. In addition to CW operation which would lower the electron beam energy (and therefore X-ray photon energy) significantly, a long pulse mode with duty factors between 5% and 50% is under consideration. This mode would provide a compromise between the high repetition rates of CW and the high peak powers of burst-mode operation, suitable for experiments needing moderate repetition rates and higher photon energies.

The team has well-developed and thorough plans to address required R&D for HDC upgrade. A Feasibility and Option Study (FOS) is underway and the report will be published in 2026. The development of CW SRF gun technology is an essential part of this upgrade. The gun R&D is being actively pursued with several prototypes of the gun being built and tested; it is expected that first beams will be produced in the DESY Photoinjector Test Stand in 2027 and CW photoinjector will be ready for installation in the European XFEL by 2030. The European XFEL tunnel has reserved space for the second injector and thus both burst mode injector and HDC/CW injector will be available if preferred by the users. The wider implications (end station, detectors, synchronisation, etc.) are also under consideration.

Space has been reserved to add a second fan on European XFEL to increase the capacity of the facility. The plans for the spreader beamlines and photon specifications are to be developed but are referenced in 2030+ upgrade plans. Some of this work, including consideration of beam distribution with fast kickers, overlaps with discussions underway as part of the HDC/CW mode upgrade. STFC is collaborating with European XFEL and DESY on the accelerator physics design of a potential second fan.

European XFEL is advancing superconducting undulator (SCU) technology as part of its facility development program. This initiative links into broader strategic upgrades, including the potential design of the SASE 4 and SASE 5 beamlines and second fan. There are several key benefits of using SCU; these can deliver the same photon energy range as currently achieved with permanent magnets in CW mode, where the beam energy could be limited to $\sim$7 GeV as compared the current operational energy of 17.5 GeV in burst mode. SCUs will be enable to reach photon energies up to $\sim$60 keV at highest beam energy of 17.5 GeV in current burst mode.

European XFEL has recently demonstrated amplified X-ray light in a resonator cavity (similar to an optical laser) [26]. Cavity-based techniques are capable of delivering high energy, near-transform-limited X-ray pulses with high stability, with first results of the European XFEL X-ray Free Electron Laser Oscillator (XFELO) demonstrating net gain at 6.952 keV with a spectral bandwidth of 0.021 eV. This demonstration opens the path towards applications of the cavity-based techniques for scientific exploitation, not just at European XFEL but at other next-generation facilities.

Through UK's membership of council, membership of the MAC and ongoing active collaborations with DESY & European XFEL, the UK XFEL team will be able to influence decisions impacting the facility's long-term direction.

5.4 LCLS

5.4.1 Introduction

LCLS is operated by Stanford University on behalf of the US Department of Energy, Office of Basic Energy Sciences (DOE-BES). LCLS started operation in 2009 as the world's first hard X-ray FEL, utilising infrastructure from the Stanford Linear Accelerator (1960s), including large sections of the linear accelerator tunnel and normal conducting (120 Hz) radio-frequency linac technology [3].

The capability of LCLS has been continuously enhanced in subsequent years, achieving SASE operation from 250 eV to 25 keV, and multiple world-first demonstrations including attosecond pulse generation [27] and 1 TW peak power X-ray pulses [7].

To maintain the US's world-leading position in X-ray science, in 2013 the DOE BES Advisory Committee (DOE-BESAC) advised the need for the US to construct “an unprecedented X-ray light source” [28]. This light source would have “the pulse characteristics and high repetition rate necessary to carry out a broad range of coherent “pump probe” experiments. In a parallel to the current UK XFEL process, this new light source – LCLS-II – would represent a facility with “a capability that is beyond that of any existing of planned facility worldwide”. LCLS-II would be developed through additional developments within the existing LCLS facility and would share some of the existing LCLS infrastructure.

The LCLS-II project achieved CD-1[6] (conceptual design) in 2014 and CD-4 (first light) was achieved in 2023. It represents a $\sim$1 BUSD investment to deliver the DOE-BESAC recommen-

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[6] The definition of the Critical Decision process is available at https://www.directives.doe.gov/terms_definitions/critical-decision

dation, installing a 1 MHz superconducting continuous operation linac within the existing SLAC tunnel (supported by a new cryoplant), a significantly expanded suite of instruments, and new variable gap undulators for rapid tuning of X-ray energy. It has also upgraded the existing LCLS linac to extend the X-ray energy reach to $>$25 keV. These upgrades have placed LCLS-II on the cutting-edge of X-ray science.

5.4.2 Status

LCLS-II began user operations in 2024. The LCLS-II linac is capable of reaching 4 GeV beam energy, supporting photon energies up to $\sim$5 keV. Initial operations were delayed by two power outages leading to Helium loss from the cryoplant. Prior to shutdown of the superconducting linac for the LCLS-II-HE, electron beam delivery had been commissioned up to a maximum repetition rate of 93 kHz; photon delivery in users runs was being reliably performed at 33 kHz.

Construction of a further 716 MUSD upgrade of LCLS-II – LCLS-II High Energy (LCLS-II-HE) – was approved by DOE in September 2024. LCLS-II-HE will add 23 cryomodules to raise the beam energy to 8 GeV to allow the facility to access X-ray photon energies of 0.25–13 keV. New instruments with improved capability will be added to the near and far experimental halls to further exploit the high repetition rate source. The superconducting accelerator at LCLS started the upgrade to 8 GeV in January of 2026 with plans for first high repetition hard X-ray science in Fall of 2027.

LCLS-II-HE exemplifies SLAC strategy to increase the capability of LCLS through a phased approach. Approval for LCLS-II-HE was contingent on LCLS-II achieving CD-4; further upgrades are linked to LCLS-II-HE achieving a similar milestone.

5.4.3 UK engagement

UK XFEL team members have been actively engaged with the LCLS facility throughout the project. Meetings with LCLS leadership were initiated in 2022 and have continued to date at quarterly intervals. Design team members in the UK have connected with their counterparts at SLAC, beginning with an in-person visit of the UK team to Stanford in November 2023 and continuing online. SLAC has hosted several STFC staff on placement, contributing to LCLS activities and providing an invaluable opportunity to learn directly as during initial operations of LCLS-II.

Several areas of joint research interest have been identified, which are of mutual benefit to STFC and SLAC in both current and future activities. These include:

- Low emittance photoinjectors
- Machine learning and data
- High power lasers and targetry for MEC experiments

At a strategic level, the UK XFEL and LCLS leadership teams are in agreement on the need, definition and impact of a next-generation XFEL facility. At a technical level, STFC staff will continue collaborative activities with SLAC, including placements to support the technical areas listed above.

The 2020 UK XFEL Science Case continues to have a positive influence on the direction of LCLS activities. Members of the UK science team are actively engaged with their US counterparts as part of future-looking activities including community workshops. Engagement with the management team is expected to continue, to ensure a common oversight of planned activities in the US and UK.

5.4.4 Strategic plans of relevance to UK XFEL

SLAC's near and mid-term strategy is described in the LCLS Strategy Plan 2023-28 [29]. It reflects that "...XFELs are still in their infancy and will likely define X-ray science in the 21st century..." SLAC is committed to engaging with the scientific community to define the scientific priorities for XFELs over the next ten years, while driving step changes in source and facility performance. This includes delivering performance requirements for LCLS-II, LCLS-II-HE, and a proposed upgrade of the Matter in Extreme Condition (MEC) instrument focussed on flagship experiments on inertial fusion energy science.

In order to reach very hard X-ray photon energies (>25 keV), SLAC plan to install a second photoinjector parallel to the current supeconducting accelerator photoinjector (including construction of a separate tunnel and cryoplant) which will deliver a significant improvement in electron beam emittance. This Low Emittance Injector (LEI) project has a pre-conceptual cost estimate of 210 MUSD and is yet to enter the Critical Decision process. Preliminary research and prototyping in advanced injector design is underway as of 2025, and will inform the decision to proceed with the project. Photoinjector performance is equally key in enabling the next-generation capability outlined by the UK Science Case, and an opportunity for UK XFEL and SLAC to collaborate.

When fully operational, the upgraded superconducting LCLS linac has the potential to deliver electrons to ten or more independent undulators. Similar to UK XFEL, this is recognised within the US as an opportunity to "...move X-ray FEL science into a synchrotron-like mode of operation..." [29] while incorporating advances in X-ray generation including cavity-based techniques (such as XRAFEL [30]) to deliver transform-limited pulses. Titled LCLS-X, this represents the US vision of a next-generation XFEL. It represents a clear opportunity for US-UK collaborative engagement, as well as an option to deliver many of the requirements of the UK XFEL case.

Ten specialized XFELs (optimised to different science areas) and dozens of instruments will enable multiple parallel experiments that will increase scientific throughput and allow greater access to multiple XFELs for a single experiment. The delivery of the ten undulators would be phased, allowing delivery to adopt new technologies as they became available, and for end stations to be tailored against emerging priority R&D directions.

LCLS-X will involve major excavation to allow the creation of a large beam transport yard, undulator hall, and two new experiment halls. A schematic of LCLS-X including the proposed position of the upgrade with respect to the existing LCLS/LCLS-II facility is shown in Figure 5.6. The concept of LCLS-X was submitted to and reviewed by BESAC in 2024 as part of an activity on new and upgraded national user facilities within DOE-BES. The concept was positively received, with the committee providing the following feedback (taken directly from the report below):

a) LCLS-X is **absolutely central** to future world-leading science because it will dramatically increase the scientific capabilities and output compared to all other XFEL facilities around the world. Currently, the limited number of parallel experiments that can be performed on a single XFEL reduces the impact of XFELs. Further, the ability to host a range of new types of XFEL sources within LCLS-X could provide 100-1,000 fold increase in average spectral brightness compared to LCLS after the high energy upgrade, together with attosecond time scales. These capabilities will enable studies of dilute systems present in nature,

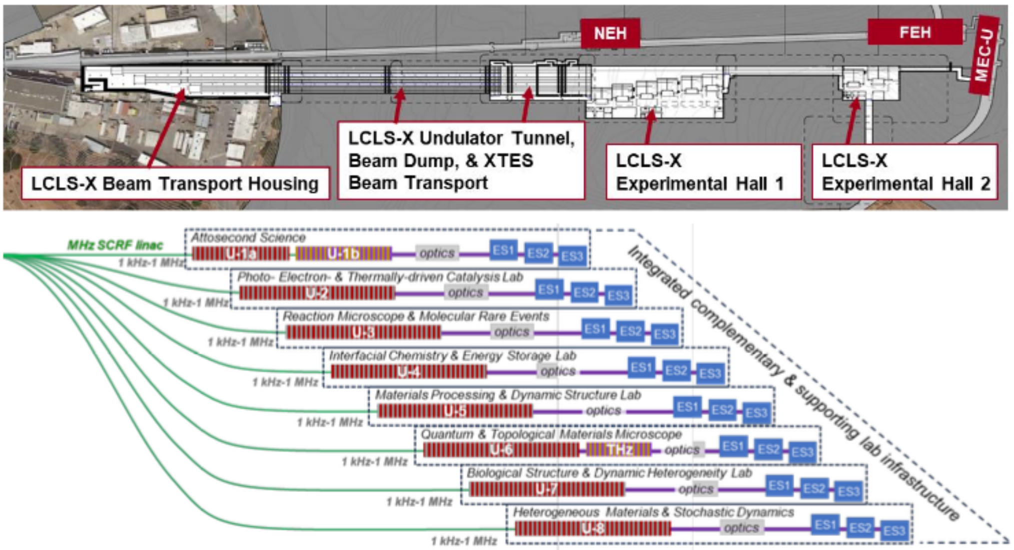

Figure 5.6: Conceptual layout of the LCLS-X facility in a new tunnel (top) and a representative distribution of a suite of new undulators and instruments (bottom). As presented in [31].

under *in vivo* and operating conditions at natural attosecond timescales, while realizing non-destructive 3D imaging on the atomic scale.

b) LCLS-X has **significant scientific and engineering challenges** to resolve before it enters the Critical Decision process (and after the LCLS high energy upgrade is complete) to determine if the accelerator will be sufficiently powerful to feed 10 undulators.

Work on a science case to support a new generation of US light sources (encompassing LCLS-X) is underway. UK XFEL is involved in this process through Science Team lead Jon Marangos. The first two workshops:

- Increasing the durability of energy technologies through the foundational understanding of failure mechanisms
- Driving critical chemical transformations with photons, electrons and catalysts
- Nonequilibrium control of the motion of ions and defects in structural materials and energy technology

occured in 2025 and have delivered completed reports.

There is no current timeline for the LCLS-X project. It has not entered the critical decision process. Completion of the project would require approximately ten years for the design. The LCLS facility roadmap, including planned and proposed future upgrades, is summarised in Table 5.3.

Project	**Date**	**Description**	**Cost [MUSD]**	**Status**
LCLS-II	2023	1 MHz continuous operation, up to 5 keV X-ray photons	$\sim$1000	Complete, in operation
LCLS-II-HE	2028	Additional cryomodules to achieve 8 GeV beam energy, up to 13 keV photons, new instruments matched to repetition rate	$\sim$720	CD3 approved 2024
LEI	-	New photoinjector, ultralow emittance to extend LCLS-II-HE photon energy to $>$25 keV	TBD	Prototyping to inform CD-0 bid
LCLS-X	-	Second tunnel, synchrotron-like operation of ten or more independent undulators, transform-limited pulses, instruments customised by science area	TBD	CD-0 tentatively proposed for 2032

Table 5.3: Summary of LCLS facility roadmap, including current and planned upgrade activities. Based on material submitted to the BESAC "Report on New and Upgraded National User Facilities in Basic Energy Sciences" [31].

6 Socioeconomic analysis

6.1 Introduction

This section explores the means of assessing and evaluating the socio-economic impact of the XFEL options under consideration. It was commissioned by the STFC UK XFEL project team and undertaken by Innovation and Research Caucus (IRC), who are supported through the Economic and Social Research Council (ESRC) and Innovate UK.

To illustrate how the socio-economic impact might differ for the three options, an outline Theory of Change (TOC) for the implementation of a UK XFEL is presented, with variations for an International XFEL and the no additional investment option. The TOC is described through a series of impact pathways, demonstrating that there are, in fact, more than three options to be considered as within each of the three options there are a series of opportunities which could be invested in, and which, if effectively implemented, could augment the overall socio-economic impact of the selected option. In addition, there are choices to be made on when certain activities commence.

The narrative description of the Theory of Change is followed by a section which considers the PESTLE[1] analysis to further understand the factors affecting the choices presented.

The chapter continues by considering the evidence on the rates of return to R&D investments, followed by a section outlining methodologies to evaluate the socio-economic impact of the selected option. A table concludes the chapter, which includes indicators which could be used to monitor and evaluate the future iteration of XFEL.

The purpose of the chapter is to both provide an enabling framework to support decision making on the options for investment, and to highlight factors to consider in developing a business case for the preferred option. It is not intended to provide a full economic options appraisal, which is a necessary next step.

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[1] PESTLE: Political, Economic, Social, Technological, Legal, Environmental.

6.2 Assessing Variations to Impact: Theory of Change

In designing a new policy or programme, a Theory of Change (TOC) helps to understand how planned inputs[2] and activities[3] will lead to the desired outputs[4], outcomes[5] and impacts[6]. A Theory of Change is a full description, while a Logic Model visually represents the TOC and the theoretical progression from inputs to outcomes.

Focusing on the socio-economic impact[7], this outlines a TOC of the three options under consideration in the future of XFEL:

1. Development of a UK XFEL, drawing in investment in the range of £2–3 billion (**Option 1: UK XFEL**).
2. UK contribution, of around £750 million to £1 billion, to an internationally-based XFEL (**Option 2: International XFEL**).
3. Current spending commitments and contributions to existing facilities (**Option 3: no additional investment**). The theory of change for the no additional investment is defined by the recent evaluation of the European XFEL [32].

In the discussion it is important to note that the examples provided are intended to evidence how relationships between activities, outputs and outcomes (the theory of change) have been described in evaluations of similar research infrastructures. The examples are not intended to demonstrate relative advantages of one option over another. A full economic options appraisal comprising a meta-analysis would be required for this, which would take account of differences in research centre design, purpose and investment, and differences in evaluation methodologies.

As stated above, there are more than three options in the implementation of XFEL. Expenditure need not just be on facilities and R&D. There are other activities which could be conducted to augment the impact of the facility. These activities would theoretically affect the socio-economic impact, and they are presented in the TOC and Logic Model, alongside infrastructure and research, as a series of impact pathways:

- Infrastructure (build and maintenance)
- Research and Development
- Financial management
- Workforce Development
- Developing businesses and sectors
- Fostering collaborations
- Public engagement

Within this description of the TOC, each impact pathway is discussed in turn, with the potential implementation of Option 1 considered first, and variations drawn out for Options 2 and 3.

This narrative assumes the activities are being conducted to a scale and quality that will deliver the expected outputs and outcomes and that interdependencies are deliberately and

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[2] Inputs: the resources committed to the programme.
[3] Activities: the things done with those resources.
[4] Outputs: the direct products of activities.
[5] Outcomes: the changes resulting from outputs.
[6] Impacts: the longer-term, broader effects.
[7] Socio-economic impact: effects on society and the economy.

successfully leveraged (e.g., activities to Develop businesses and sectors are aligned with Research and development, Workforce development and Collaboration activities). Interdependencies are widely recognised in the literature. For example, in writing on the role of large research infrastructures for regional innovation, Crescenzi and Piazza note:

> *The generation and diffusion of new knowledge in national, regional, and local economies depend not just on efforts and investment in research and development (R&D). Evidence suggests that this type of investment can enhance regional innovation only when coupled with a supportive endowment of human capital and other systemic conditions* [33, pp. 14–1].

The TOC takes into account some externalities and highlights these throughout, though this is not a full consideration of all potential (positive and negative) effects on third parties. Nor does the TOC provide a full risk assessment, which would require further consideration (e.g., availability of materials or skilled labour, sustained political support).

The descriptions which follow are based on a combination of evaluation guidance issued by the Government (The Magenta Book, HMT [34]), other evaluation guidance issued by relevant government departments and evaluations of research, innovation and workforce development programmes.

6.2.1 Infrastructure (Build and Maintenance)

Pathway Description

This impact pathway encompasses the design and build of the asset, longer-term maintenance and enhancement.

Option 1: UK XFEL

The initial activity is the design and build of the asset. This requires close working between the scientific and industrial communities, which will build on existing expertise and collaborations. The businesses with the required know-how to build the infrastructure and manufacture the equipment for UK XFEL may not be located in the UK or in the selected UK region, so it should not be assumed that all design or manufacturing activity will be in the UK, though assembly and construction will be.

The build would generate significant (economic) activity in the chosen location including jobs in the construction sector (see also discussion in Section 6.4 on timing of economic value [35]). Highly skilled jobs would also be generated in the supply chain such as legal services, sourcing of raw materials, engineering sector and design and manufacture described above (these will all be non-location specific). There would be a measurable number of direct and indirect jobs generated from the build as an initial short-term output, alongside the delivery of the asset itself.

Workers employed in the initial build may be able to secure improved employment through their experience, generating a positive medium-term outcome. This will arise through the accumulation of specialist human capital.

Medium-term outcomes might also be derived from the firms procured, which are able to use this experience/innovation to grow capacity and enhance reputation to secure other work and longer-term business benefits. Although as noted above, these firms will not necessarily be in the UK.

As the facility becomes established, other sectors in the locality might benefit from local employment of highly skilled workers through their spend in the local economy (induced effects), presenting a positive medium-term outcome. Although, if not properly planned for, it may also lead to less positive outcomes, such as rising house prices and pressures on local school and medical services. It follows that the locational choice will fundamentally impact on these potential benefits and costs at the local level. A current example would be the effect on Jaguar Land Rover skilled workers relocating to Warwickshire on local rental and housing availability and prices.

The outcomes for UK firms and workers could yield positive longer-term economic impacts through increased tax revenues. A better skilled individual also enjoys improved health outcomes [**Garrett2010**], has higher work attendance, and superior productivity, thus reducing costs in other parts of the public sector.

The immediate location may also further benefit from a UK XFEL if the facility attracts businesses to locate nearby to maximise use of the facility and benefit from opportunities to network with experts, thus potentially attracting a sectoral cluster to the location. For example, the evaluation of the Hartree Centre reports that the Centre has been ‘influential’ in attracting new tenants to the Sci-Tech Daresbury Campus, in which it is located. However, the evaluators ‘did not feel confident enough in the links between the centre and the growth of the campus to claim any part of the economic output or employment of tenant firms’ [36, p. 31].

Other research would also suggest the co-location of spinouts or spin-offs, or re-location of existing firms nearer to the UK XFEL, is not guaranteed [33]. Existing businesses may choose to stay in their current location, in another region (nation) if there is sufficient ‘cognitive proximity’[8] to the UK XFEL and the cost of relocation is prohibitive. New businesses also may not need to co-locate for the same reasons. Those which do relocate might be displacing economic activity from another region as has been argued for freeports.

In addition to these economic impacts, the infrastructure pathway should also deliver a well-designed facility which would add to the overall UK stock of facilities within the UK R&I system.

Option 2: International XFEL

As described in Option 1, some of the design and manufacture activities could be undertaken in the UK, depending on expertise and procurement outcomes. Therefore, UK firms and their workers may benefit from these opportunities. It may also be the case that there may be the potential for skills and knowledge transfer from specialist firms outside of the locality to indigenous local workers. However, UK workers are less likely to be employed (at scale) in construction, for example, than if XFEL is in the UK. The example of the ITER illustrates that a ‘significant share’ of the 2.25 billion Euro has in-kind contributions had gone to contractors in France – the host nation and largest contributor [37].

The UK would not benefit from local medium-term outcomes associated with the build and ongoing use of the infrastructure.

In terms of impact, the UK may benefit from the growth of new firms or sectors based on the science, if the UK is able to attract new firms, based on the science, to locate here, but this would seem less likely than in Option 1.

The evaluation of CERN illustrates the theory of change for an international XFEL. For example, CERN membership gave UK companies access to contract opportunities, with around 500 UK firms having sold goods and services to CERN in the past decade leading to additional revenue

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[8] Cognitive proximity: the degree to which actors share the same knowledge base, facilitating knowledge transfer.

for those firms and supporting employment. UK suppliers were also reported to realise wider benefits, beyond the value of the contracts themselves: through the development of innovative technologies or access to new market opportunities and through the prestige bestowed on CERN suppliers which aids new sales. Half of UK suppliers reported that CERN contracts had resulted in an increase in other sales income, and the evaluators estimated that a further £1bn in turnover and £110m in profit has been supported amongst UK suppliers in the past decade, on top of the direct income received through contracts [38]. For reasons stated above, it is not possible to draw comparisons between this level of impact and other evaluations. The example serves to illustrate the relevance of the theory of change.

Option 3: No Additional Investment

The evaluation of European XFEL [32] reported UK financial inputs to the facility of 2% contribution to the construction costs and an annual 2% (around 3 million Euro) to the operational costs. No data is provided on UK firm involvement in the construction; however, between 2018 and 2020, 65 UK based suppliers had won contracts worth 700,000 Euros (activity). The report states these contracts have helped enhance the reputation of UK suppliers and improved the country's skills base[9] (outcome). STFC has also secured contracts to provide equipment.

Timing

These will be the first activities, outputs and outcomes, delivering outcomes (such as business growth for firms involved in the build) before R&D activities have commenced. Whilst design will commence in Year 1, there is potential to prepare UK firms, which might be well-placed to bid for design contracts, ahead of this. A rolling programme of then preparing UK firms for machine build, civil construction, etc., could then take place, regardless of whether Option 1 or 2 is selected. Outputs (e.g., jobs) from the design phase should be evident in Year 1, with outcomes for workers and firms in the design phase likely to be evident at least one year later.

Jobs in construction and in the locality will start to be realised on commencement of construction in Year 4 with similarly deferred outcomes.

The Hartree Centre evaluation reported four years after the opening of the centre and indicates that attraction of firms to the area can happen within that time period, by Year 17 in the case of UK XFEL [36]. A further illustration of the timing of economic impacts of an infrastructure project is described in Section 6.4.2 below for ITER.

6.2.2 Research and Development

Pathway Description

This impact pathway encompasses the research and development activities to be undertaken in the XFEL option and the economic impact of scientific enhancements and societal benefits. This does not include innovations associated with the design and build (see Section **??**) but is focused on the scientific output and so will fully commence when the facility is opened.

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[9] See [32] for further detail on skills outcomes.

Option 1: UK XFEL

The activities under this strand are the R&D activities which would be undertaken at the UK XFEL consistent with a large-scale, world-class facility. After construction, UK XFEL may employ direct researchers; otherwise, activities would be conducted by academics or industry staff, domestic or international, with benefits experienced across users.

Research and development activities could lead to knowledge outputs, such as publications, patents or spinouts, which in turn could lead to medium-term knowledge outcomes, such as an increase in scientific knowledge (including attracting/retaining staff in UK), citations of publications, and new or improved technology, processes, products or services.

The benefits of research and development activities could be experienced in the UK or abroad. Even if research is initially conducted by a UK body, it is not necessarily the case that outputs, outcomes and impacts will be generated for the UK. These factors would need to be considered in monitoring and evaluation.

However, overall, the impacts of this activity could be an enhanced UK R&I system, economic impacts derived from more competitive businesses and sectors and societal impacts from the implementation of scientific advances (such as improved health or environments), which in turn might deliver further economic impacts.

The evaluation of the Diamond Light Source [39] illustrates the theory of change for R&D, e.g. by measuring use of the centre as an activity; the publications of articles as outputs; improvements in knowledge, skills and capabilities as outcomes for users; and patent valuation as an example of economic impact.

Option 2: International XFEL

Some of the socio-economic benefits described in Option 1 may be realised for the UK if users (academic or industry) of an International XFEL are UK based. The evaluation of ESRF [40] illustrates this theoretical relationship between scientific activity and publications by reporting that the proportion of UK publications linked to ESRF at 17% is higher than the UK's shareholding.

However, access to the XFEL would be reduced in comparison to a UK centre by virtue of ease of access and the benefits would not be so enmeshed across the R&I system.

Societal improvements from the scientific advances ought to be realised as knowledge is shared but may impact more slowly in the UK, depending on technology adoption.

Option 3: No Additional Investment

The European XFEL evaluation [32] detailed a pathway from UK researcher activity at the facility to outputs and outcomes. For example, it reports there have been 86 UK users since 2017 and in terms of outputs, UK researchers have been involved in 150 publications linked to European XFEL.

Qualitative outcomes are illustrated through examples of new knowledge generated through use of the facilities, which would not otherwise have been possible. Similarly, examples are provided of impacts which focus on scientific contributions to UK government priorities (e.g. facilitating research that can help explore alternative energy sources). The evaluation also explored with users whether European XFEL has helped to attract and retain skilled researchers and engineers to the UK.

Timing

The maximum timeline suggests the start of early science in Year 13. The Hartree evaluation [36] reported, for example, 167 industry projects within the first four years of operation and commercial economic benefits to users reported in this time frame, thus by Year 17 in the XFEL timeline.

6.2.3 Finance / Financial Management

Pathway Description

This theme encompasses activities to ensure effective management and spend of resources and the generation of future and on-going resources.

Option 1: UK XFEL

UK XFEL may dedicate resources to the effective management of finances. Activities could encompass managing the initial capital (and revenue) investments to ensure they are effectively spent, applications for further public sector funding, fundraising in the private sector, developing a network of (potential) investors and promoting R&D developments, licensing opportunities and so on.

Activities in this strand should include monitoring and evaluation activities across the facility as a whole.

Effectively delivered, these activities could lead to on-going public and private revenue streams (shorter-term outputs) and improved funding levels (medium-term outcomes). Effective management and on-going evaluation ought to ensure improved impacts of the UK XFEL, as funding is secured, which attracts and develops talent, who deliver high quality research and innovation outputs, aligned to a market or social need. The potential role for the British Business Bank regional funds should be considered here.

The Hartree evaluation [36] reported £1m in grant and other income in the first four years of operation and the securing of phase 3 government investment.

Option 2: International XFEL

The UK is unlikely to be directly involved in financial activities to manage existing or generate new funding. However, funding/supply opportunities could be promoted, and the UK may still liaise with potential UK-based investors, which may then reap financial rewards for the UK.

Option 3: No Additional Investment

No data is provided in the European XFEL evaluation report [32] pertaining to this activity, perhaps because no specific activity to drive additional financial output and outcomes is undertaken within the UK (or was not evaluated).

Timing

Effective financial management should begin as soon as finance is committed, and possibly networks of financial investors should be engaged from the outset.

6.2.4 Workforce Development

Pathway Description

This impact pathway encompasses activities to develop the R&I workforce and other educational opportunities when the XFEL is operational. This does not include workforce development of those involved in the build (see Section **??**).

Option 1: UK XFEL

UK XFEL would likely develop the R&I workforce and enhance skillsets through use of UK XFEL facilities and other workforce development activities. Immediate outputs may include measures of the training activity undertaken (such as number of courses and PhD students) and medium-term outcomes may include enhanced skills in academia and business.

A better educated workforce would lead to improved impacts within the R&I system; firms and sectors would benefit from having access to a higher skilled workforce and societal impacts would be enhanced through improved research and innovation, and in the longer-term higher productivity.

The evaluation of the Diamond Light Source [39] illustrates the theory of change for workforce development. It reports on a range of development activities, including training events, as activities; numbers of attendees are recorded as outputs; outcomes include encouragement of careers in STEM. The impact reported in this example is the value of free training offered.

Option 2: International XFEL

UK users are likely to develop their skills with spillovers in their own institution or firm. For example, the evaluation of the ESRF [40] reported that a senior researcher would take a team of 2–3 early career researchers with them when they visited the facilities. No records were kept of the scale of this development opportunity and inferences were made that ‘many early careers researchers are likely to visit ESRF and in turn benefit from the skills development opportunities it provides’ (p. 22), but what is important for this discussion is the theory that use of the facility will enhance skills.

However, given likely higher costs associated with such visits compared to a UK XFEL, development opportunities for other businesses, academic staff and students are likely to be fewer. Potential outcomes of improved skill levels within the sector and within the academic community are therefore not as likely to be realised as under Option 1.

Option 3: No Additional Investment

The evaluation of European XFEL reports STFC funded scientists to take PhD students with them to conduct experiments at the facility, which seems to be the only specific workforce development input and activity. Other skill development is derived from usage of the facilities with a survey of users exploring impact on their own skills (output) and reported impact on the scientific community more generally (outcome).

Timing

Development of R&I staff and training opportunities will not commence until the centre is fully open, but enhancements to skills are likely to begin as soon as users engage.

6.2.5 Developing Businesses and Sectors

Pathway Description

This impact pathway encompasses the activities which could be undertaken to support businesses and sectors to optimise the value of scientific advancements. Some of this activity (e.g., sector development) should begin as soon as funding is agreed, allowing a clear lead into the development of the facility; others may commence as it is in development (e.g. access to experts).

Option 1: UK XFEL

UK XFEL might undertake specific activities to develop business. This might be in funded access to infrastructure, facilitating connections to experts or finance or in access to support such as Knowledge Transfer Partnerships. Shorter-term outputs from this activity at firm level might include new products or services [36], new intellectual property and new start-ups, leading to increased turnover, employment and efficiency (outcomes).

Wider activities to support sectors might include engaging regulatory/government bodies and influencing scientific and sector development, leading to sectors better positioned to take advantage of scientific developments. Outcomes for developing sectors might include stronger or new supply chains, better decisions by government and regulators and a stronger, more collaborative sector [41].

Impacts from this pathway could include improved firm and sector performance measures (such as turnover, employment, exports and inward investment). Again, the Hartree Centre evaluation reports estimates of net economic impact of up to £27.5m in commercial benefits to users [36], illustrating the theory of change from business engagement to economic impact.

Further, there may be knowledge spillovers to other sectors. [42] has highlighted how spillover effects occur in a recent paper exploring the pathways from R&D investment to growth. He reports that in addition to the immediate recipients of public support for R&D, there is also consistent evidence of the positive benefits of spillovers both to innovation (in other firms) and productivity, occurring through three main mechanisms (Figure 6.1):

- From firms' innovation activities ('process spillovers') which lead to the introduction of that innovation in other firms. This may be due to knowledge leakages, imitation or demonstration effects, knowledge-base effects or work through increased R&D productivity.
- From the innovation itself ('innovation spillovers') which may influence both innovation and productivity in other firms and occur either through supply chain linkages or – potentially negative – competition effects.
- Spillovers ('labour market spillovers') may also occur through the labour market as knowledge moves between enterprises as a result of job changes.

Studies also suggest factors which may intensify or reduce the effect of innovation and productivity spillovers in any given context. Two factors in particular stand out as important in the context of UK XFEL:

- Strong connectivity and co-location between assisted and other firms supports stronger spillovers.
- The level of absorptive capacity of recipient firms (with the UK ranking lowly on this in the annual Global Innovation Index[10]).

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[10] Global Innovation Index, WIPO annual publication.

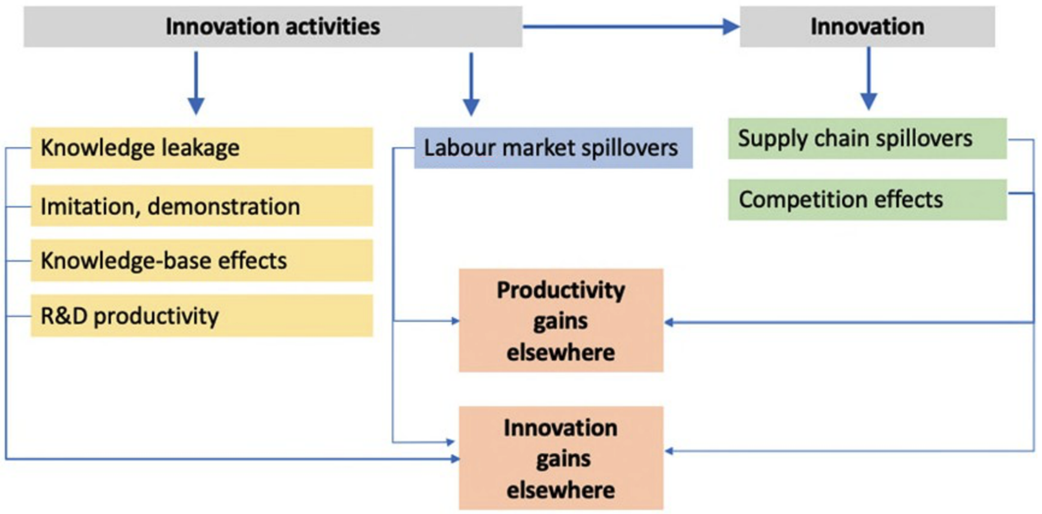

Figure 6.1: Spillover mechanisms [42].

Business and sector development activities by UK XFEL could, therefore, include a focus on enhancing absorptive capacity and widening spillover effects.

Option 2: International XFEL

The possibility of facilitating UK business access would still exist, as would opportunities to integrate with business support activities, but these efforts might be less successful without control of access to the facilities and because of the distance to the facility, as in other impact pathways.

Consequently, outputs, outcomes and impact would be reduced. Businesses which do successfully engage with the facility may relocate nearer to the new facility to benefit from any cluster which may arise (if geographical proximity is an advantage).

Option 3: No Additional Investment

No data is collected by European XFEL to measure business use [32], but an example is provided of a UK business which expects to introduce a new product (output) with associated sales and revenue at least partially attributable to its use of European XFEL (outcome). No sector development activities are reported.

Timing

Business development activities, associated with the science rather than the build, are likely to begin to some degree as soon as the XFEL choice is announced, ensuring relevant businesses are aware of the opportunity and might perhaps plan their own R&D activities accordingly. Less engaged businesses might need to see something more tangible, so wider engagement could commence deeper into the construction process. Similarly, the development of sector activities could follow the same staggered approach. The Hartree evaluation [36] shows engagement with 55 UK based clients four years after first opening, including SMEs, multi-nationals and universities.

6.2.6 Collaborating

Pathway Description

This impact pathway encompasses activities which could be undertaken to foster connections between businesses and academics and within the R&I system.

Option 1: UK XFEL

Activities to bring people together could lead to new or improved partnerships and consortia, working together to produce multidisciplinary and international publications (outputs). Although the Diamond Light Source evaluation records the number of formal scientific collaborations as an activity within a ‘Collaborative activities and ventures’ pathway, it does not go on to record outputs of this activity [39].

Medium-term outcomes might include increased levels of cooperation between firms, increased engagement with the facility, stronger networks for individuals and better-quality innovations.

As collaboration brings skilled and knowledgeable people together to enhance the scientific endeavour, this should yield positive impacts to the UK R&I system; economic benefits to firms and sectors and improved societal benefits. For example, the baseline evaluation of the Hartree Centre reported 100 collaborative projects with UK companies, with consultees reporting they expect to see an increase in sales as a result of their collaboration with the centre. Consultees also report that the centre is making contributions to innovative capacity, visibility, reputation and international competitiveness of its clients and users [36]. This example illustrates the theoretical pathway from collaboration to business outcomes.

Option 2: International XFEL

The opportunity to instigate connections and collaborations would be reduced in an international XFEL. The possibility of promoting the facility and convening UK (and wider) academic and business experts would still exist, but these efforts might be less successful due to access and distance.

Outputs, outcomes and impact would therefore likely be at a smaller scale.

Option 3: No Additional Investment

The evaluation of the European XFEL reports no specific activities regarding the promotion of collaboration, but reports outputs of collaboration in that 65% of publications are multi- or interdisciplinary and all bar one of the UK authored publications have at least one international partner. Further, users report positive outcomes as international networks and relationships were strengthened by their use of European XFEL. This illustrates the theory of how collaboration activity might deliver collaborative outputs and outcomes.

Timing

This could begin at any point following agreement of funding, preparing to take advantage of the opportunities available, but is likely to be more effective and impactful as the centre becomes more tangible and is preparing to open.

6.2.7 Public Engagement

Pathway Description

This impact pathway encompasses activities to engage the public and promote science to the wider community. Some aspects of this will begin before agreement of funding (e.g. engagement of local stakeholders if Option 1 is pursued), but other engagement is likely to be dependent on tangible demonstrations of progress or visits to the facility.

Option 1: UK XFEL

STFC have published an evaluation framework for public engagement, including a Theory of Change, which has informed this section, along with the Diamond Light Source evaluation [39].

UK XFEL may choose to embark on an active programme of public engagement, welcoming visitors, facilitating open days, online events and work experience opportunities. More specific activities locally might include active engagement with local councillors and other stakeholders, ensuring they are heard in the design, build and operation of the facility. Media engagement would also fall into this impact pathway.

Effective activities might deliver short-term outputs in terms of measurable engagement activities and medium-term outcomes of, e.g., a greater interest in STEM careers.

Longer-term impacts of these activities could include increased scientific awareness in general, improved favourability to the facility and scientific processes and enhanced quality of life for local residents, through close collaboration with civic stakeholders.

Option 2: International XFEL

The opportunity for public engagement is likely to be reduced, with perhaps some opportunities for school visits or online engagement events.[11] Media activities, using UK users (and results) as examples, could support the implementation of societal impacts.

Option 3: No Additional Investment

No public engagement activities or associated outputs and outcomes are reported in the European XFEL evaluation.

Timing

In the event of Option 1 being selected, public engagement in the locality selected is likely to have commenced prior to the announcement of the decision. Broader public engagement in the locality might also begin at the outset and media activities might include regular updating of the design and build process. This is not likely to be necessary if Option 2 is selected. Engagement with schools etc. is therefore most likely to commence on or close to opening of the facility.

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[11] For example, schools engagement events delivered online.

6.2.8 The Logic Model

The XFEL Logic Model, Figure 6.2, summarises the narrative TOC above. It visually demonstrates the capital and non-capital inputs to XFEL, enabling activities which, as discussed in the TOC, should deliver desired outputs, outcomes and impact along impact pathways. The arrow in the lower section of the Logic Model illustrates:

Outputs will be evident in the shorter-term, but outcomes and impact in the longer-term. As indicated in the TOC narrative, the timeline for each impact pathway varies, with different start dates and with outputs, outcomes and impacts taking different lengths of time to materialise (and be measurable), even within the same impact pathway. Outputs can be more demonstrably measured and attributable to the activities, while outcomes and impact are less attributable and require evaluation techniques to identify, for example, displacement (has XFEL reduced economic activity elsewhere?) and deadweight (would outcomes have happened anyway?). These techniques are considered in Section 6.5 below. As suggested throughout this section, the extent to which each of the boxes (impact pathways) is relevant will depend on choices of which activities are progressed.

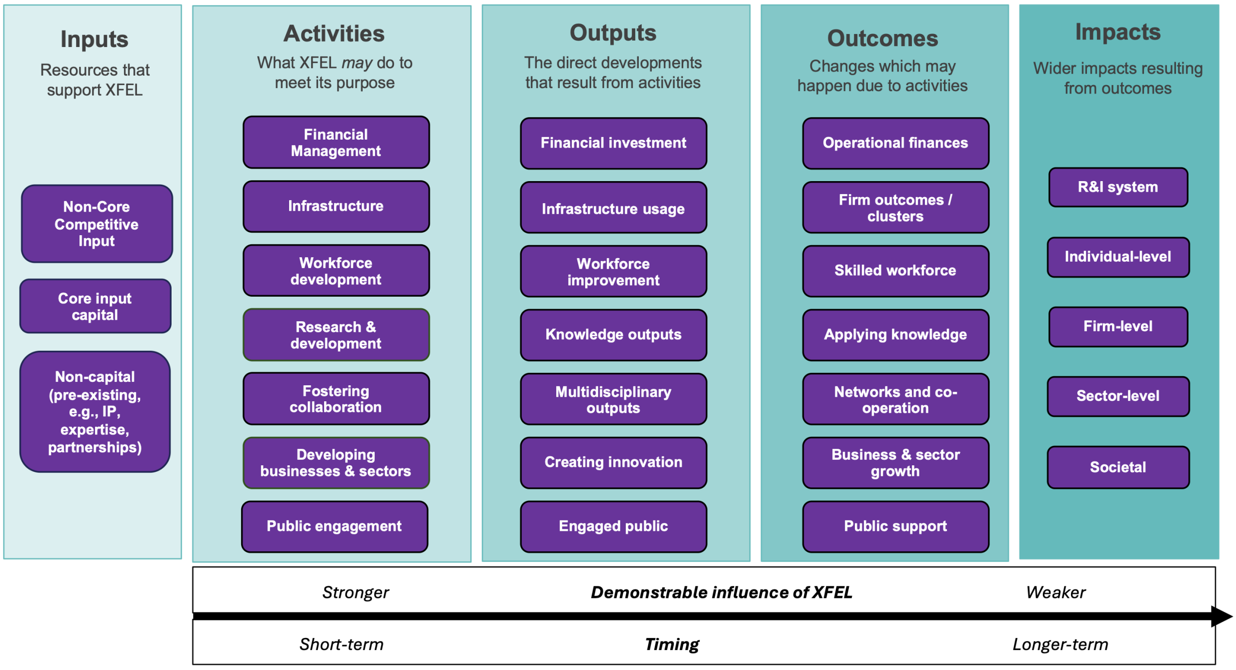

Figure 6.2: XFEL Logic Model

The description of the TOC suggests the scientific and socio-economic benefits might be quantitatively or qualitatively enhanced through effectively co-ordinating activities across the impact pathways and viewing the opportunity systemically. This means that there are not just three options, but within Options 1 and 2, there are multiple choices to be made in determining investment in activities other than infrastructure and R&D.

Further, within Option 1, there is the decision to be made about the precise location within the UK, with considerations about the importance or not of geographical proximity to existing expertise being just one factor to consider, alongside other scientific, social and economic imperatives.

In reviewing the evaluation of European XFEL to inform the TOC of the No Additional Investment (Option 3), it would appear that the UK has not made significant investment in non-R&D activities. But this need not be the case for an enhanced International XFEL and the TOC suggests if it did (as described in Option 2), it might yield different results.

However, while the same set of activities could be undertaken for both a UK and International XFEL, ease of access and control would mean inputs and activities will be greater in the event of a UK XFEL, with corresponding greater outputs and outcomes.

Therefore, overall, Option 1 is likely to deliver greater benefits to the UK than international options. Clearly, this would require much greater investment from the UK. The next section explores evidence on the rates of returns to R&D, and in particular, large research infrastructure investment.

6.3 PESTLE Analysis

In understanding the factors affecting the choices between Options 1–3 there is value in undertaking a PESTLE analysis. A PESTLE analysis represents a simple framework through which external factors affecting a business, or here a major scientific infrastructure project, might be understood. The elements considered in a PESTLE analysis include:

- **Political:** factors such as government policy that could impact the development and operation of an XFEL facility, or the choice between the development options.
- **Economic:** factors such as domestic and international growth projections, inflation, labour market conditions etc. that could affect the choices between Options 1–3.
- **Social:** factors such as public attitudes, demographic changes, consumer trends that might affect choices between a UK-based XFEL investment and alternatives.
- **Technological:** factors that might affect the operation of scientific infrastructure such as new invention, and innovation in the ways in which research is carried out.
- **Legal:** laws and institutions that affect the development and operation of scientific infrastructure, or differences in legal frameworks between different states that affect the choices between Options 1–3.
- **Environmental:** factors such as environmental conditions affecting development and operations of scientific infrastructure.

A PESTLE analysis is particularly useful given the long time-scales connected with the development and construction that might, for example, be connected to Option 1 – UK XFEL. The PESTLE analysis can then bring to light factors that could impact on the long-term outcomes and impacts associated with different options.

Ideally a PESTLE analysis is undertaken in close collaboration with the project stakeholders. In this case the PESTLE is developed in terms of the external factors which XFEL stakeholders might consider and then how these factors might link through to the outputs, outcomes and impacts covered in the logic model and theory of change. The analysis then considers the Importance that might be associated with each factor and then its relevance to the scenario Options 1–3.

This PESTLE analysis is undertaken at a high level and the individual factors are not weighted in terms of their impact on the decision process between Options 1–3. This represents a start to an analysis, and with stakeholders perhaps identifying some of the factors as irrelevant and replacing them with others through time. It is accepted that some of the interim conclusions on factor importance and relevance to the different Options will be contested; however, that is part of the process of undertaking a high-level PESTLE analysis.

The PESTLE is presented below, and then with some headline commentary on the individual groups of factors.

6.3.1 Political Factors

The factors outlined under the Political heading include those linked to government decisions on trade, immigration and labour markets. For example, over the time-scale being considered for Option 1, it is likely that there could be a series of changes in UK Government and with policy towards the UK's main trading partners possibly changing. This could, for example, be important in respect of Option 1 where restrictions on free movements of labour affect the UK supply side during both the construction and operation of a UK-based XFEL.

Political factors are not restricted to UK actors. Geo-political tensions have increased markedly, and with this potentially affecting choices in Option 2, not least in respect of XFEL international locations. Other factors considered under the Political heading include issues of continuity in political decision making and UK Government spending priorities. As highlighted above, each identified factor is given an Importance rating and then, in summary form, how far the identified factor might link to the Options appraisal. So, for example, high importance in this analysis are associated with public spending pressures and the continuity process in government decisions around major infrastructure. In both cases this could be seen to make the No Additional Investment scenario under Option 3 more likely.

However, examination of the individual identified factors shows that the majority would need to be factored into consideration of each Option. For example, increasing global geo-political tensions are relevant to all Options 1–3.

6.3.2 Economic Factors

There are interconnections between the selected Political factors and the Economic factors in the PESTLE analysis. The focus in the PESTLE annex is largely around UK economic factors and with these expected to have a bearing on the availability of public funding which is a critical differentiating factor in Options 1–3. It is difficult to forecast longer term UK economic growth prospects, but the current economic situation is very much low growth, high uncertainty, and with continued poor UK productivity growth. Current economic growth projections are expected to place pressure on public finances until the end of the current parliament, and this in turn restricts the amounts of public money available to support R&D infrastructure. The PESTLE annex shows that this might be seen to be very relevant for choices between Options 1 and 2. Were the availability of public finances to tighten further there would be more pressure to maintain the 'No Additional Investment' Option 3.

The economic factors identified link through to the critical issue of the effective use of scarce public money to develop the infrastructure. While the Theory of Change model (presented earlier) seeks to connect grant funding to outcomes and impacts, this does not necessarily reveal whether the strategic infrastructure would be an appropriate use of the public money. XFEL stakeholders need to be mindful of deadweight in terms of the outcomes and impacts that would occur anyway and how far such deadweight assumptions are served under scenario Option 3. There are also subtle issues of displacement to consider. The economic deadweight and displacement effects will vary considerably between the three options. For example, a discrete UK XFEL facility under Option 1 might work to displace more opportunities for related UK scientific infrastructure than would the No Additional Investment scenario under Option 3.

Economic factors considered here also embrace the strength of the UK supply side in terms of labour and construction engineering. For example, identified limits on the availability of UK construction engineering skills could have direct ramifications on the choice to develop a discrete UK facility under Option 1, compared to making direct contributions overseas under Option 2 which would reduce pressures on the domestic construction engineering sector. This factor might be understood as favouring Option 2 where less burden is placed on the UK supply side. Similarly, the future state of the UK economy would be expected to impact upon UK industry growth and with this then affecting how far UK industry can engage with a UK-based XFEL project.

6.3.3 Social Factors

While political, economic and technological (see below) factors might be uppermost within the XFEL Options appraisal, there are a series of Social factors that might be considered. Potential factors include the challenge of demonstrating the relevance of an XFEL facility and related research, or spending on a facility/capacity at home/abroad, to a wider public stakeholder group. This can be inter-linked with social approval (or otherwise) of the type of research being supported by an XFEL facility. A further factor identified here is wider public/stakeholder understanding of the XFEL business case and its relevance to socio-economic needs. Societal benefit might vary between the different Options. For example, stronger public understanding of the strategic relevance of XFEL-related research, and the attendant local economic development benefits, might be very relevant to an appraisal under Option 1 and a discrete UK facility.

Under the social heading the PESTLE table also lists factors which could impact the operations of an XFEL facility. For example, changing patterns of remote working might affect the operations of an XFEL facility, while changing UK consumption patterns could work to change the research priorities of an XFEL facility whether placed in the UK economy or overseas.

6.3.4 Technological Factors

To a large extent the XFEL proposals result from changing technological requirements from private and public sector user groups. A series of Technological factors also affect future choices between Options 1–3. Factors here include the potential redundancy of XFEL facilities following future technological innovation, but also the impacts of technological development in ‘competing’ XFEL facilities. Option 1, in particular, represents high levels of sunk costs in a specific asset (an asset with few alternative uses) expected to be operational for many decades. So the redundancy factor in the wake of high upfront capital costs is an important issue in terms of risk.

There are also related factors in terms of the significance of the scale of developed facilities in gaining the expected outcomes. Technological factors that increase uncertainty might, for example, be seen as strengthening the case for Option 2 and contributions to an international facility as this represents a form of risk sharing, particularly through the higher risk facility development process. With respect to the facility scale factor there is an implicit assumption that XFEL activity under Option 1 would be sufficient to deliver the outputs and outcomes in the presented logic model. Also relevant to questions on facility scale would be how far related/competing operational facilities in Europe and the US are working at full capacity. Inevitably slack capacity in related facilities could reduce the demand placed by users on a discrete UK facility under Option 1 and then be a factor in strengthening the case for Option 2. Finally, longer-term changes in the technological demands of UK users are categorised here as of high importance and then a factor perhaps favouring more risk sharing and time-share flexibility (i.e. the UK contributing to a larger international XFEL project under Option 2).

6.3.5 Legal and Regulatory Factors

Options 1–3 have a series of geographical implications. Option 1 focuses on a discrete UK XFEL facility under the auspices of UK regulations in respect of patenting law (and protections), health and safety laws, employment laws and fiscal regulations in terms of factors such as R&D tax credits for businesses. Were contributions made to an international XFEL facility under broad timeshare arrangements then research would be undertaken under a different regulatory and institutional framework. It is difficult to disentangle what are very complex regulatory factors but in the PESTLE table we identify a series of high-level legal and regulatory factors that would be relevant to the Options appraisal.

For example, were a UK-based XFEL facility preferred (Option 1) then there is a question on the acceptability of UK regulatory frameworks to potential international users, and vice versa were Option 2 to be preferred. Here UK users would need to consider regulatory and institutional frameworks in wherever the overseas XFEL facility was placed or supported by UK contributions. The legal and regulatory factors noted would seem to be most relevant for the appraisal of Options 1 and 2. Currently the UK economy is understood to be slightly 'less regulated' than the European Union, but then with legal and regulatory frameworks that diverge from those in the EU. A further complicating factor under Option 2 is whether shared facility/contributions would be made outside of the EU. So, for example, a US or Asian location would give rise to very different legal and regulatory frameworks compared to a UK location. Here differences in IP regulations and GDPR might be very important in cases where industry is collaborating with UK higher education partners or projects which tie to sensitive commercial outcomes, or require the sharing of commercially confidential information.

6.3.6 Environmental Factors

Finally in the PESTLE analysis we identify a series of environmental factors that could be relevant to the appraisal of Options 1–3. These include land use and with Option 1 UK-XFEL leading to the potential development of a greenfield site and then consequent planning procedures. Environmental factors include energy usage of an operational site and its associated carbon footprint (total energy usage would be expected to vary significantly between Options 1–3), and then changing energy costs and access to grid resources. Then, for example, Options 2 and 3 might reduce exposure to domestic variations in energy costs or domestic electricity supply side constraints in terms of access to the national grid.

6.3.7 PESTLE Conclusions

In Figure 6.3 we seek to summarise how some of the factors rated as of high importance in deciding between options might favour one option over another. For example, public spending pressures in the UK might make Option 3 more likely. Changing technical demands placed by users might favour risk sharing under Option 2 as opposed to Option 1. Similarly land use planning in the UK and difficulties in gaining development consents might favour International XFEL under Option 2. It is stressed that this is a starting point for analysis and with stakeholders expected to identify other factors not included in this PESTLE.

There are some final concluding points in respect of key socio-economic factors coming out of the PESTLE analysis, and their connection to the findings in the wider socio-economic primer:

- There is a tendency to downplay the pre-development and construction process in infrastructure development and focus on operational benefits. A series of studies have identified gains to local economies during the construction and development process of strategic infrastructure. This is in part associated with the nature of the managing contractor and whether it is a UK or overseas-based business. However, there is real potential under Option 1 in terms of strengthening the construction engineering sector, not least in gaining knowledge that can be taken to other strategic projects. There is also the prospect of

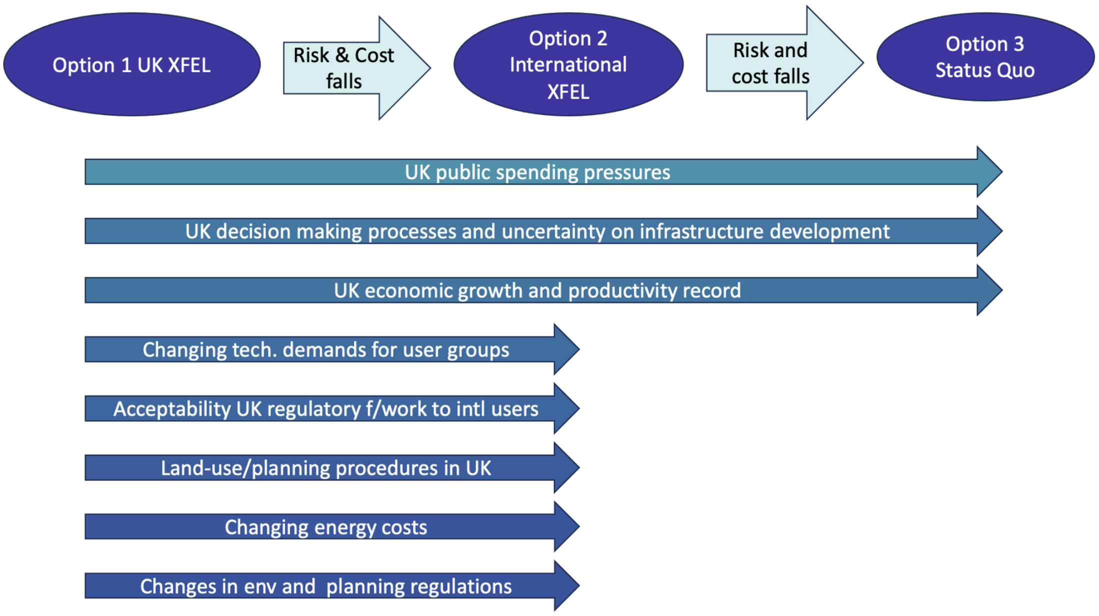

Figure 6.3: Examples of PESTLE factors rated as high importance.

workforce development in the construction process. The build phase under Option 1 would then represent more than a £2.5bn shock to the UK construction sector.

- There is uncertainty on the scale of construction impacts associated with the development phase of Option 1 and with this associated with a series of actors identified in the PESTLE analysis. Recent strategic infrastructure projects in the UK have revealed limitations in the construction engineering supply side in the UK and with costs affected by the matrix of other large projects occurring at the same time. Moreover, the nature of the managing contractor (UK-based or otherwise) is expected to have a major impact on the willingness to use local supply chains and with this an important determinant of economic impacts during the development and construction stage. Commonly used economic modelling approaches to consider construction effects (such as Input-Output analysis) deal poorly with strategic projects that are of sufficient scale to change the supply side of the economy.
- There is a critical issue in terms of the effective use of public money to develop the infrastructure and this tied to a series of Political and Economic factors summarised in the PESTLE analysis. While the logic model seeks to connect grant funding to outcomes and impacts this does not necessarily reveal whether the strategic infrastructure was an appropriate use of the public money. Elements of the socio-economic XFEL primer treat econometric techniques that seek to control for a counterfactual. However, as revealed earlier in this section, XFEL stakeholders need to be mindful of establishing exactly what might vary between the development scenarios, and set marginal outcomes and impacts, against marginal uplifts in capital and revenue spend that differentiate the three scenarios.
- Finally, within the PESTLE it is difficult to comment on the wide range of factors that could form part of Option 2 International XFEL. So, for example, the political, economic and regulatory factors covered may be very different were the International XFEL investment in an EU, US, or other international location. Then were Option 2 to become preferred, further analysis would be useful to differentiate the PESTLE factors relevant to different locations. For example, currently in the political sphere there are high levels of uncertainty in terms

of the development of scientific infrastructure in the US in the wake of quickly changing spending and wider mission priorities.

6.4 Rates of Return

This section presents estimates of returns to R&D investment which might be considered in a fuller appraisal of the XFEL options. Firstly, recent advice to DSIT on appraising the case for public support to R&D is presented. This is followed by a brief review of evidence on returns specifically to large infrastructure projects and a brief review of assessments of impact of UK contribution to international facilities.

6.4.1 Rates of Return: Advice to DSIT on Appraising R&D Projects

A 2023 meta-analysis of international evidence relating to private returns to R&D investment reported to DSIT [43] considered most studies which estimated returns in the short-term, typically the year following investment. R&D investment has an impact beyond the short-term, but will decline over time as R&D depreciates in value. The authors consider that short-term estimates of return generally under-estimate the true return. Based on their analysis, they reported a conservative estimate of the average private rate of return to firms of their own investment in R&D to be around 20%.

The study goes on to consider social rates of return, moving beyond the impact on firms' output to spillover effects on the output of firms not involved in the R&D, but which still benefit from the knowledge created. Overall, they provide a conservative approach to modelling the benefits to R&D which would be to assume social returns to R&D are twice those of private returns.

The authors recommend these estimates are used in appraising the case for public support to R&D.

The study also explored variations of interest to XFEL, because they pertain to public spending, not just firm-level inputs:

- Country-level estimates of returns (including R&D spend by business, higher education, government and not-for-profit sectors) generated a median estimate of return of 15% and mean of 36%, although the authors do not draw on this further because of the small sample sizes and greater concern regarding unobserved factors at country-level.
- The evidence on R&D conducted in the public sector (through public research centres, higher education or in government departments) was limited, but they cite an earlier study [44] which estimated a social return to public R&D of around 20%.

Because of data quality, these variations did not impact on the overall recommendation.

6.4.2 Rates of Return: Examples of Large Research Infrastructure Investments

The advice to DSIT did not seem to specifically consider evidence on the returns to large research infrastructure projects. In this section, we consider some of these examples and the measurement issues they raise, but it is not a systematic review or meta-analysis.

2013 Review

An earlier review of rates of return of large research facilities [45] found economic impact assessments tended to follow a broadly similar methodological approach, wherein evaluators take expenditure and employment data and feed those historical data into an input-output analysis to estimate the direct (spend on the project), indirect (spend in supply chains) and induced benefits (from increased personal income and spend). The evaluations arrived at economic multipliers that typically range between 2 and 3, that is, every £1m in public expenditure is generating an additional £2m to £3m in wider economic activity. While this is much higher than the 20–40% rate of return reported above, the authors note that none of the evaluations reviewed made adjustments for additionality or displacement costs, reporting gross rather than net assessments of economic impact.

Hartree

A baseline evaluation of the Hartree Centre, assessed the impact of the centre four years after opening [36]. It estimated that the Centre's direct work with industry generated a total net economic impact of up to £27.5m in commercial benefits to users, in addition to £7.1m net impact from operational expenditure of the centre in phase 1 and 2. The authors argue these were strong results for a young centre and close to the £37.5m initial capital expenditure. They expect the impact to increase over time. These estimates were derived from a survey of business users, rather than the input-output models, and is a net assessment, as the evaluation accounted for attribution, deadweight, displacement and leakage.

ITER

[35] reports on the timed sequencing of impact, drawing on the example of the international fusion project (ITER) in France, a global collaboration to demonstrate the scientific feasibility of fusion on a scale needed for a future energy source. The programme began in 1986, design and development in 1992 and actual construction in 2007. Construction will progress through to 2035. The European Commission have started recording and analysing data about the impact of the design, manufacturing and research contracts awarded to European industry and research institutions. In 2017 and 2020 they commissioned two econometric impact studies that evaluated the impact of ITER design and construction activities.

The evaluation estimated direct and indirect GVA impact of 1.2, akin to the 20% private return in advice to DSIT. However, this ratio increased from 0.5 in early years and is expected to stay above 1 for the duration of construction. As the project started as a 'green field' project, early expenses were low value-added site preparation activities. The GVA has a bigger impact on the industrial sector and is expected to peak at 2.4 in 2035. Similarly, the job ratio is estimated at 1.2, meaning that more than one indirect job is created for each job directly linked to ITER contracts. Again, this is higher for the industrial sector and is expected to peak at 2.9 in 2035.

DORIS

[46] reported on the evaluation of the 'Doppel-Ring-Speicheranlage' (DORIS) in Hamburg. Again, using input-output models, they report that around 1.4 billion Euros was invested in DORIS over 40 years of its lifespan (1970–2013), including construction and operation. For every euro spent, the analysis generated an indirect multiplier of 1.83 and an induced multiplier of 1.90 Euros.

Monetising Impacts: Diamond Light

Finally, in this section, we consider evidence from the socio-economic impact assessment of the Diamond Light Source [39]. This study estimated that between 2007 and 2020 Diamond had a cumulative monetised impact of at least £1.8 billion, compared to the £1.2 billion investment in the facility (£1 billion from UK Government), including all capital expenditure and operational costs. They report this impact is only likely to grow given the relatively early stage of analysis. The total is arrived at through monetising the impact of several different outputs, including, but not limited to:

- £551.5 million in direct benefits to individual users each year through access to beamtime and support (inferred from fee payment).
- £352 million through Diamond's contributions to structures deposited in the world's Protein Data Bank (PDB) (based on an economic analysis of the likely costs to replicate the archive in 2016 and Diamond's proportional contribution to this archive).
- Patents which cite Diamond publications are valued at £10.2 billion. A conservative estimate of the proportion attributable to Diamond of 1% is applied (£103 million).
- £8.8 million in free training, based on commercial rates paid for similar courses.

The report also identified other monetised benefits, but for which fewer data points were available, including up to £50.5 million in net direct benefit to Diamond's suppliers each year. This is extrapolated from 5 suppliers who, on average, reported that each £1 of contracts with Diamond had led to an additional £2.40 in additional sales to other organisations.

The Diamond Light socio-economic impact study also developed 28 case-studies to illustrate impact and identified wider societal benefits including the number of visitors reached through a programme of engagement to support the UK Skills' STEM agenda and widespread awareness of the value and relevance of STEM subjects through news articles and outreach activities.

The small sample of infrastructure evaluations reviewed in this section demonstrate variations in methodological approach, but overall suggest positive economic returns, roughly at the same order of magnitude. On the basis of this brief review, it would appear reasonable to adhere to Frontier Economics advice reported above in appraising the case for a UK XFEL, but which may not apply to an international XFEL.

6.4.3 UK Returns to International Facilities

Three studies provide some insight to the returns to UK investment in international facilities.

As reported in Section 6.2, the UK contributed 26m Euro (2005 prices) to the construction costs of European XFEL in 2018 and makes an annual contribution of around 3m Euro annually. The monetised impact reported in the evaluation [32] is 700k Euro of contracts won by UK-based suppliers.

Using a similar methodology, an impact evaluation of ESRF [40] reported current UK contribution of 9.5m Euro annually plus 1.7m Euro to XMaS beamline. The evaluation reports that the UK has been a member since 1988, but it does not indicate total financial input. Between 2015 and 2021, nearly 16m Euro of contracts were awarded to UK-based suppliers.

An evaluation of UK investment in CERN [38] identified that the UK had invested an average of £152m per year over the last decade and reported some monetised benefits, e.g.:

- Approximately 500 UK firms sold goods and services to CERN in the past decade, bringing in an additional £183.3m in revenue and supporting employment. Half of UK suppliers reported that CERN contracts had resulted in an increase in other sales income, with the evaluators estimating a further £1bn in turnover and £110m in profit has been supported on top of the direct contracted income.
- £33.4m awarded to UK firms for CERN experiments and by the CERN Pension Fund.
- £4.9m worth of free training.
- Young UK researchers who have engaged with CERN are estimated to earn 12% more across their careers as a result (with an extra £489m in additional wages realised in the past ten years).
- The capabilities developed at CERN could help address STEM skill shortages which cost UK firms £1.5bn a year in recruitment, temporary staff and additional training.
- A separate study showed high favourability, with the UK public willing to pay (through taxation) around £1.2bn for CERN over a decade.
- Despite the evidence of returns, the 2023 UK CERN engagement strategy [47] reported 'our current return on investment needs improvement'.

These three international examples do not suggest a strongly positive socio-economic impact, though of course, that does not mean there are not significant scientific impacts nor other impacts which have not been measured. However, overall, UK returns to international infrastructure appear lower, in keeping with expectations in the TOC.

6.4.4 Rates of Return: Conclusions

The sample of evaluations reviewed demonstrate economic impact assessments use different methods, measures and cover different time-spans. It is also evident that most evaluations do not encompass the full range of potential socio-economic impacts described in the TOC.

The incomparability and limited evidence mean it is difficult to provide a clear estimated (or comparative) rate of return for any of the 3 Options, on the basis of this brief review. However, as expected in the TOC, returns to the UK would appear to be higher for UK-based infrastructure than international infrastructure.

While a fuller appraisal might encompass a systematic review of returns to research infrastructure to home and contributor nations, this section illustrates the factors to consider in development of a fuller business case and in how the investment should be evaluated, the subject of the next section.

6.5 Evaluating the Socio-Economic Impact of XFEL

This section outlines an approach to evaluating the socio-economic impact of a XFEL and factors to consider in designing a Monitoring and Evaluation Strategy. As well as drawing on the evaluations reviewed for this chapter, it is also grounded in recent work for DSIT and UKRI in what makes for effective evaluation.

The approach and methods apply to all Options considered, but evaluation should be proportionate to programme expenditure. Thus, in the event of a UK XFEL, a fuller evaluation programme and more novel approaches to evaluation should be considered, which would be unlikely (disproportionate) under Option 3.

6.5.1 What Makes for Effective Evaluation of R&I Programmes?

Recent studies for DSIT [48] and UKRI [49] identified challenges in the evaluation of research and innovation investments. Some of these are already apparent from the preceding sections (i.e., complexity of the impact pathways, the varying time lag between intervention and outcomes, assessing wider impacts). Other challenges identified in these studies included:

- Selection of participants is usually based on competitions, creating a selection bias problem.
- Beneficiaries receive multiple treatments over time, making it difficult to disentangle the impact of specific interventions.
- Lack of clear control groups.

Following these reports, UKRI issued an evaluation strategy [50] which acknowledged these challenges and presented mitigation strategies:

- Use of mixed-method approaches.
- Establishing an understanding of the starting point and what would have happened if no funding was provided (a baseline counterfactual scenario).
- Undertaking interim evaluations during the lifetime of the programme.
- Ensuring that adequate data is collected through monitoring processes while the programme is progressing.

The strategy expresses a preference for theory-based methods of evaluation over experimental and quasi-experimental methods, largely because most R&D funding is not allocated randomly.

There are good reasons for advocating a theory-based approach to evaluating XFEL, and indeed, it is the focus of this chapter. However, in their review of counterfactual methodologies, [49] recommended UKRI consider use of these methodologies where circumstances allow (alongside a theory-based evaluation). Given the potential investment in UK XFEL, this might be warranted. Of particular relevance to UK XFEL might be:

- Differences-in-Differences methodologies, for firm-focussed interventions.[12]
- Qualitative counterfactual methodologies, where sample sizes of treated and control groups are smaller and the potential conditions leading to success are not straightforward binary factors (present or not).
- Synthetic Control Method where one or a few units (such as universities, firms, sectors or areas) are exposed to an intervention, and where high-quality secondary data over a period of time on both treatment and control units are available.

While these reports and strategies are important to note, they do not specifically cover research infrastructure. In a paper on methodologies to evaluate the socio-economic benefits of large-scale research infrastructure, [51] suggest the use of social cost-benefit analysis.[13] They note use of

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[12] See [49] for a full discussion.

[13] CBA: cost-benefit analysis.

CBA is recommended by the European Commission in the Horizon 2018–2020 Work Programme. It should also be noted that there are active debates on valuation mechanisms for the return to R&D and better means of estimation might be available as the XFEL project progresses.

We do not elaborate on alternative methods here but suggest consideration might be given to them if Option 1 is selected.

6.5.2 Evaluating the Socio-Economic Impact of XFEL

By considering monitoring and evaluation at this stage, the STFC is adopting best practice in evaluation design, allowing more options to be considered and data collection arrangements to be embedded at the outset.

The annexed table presents examples of data which might be collected to inform progress along the impact pathways described in Section 6.2 (shown in Column 1). Measures, which describe the broad areas of interest discussed in Section 6.4, are shown in Column 2. Indicators are ways in which the measures could be expressed and operationalised through data collection and are presented in Column 3.

The column 'Relevant to Option. . . ' indicates which of the options the measure and associated indicators might be relevant to. The majority of indicators are relevant to all 3 options IF the activities described are undertaken, at least to some degree. However, as stated above, the investment in monitoring and evaluation should be proportionate to the spend.

The 'Evaluation source' column indicates how the data could be sourced and so the monitoring and evaluation activities which will need to be put in place to assess the socio-economic impact. The sources are:

- Economic impact assessment, building on the discussion and examples provided in this chapter to ensure a robust socio-economic impact evaluation, relevant to stakeholder needs. Whether through monetising benefits, an input-output analysis, a combination, or methodologies which emerge in the coming years, these should take deadweight, displacement, leakage and multiplier effects to present a net assessment. All other evaluation activities should be designed to inform this assessment.
- Monitoring processes to collect, collate and report on a range of input, activity and output data.
- Bibliometric analytical services.
- Supplier surveys to assess the short- and medium-term impacts on businesses.
- Surveys of users (academics and industry) to explore tangible and intangible outputs, outcomes and impacts and to direct to case studies (supplemented by qualitative research to understand 'how' and 'why' and inform continuous improvement).
- Survey of users (public) to explore perceptions of the facility and the science.
- Stakeholder survey.
- Qualitative impact case studies to explore and demonstrate socio-economic and scientific impacts.

6.5.3 Evaluating the Socio-Economic Impact: Conclusions

The precise design of the evaluation will depend on the option selected and spend. STFC are right to consider the evaluation at this stage as this should allow for data collection and collation processes to be embedded at the outset. This will support a fuller assessment of impact and perhaps improve on evaluations reported on in this chapter.

6.6 Conclusions

This chapter has presented an initial exploration of how the socio-economic impact of the three broad options under consideration for the future of XFEL might be appraised and evaluated.

In considering the socio-economic impact, it is apparent that there are not just the three broad options to consider, but within each option there are a series of opportunities which could be invested in, and which, if effectively implemented, could augment the overall socio-economic impact of the selected option. For many of these ‘additional’ activities, there are also options about when to start them, at what stage of construction.

In a similar exploratory vein, the chapter presents a high-level PESTLE analysis, a starting point of the key issues to consider in progressing the options and how they might influence the theories of change.

A brief review of evidence on rates of return to UK investment suggests that returns would be higher for a UK XFEL than an enhanced international XFEL. This is consistent with the expectations within the theories of change and the likelihood of a higher level of activities, outputs and outcomes at a UK facility. However, this does not represent a meta-analysis, but as with the chapter as a whole, is a first step towards fuller option appraisals and stakeholder engagement which is an important next step for STFC.

6.7 Acknowledgments

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About the Innovation and Research Caucus

The Innovation and Research Caucus supports the use of robust evidence and insights in UKRI’s strategies and investments, as well as undertaking a co-produced programme of research. Our members are leading academics from across the social sciences, other disciplines and sectors, who are engaged in different aspects of innovation and research systems. We connect academic experts, UKRI, STFC and the ESRC, by providing research insights to inform policy and practice. Professor Tim Vorley and Professor Stephen Roper are Co-Directors. The IRC is funded by UKRI via the ESRC and Innovate UK, grant number ES/X010759/1. The support of the funders is

acknowledged. The views expressed in this piece are those of the authors and do not necessarily represent those of the funders.

7 Options analysis

7.1 Introduction

The options analysis considers the following investment scenarios (ordered by increasing scale of investment) which could provide UK access to next-generation XFEL capability by the 2040s.

1. Maintaining the status quo, in which the UK does not make any additional investment towards next-generation XFEL capability
2. Delivering the capability through an upgrade to one or more existing XFEL facilities
3. Delivering the capability through construction of a new next-generation XFEL facility within the UK

The first two options are not mutually exclusive. A hybrid approach – e.g., combining investment in both an international upgrade and creation of a domestic facility – could achieve the same objectives with additional benefits (and risks).

All options must be consistent with the essential criteria outlined in Chapter 4. The impact on environmental sustainability must also be considered.

Each option is explored in detail below, in order of increasing investment required.

7.2 Exploration of option types

7.2.1 No additional investment

This option considers the feasibility of achieving the project's objectives without requiring further financial contributions from the UK. The term *"additional investment"* is used deliberately to reflect the UK's existing financial commitment to European XFEL. In 2025 this was $\sim$7 MGBP (5.16 % of the 154.6 MEUR operations budget [52]). Further detail is presented above in Section 5.3.

7.2.2 Investment in existing XFEL capability

As outlined in Section 5.1, **the most relevant existing facilities to UK XFEL are European XFEL and LCLS.**

7.2.2.1 Capability

European XFEL's current burst mode structure is not compatible with the UK essential criteria EC-I. To achieve compatibility, a significant increase in duty cycle would be required through the proposed HDC upgrade. The Feasibility and Options Study (FOS) currently underway is assessing both the technical and strategic implications of such an upgrade. For instance, transitioning to full CW operation would constrain the accelerator to ∼7 GeV, aligning it with facilities such as LCLS-II-HE, SHINE and the UK XFEL concept – potentially placing European XFEL in direct competition with other facilities. Therefore, one plausible outcome of the FOS is to recommend a moderate elevation in duty cycle as compared to full CW operation, preserving European XFEL's strategic differentiation. The FOS is due to report in late 2026.

Several mid-term R&D activities are well aligned with creation of transform-limited pulses, **supporting essential criteria EC-II**. These developments should be implemented post-2031, aligning them with the UK XFEL objective timeline (2040s).

European XFEL currently operates three FELs (SASE 1-3), with an additional two tunnels (SASE 4-5) available for installation. The facility is designed for simultaneous operation of all FELs, enhancing throughput and increasing opportunities for UK access. **Full utilisation of all five FELs would be consistent with essential criteria EC-III.** European XFEL are currently engaged with stakeholders to define the future of SASE 4-5, with proposals including new FELs optimised to specific X-ray photon energies and an upgrade (including new laser infrastructure) to the HED instrument to support Germany's 'Fusion 2040' programme. In addition, European XFEL also has space for a second 'fan' of FELs which could double the capacity of the facility from five (assuming occupation of SASE 4-5) to ten XFELs – **supporting EC-III further**. The concept of a second fan has been previously introduced at user meetings but little detail has entered the public domain. A second fan would need significant civil construction (e.g., tunnel boring) in addition to major accelerator upgrades. No cost estimate is available, although this is expected to represent at least a ∼1000 MEUR investment. As with other upgrade activities, design considerations for a second fan would be performed during the period 2025-2030, with construction activities potentially beginning mid-2030s, if approved.

The planned LCLS-II upgrade – LCLS-II-HE – will enable the generation of X-ray pulses at ∼12 keV and 1 MHz repetition rate. Higher photon energies could be achievable through improvements in injector emittance, such as those anticipated through the planned LEI upgrade. LCLS-II-HE will also employ self-seeding schemes for increased spectral brightness and there are active programmes pursuing novel FEL modes, including cavity-based XFEL methods and attosecond pulse generation. **These developments indicate a clear trajectory towards near-transform-limited X-ray pulses, consistent with the essential criteria EC-II.**

LCLS-II-HE will initially support parallel operation of two FELs (soft X-ray, hard X-ray), with the additional option of driving one of these from the higher energy LCLS copper linac at 120 Hz. A further major upgrade, LCLS-X, proposes an additional eight FELs operating at 100 kHz, **representing the maximum utilisation of LCLS-II-HE linac and aligning with EC-III**. LCLS-X also has an explicit aspiration towards achieving widespread 'full 3D-coherence' (transform-limited operation), **further reinforcing compatibility with EC-II**.

Information on the LCLS-X proposal is available in the public domain as part of a recently published roadmap on new and upgraded national user facilities within DOE-BES. The project has not formally entered the critical decision process. Key aspects including capability are under consideration, with SLAC engaging their community to assist in prioritisation. Based on engagement to date, the output of this process is unlikely to diverge significantly from UK community interests. The proposal also acknowledges flexibility to tailor capability of future beamlines against emerging US national priorities.

7.2.2.2 Delivery

A UK investment would likely take the form of an in-kind contribution – for example, providing equipment or expertise – as part of an **already planned** upgrade project. In such cases, the possibility of UK investment could be leveraged to increase the chance of a specific upgrade happening; or in cases where an upgrade is based on multiple options, try to direct this towards the option most aligned with UK requirements.

The UK could leverage its membership to deliver investment at European XFEL. The UK does not have an equivalent agreement with LCLS, however a similar approach to that originally proposed for the UK's contribution to the Electron Ion Collider (EIC) could be taken as a useful precedent.In ideal circumstances, any investment of this scale should be built upon an existing programme of collaborative activity. This would:

- Promote closer ties and experience of joint working ahead of more complex activities.
- Build trust and demonstrate the UK's long-term commitment to the relevant institution(s).
- Promote sharing of information, helping to identify new opportunities as they arise, and ensuring UK interests are represented in a timely manner.

As sketched in Figure 7.1, both the type and level of joint activity could be progressively increased in time, starting with smaller-scale low-level collaboration and building through to more substantial and well-defined contributions.

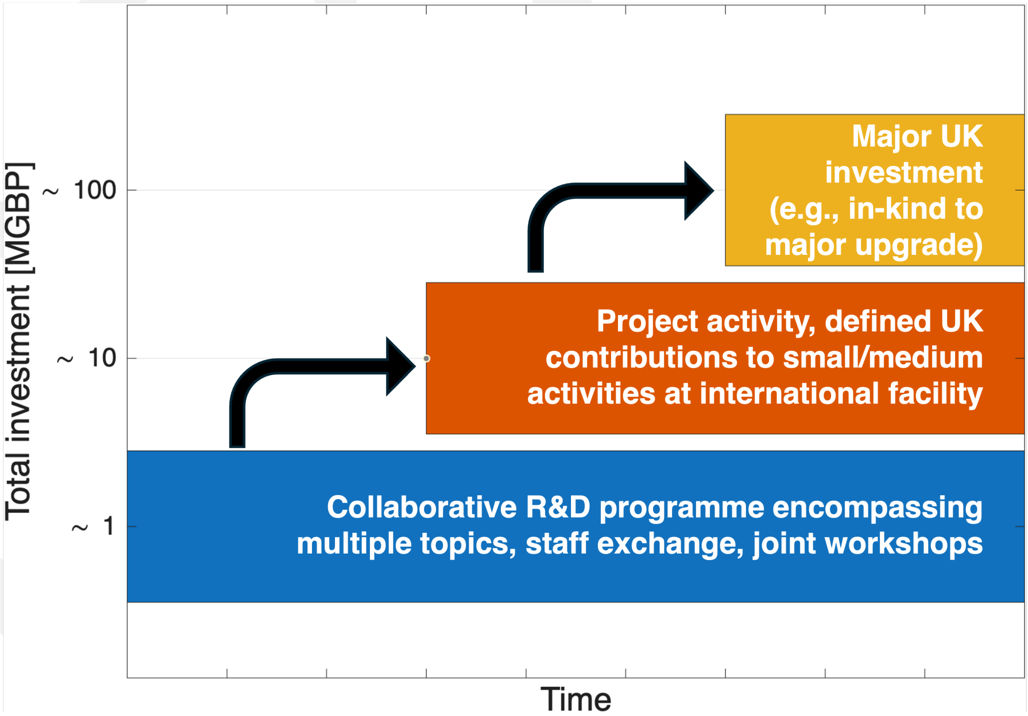

Figure 7.1: Pathways towards a large-scale investment in an international XFEL facility, building upon a platform of progressive (lower value) investments with time. Values given are strictly indicative only, and used to represent a progression from small to medium to large relative funding levels.

STFC and members of the UK community should influence DESY and European XFEL towards an outcome of the HDC FOS aligned with UK requirements (EC-I). Regardless, the specific timeline and steps following conclusion of the FOS are unclear. This process is expected to involve substantial capital investment, including that required for civil construction work. European XFEL could seek input from members regarding both the decision to upgrade and associated funding. Any upgrade would be likely to start early 2030s and lead to user access to the capability by the end of the decade – meeting UK XFEL objectives.

The deadline for decision on the SASE 4-5 tunnels is unknown, but could be expected to take place within 1-2 years. A second fan upgrade would be a much larger and complex activity, both technically and in terms of stakeholder engagement. European XFEL has not yet clarified a timeline for this process; it has also not stated how it intends to solicit input from members on capability and funding.

LCLS-II-HE is fully funded and has entered a construction phase. While the scope for UK involvement in this phase is unclear, there may be opportunities in both the short- and mid-term towards an injector upgrade. This would provide a strategic platform on which to build a larger future investment, such as a major in-kind contribution to LCLS-X.

LCLS-X and its timeline are well aligned with UK requirements. Although the project is at a pre-critical decision phase, confidence should be taken from the recognition of LCLS-X as “absolutely essential” to future world-leading science by DOE-BES [31]. This exercises mirrors the process that led to LCLS-II.

7.2.2.3 Funding

The financial value of an investment in an existing facility can be tailored to UK requirements. Key factors would include:

- The total cost of the upgrade activity
- Any committent to ongoing operating costs
- Strategic leverage achieved, both in capability enabled and improved international relationships.

Any UK contribution to the upgrade of European XFEL would need to be negotiated alongside contributions from other shareholders, which could introduce constraints. Ideally this would include UK exploitation of in-kind contributions to the facility construction including technology delivery. While in-kind contributions are unlikely to confer direct ‘ownership’ of part of a facility (e.g., a UK-only beamline), they do potentially offer more access as compared to the relative financial value of the contribution. Likewise, the UK scientific community should be engaged as appropriate in the capability and design of new beamlines and instruments, drawing upon the engagement and work performed as part of the UK XFEL Science and Technology Case.

Upgrade activities at European XFEL and LCLS are expected to result in increased operations costs compared to the status quo. As a member nation of European XFEL, the UK could be obliged to meet these additional costs unless renegotiated.

In the US, ‘Collaborative Access Teams’ (CAT) – large research partnerships typically including contributions from academia, national laboratories and industry – can receive ring-fenced access in exchange for a contribution to beam-time operating costs, which support both the CAT and general users. It is unclear if this model could be scaled to meet the needs of the broader UK community.

There is limited public information on the financial values of major upgrade activities at European XFEL. A second fan is anticipated to require at least ∼1000 MEUR although no formal valuation has been published. The published estimated value of the LCLS-X upgrade is ∼1500 MUSD (Table 5.3).

Given these uncertainties, it is not appropriate for this options analysis to propose a specific value of an international investment. A reasonable level of investment based on current knowledge would be ∼100 MGBP, representing ∼10 % of a ∼1000 MGBP project consistent with the examples above.

7.2.3 Investment to create a new XFEL facility in the UK

7.2.3.1 Capability

A conceptual design for a new international-scale facility has been developed which is **fully aligned with the priorities of the UK science and technology case, and meets all of the essential criteria in Table 4.1**. This facility, shown in Figure 7.2, represents the full realisation of what is currently imaginable with XFEL technology. It is based on:

- An 8 GeV superconducting linear accelerator, operating at a fixed beam energy and a repetition rate of ∼1 MHz **(EC-I)**.
- Application of a suite of advanced FEL techniques, including cavity-based methods for the creation of transform-limited pulses across the full energy range, spanning soft to hard X-rays as required **(EC-II)**.
- Six FELs operating in parallel, multiplexed from the linear accelerator, each operating at ∼100 kHz and covering a collective photon energy range of ∼100 eV to 20 keV, supplying light to fifteen end stations **(EC-III)**.
- An additional FEL customised for research in Matter in Extreme Conditions (MEC), accessing photon energies >20 keV through a normal conducting booster linac, with two specialised end stations supported by high power laser infrastructure.
- Two photoinjector electron sources, configured such that all FELs can operate in an optimised configuration and deliver transform limited X-rays at the fixed beam energy of 8 GeV.
- An ‘applications’ beamline for exploitation by users requiring access to the electron beam only, and provide a platform for ongoing accelerator technology development which does not compromise user access.
- Expansion space for a second array of FELs and further end stations, which could be realised as part of a major upgrade activity (or activities).

The facility design is fully capability-driven, prioritising requirements without being constrained by cost or location considerations. This approach reflects lesson learned from previous strategic exercises. Notably, the 2016 STFC FEL Strategic Review recommended a normal-conducting, ‘SwissFEL-like’ option with an estimated facility value of ∼500 MGBP [12]. This assessment precluded consideration of higher-performance options, including higher repetition rate technology which is now essential (EC-I) to the UK community.

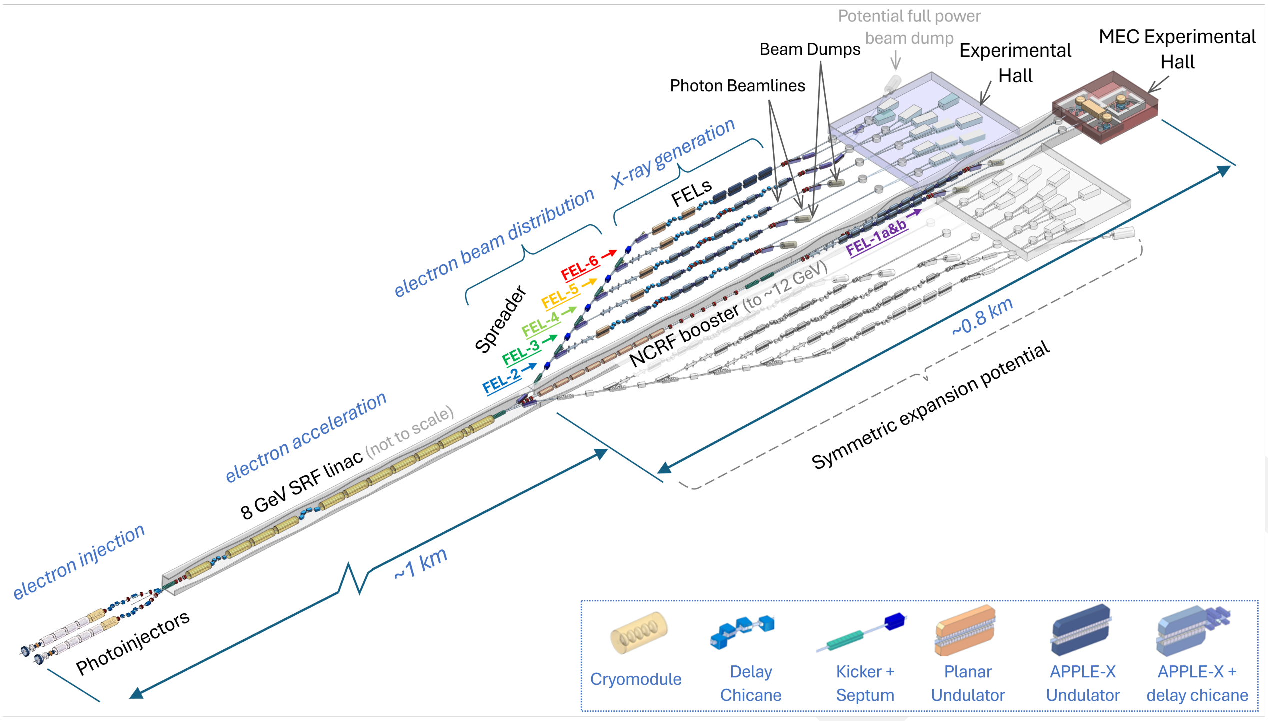

Figure 7.2: Layout of the new next-generation XFEL facility baseline design, consisting of an 8 GeV superconducting linac supplying six FELs in parallel, with space to expand symmetrically as part of a major upgrade.

7.2.3.2 Delivery

The delivery of the facility shown in Figure 7.2 would be an ambitious project, with a decade spanning the start of technical design to first science. During this period new capabilities may arise at existing facilities, and national priorities may evolve in response to technological advances and changes in government policy.

To deliver sustained impact, it is essential that the scope of the proposed facility can evolve in response to such external factors. This can be achieved by spreading the delivery over a series of phases. The facility concept has been designed in such a way to allow multiple possible configurations: an example of one possible approach is presented below.

Phase 1a

To enable early science, Phase 1a consists of a single photoinjector with two FEL beamlines supporting SXR and HXR (up to ∼8 keV photon delivery. The linac energy would be set at 8 GeV, as the anticipated cost/time savings of a lower energy linac are expected to be outweighed by reconfiguration downtime, disruption to operations, and integration costs.

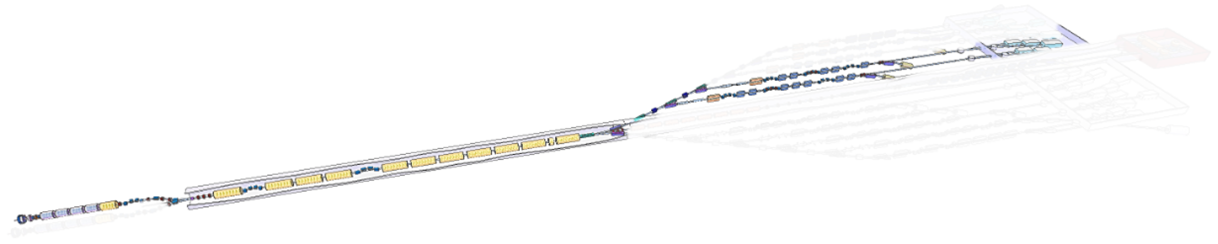

Figure 7.3: Phase 1a, consisting of a 8 GeV superconducting linac driven by a single photoinjector, and 2 FEL beamlines (SXR/HXR).

Phase 1b

Once operational, Phase 1a could be expanded to include the interleaved dual photoinjector, and MEC infrastructure including normal conducting booster, dual FEL beamline, and hall including target areas and high power/high energy laser infrastructure.

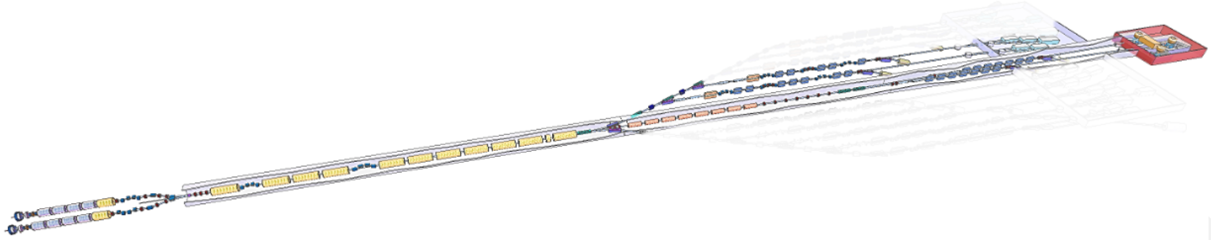

Figure 7.4: Phase 1b, including dual photoinjector, normal conducting booster, and MEC hall including beamlines and laser infrastructure.

Phase 1c

This would see completion of all FEL beamlines covering (continuously) a nominal photon energy range of ∼100 eV to 20 keV, supplying up to 18 end stations. This configuration represents the 'nominal' facility concept outlined in the UK XFEL Conceptual Design Report.

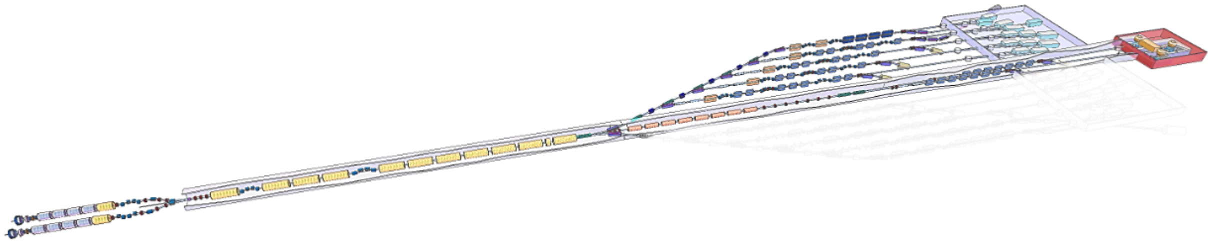

Figure 7.5: Phase 1c, representing the 'nominal' configuration based on 6 FELs supplying up to 18 end stations.

Upgrade

Following scientific exploitation, a second array of beamlines could be installed on the opposite side of the linac. This array could combine FEL and electron-only beamlines, and represent the maximum utilisation of the 1 MHz linac. The specific beamlines installed would account for the usage of beamlines as experienced in Phase 1 as well as accounting for new/emerging areas of interest.

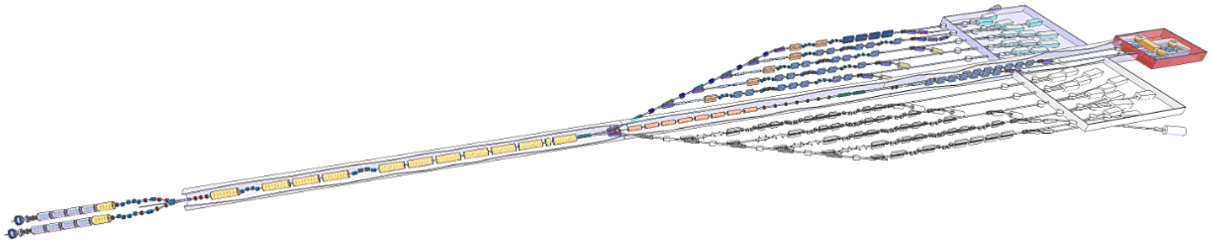

Figure 7.6: Maximum utilisation of the superconducting linac, with ten beamlines supplying up to 30 end stations, which could be delivered as an upgrade to Phase 1.

A phased approach has the following advantages:

- An initial reduced-scope phase would allow the UK to establish a firm foundation in XFEL construction and operation, deliver early scientific outcomes, while mitigating overall project risk
- The total investment for full realisation can be distributed over an extended timeline. This allows for controlled budgetary profiling through the strategic scheduling of upgrade activities.
- A phased approach supports adjustment of both capability and cost in response to external factors, as described above.

Disadvantages in a phased approach include the total time to establish full capability, overall increased cost (as compared to a single-phase build), skills retention, and impact on user operations which would be disrupted by upgrade periods. Recommissioning of components may be required. A single phase build would be financially more efficient, but would not be the quickest way to realise early benefits.

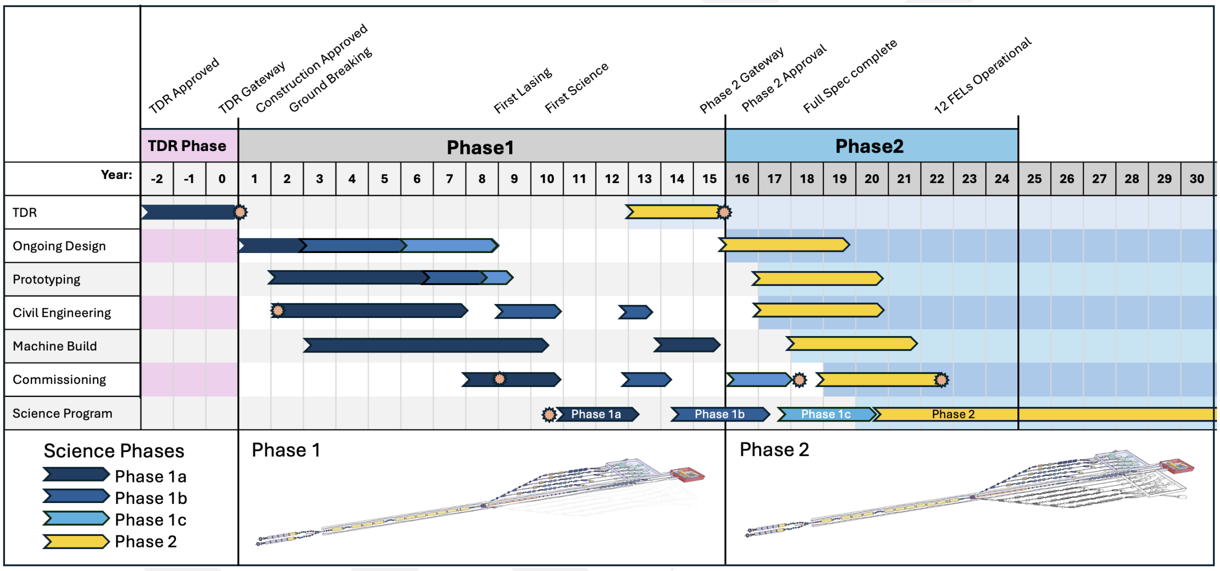

Figure 7.7: Estimated timelines for design and build of the two main phases of the project.

Figure 7.7 Assumes that a greenfield site is located during a Technical Design Report (TDR) phase, that there is no delay between a TDR are the start of the build process, and that there would be suitable delays between phases to asses user requirements. It does not show any processes for re-evaulating these parameters showing only the top level work breakdown. As such it is simplified and detailed breakdown of the phases is not shown. On a timeline such as this UK XFEL would achieve first science within 10 years of project approval, building out to the nominal configuration within 18 years (allowing for delays to asses user requirements). Due to the modular nature of the FEL design, every stage other than commissioning can progress without the requirement of beamdowntime - this improves upgradability and access to early science significantly.

7.2.3.3 Funding

A next-generation XFEL located in the UK is expected to be a billion-pound scale activity which would attract significant interest, both within the UK (including industry, defence and the public sector) and potential international partners. It is assumed that multiple partners would be engaged to provide technical, in-kind and direct financial contributions. This partnership may represent a diverse range of economies, and extend to nations that do not currently use XFEL technology. Comparable cases include the European Spallation Source (∼50 % contributions from international partners [53]) and European XFEL (∼42 % [54]). Such a partnership could significantly reduce the net cost to the UK, while strengthening international collaborations.

7.3 Discussion

The primary goal of the options analysis (Chapter 3) is **to evaluate investment options which could enable UK user access to next-generation XFEL capability in the 2040s**.

Key considerations for the two investment pathways – enhancing an existing XFEL facility, and establishing a new facility in the UK – are outlined in Section 7.2 under the themes of capability, delivery, and funding. The socioeconomic implications of each option are summarised in Chapter 6. Together, these references provide a robust foundation for critically assessing the strategic options available.

7.3.1 No additional investment

Developments in the international landscape (Section 5.1) – in particular, those at European XFEL, LCLS and SHINE – may lead to XFEL facilities achieving next-generation capability on a relevant timescale. UK users currently have access to European XFEL and LCLS (SHINE is yet to begin user operations) and are among the top non-domestic users of these facilities (Figure 5.3). Achieving the objectives of UK XFEL without additional investment would require:

1. One or more of those facilities to choose to proceed with the planned upgrade developments (e.g., HDC at European XFEL, LCLS-X at LCLS, etc.)
2. These projects are successfully funded and delivered through to operations, within the scope proposed and relevant timescale (e.g., operations by the 2040s)
3. UK users have open access to capability once operational

The first point is subject to multiple factors which introduce uncertainty. This includes suitable funding (∼1000 MGBP) being obtained from the relevant national bodies and international partnerships. This is expected to coincide with a period of economic strain as well as challenging international politics. It would also require the technical directions of those upgrades to remain aligned with UK next-generation requirements; European XFEL may not, for example, pursue continuously spaced X-ray operation, to maintain a strategic differential to SHINE and LCLS-II. The scope of LCLS-X is to be defined, although clearly represents the US-definition of a next-generation XFEL facility.

For the case of no additional investment, UK influence on these processes could not be expected to change significantly from the status quo. As a major (non-domestic) user, the UK community currently has some degree of influence on the strategic direction of these facilities (e.g., via European XFEL council membership), but such processes take into account a wide range of views from other users and member countries.

UK access to both European XFEL and LCLS is based on scientific merit alone. There is currently no reason to suspect the UK community would not at least retain similar levels of access as to what it currently achieves, however political and regulatory change (e.g., US as compared to the

UK) may effectively limited access. The UK position on access to SHINE is not currently defined. Defence and other sovereign research activities (e.g., as outlined in the Science and Technology Case) are only possible at a UK-based facility.

In summary, while the UK might be able to access next-generation XFEL capability without additional investment, this would be at risk from multiple factors. These includes a limited ability to shape the strategic direction of the required upgrade activities, and a lack of mechanisms to influence enhanced or prioritised user access for the UK community.

General access to international XFEL facilities is oversubscribed and limited by the relatively small number of facilities and beam-time hours that are available. The degree to which UK access is oversubscribed is expected to vary by facilities. Informal feedback from the UK science team indicates that approximately only 25 % of proposals are accepted. Data from European XFEL, for which the UK has had particular recent success in access (see Figure 5.2), indicates that on average 42 % of proposals were accepted between 2021 and 2024, with UK visits representing ∼12 % of all visits to the facility in 2024 (compared with ∼6 % across all facilities the same year).

Without additional investment or otherwise, efforts to increase beam-time, including through upgrade activities (LCLS-X, etc.) could be expected to benefit all facility users equally (including domestic users), and therefore will not fully alleviate the unmet demand for access from the UK. Likewise, new capability as introduced at specific facilities is likely to generate increased international interest, making access to such facilities more competitive. It is therefore possible to conclude that **should no additional investment be made, large fractions of the UK science and technology community will have their access to XFEL capability (next-generation or not) restricted by the lack of beam-time and competition from other countries**.

A summary of the major strengths, weaknesses, opportunities and threats associated with no additional investment is presented in Table 7.1.

7.3.2 Investment in existing XFEL capability

As established above (Section 7.3.1), the UK could have access to next-generation XFEL capability through proposed developments at existing international facilities – European XFEL, LCLS and SHINE. This could be achieved without additional investment, but is impacted by multiple risk factors including access, strategic alignment with UK requirements, and uncertainty in those proposals being followed through.

The UK has the option to invest in those proposed developments, as a means to address some of these risk factors. As discussed in Section 7.2.2.2, the likely most effective means to do is through some form of in-kind contribution to these proposals. This approach has multiple benefits:

Strategic influence: An in-kind contribution would demonstrate UK commitment to the relevant facility and increase the likelihood of the proposed upgrades being aligned with UK requirements. The value of the in-kind contribution could be important in surpassing a threshold which would allow those projects to proceed. Any such influence generated would be in addition to that of the UK user community, as discussed in the case of no additional investment (Section 7.3.1).

User access: An in-kind contribution could be a platform on which the UK could negotiate sustainable access to the capability on behalf of its users. The level of this access could exceed the associated financial value of the in-kind investment (as compared to the cost of any upgrade project as a whole).

Strengths	**Weaknesses**
■ The UK avoids major project, technical and financial risks by leveraging international efforts to develop next-generation XFEL capabilities, while still benefiting from access to that capability (should it be successfully realised). ■ The UK can optimise returns from its European XFEL membership while retaining flexibility to respond to (e.g.) cost changes.	■ UK strategic influence over international XFEL facilities is limited. ■ UK users are reliant on these international facilities and are limited to the capability provided, which may not fully meet their requirements. ■ UK is unable to achieve a guaranteed higher level of access and is constrained in user numbers. This will limit the ability of the community to deliver impact in the short-term, and will hinder the growth of the community, both in number and intellectually, in the long-term. ■ Skills development and associated pipeline benefits are primarily realised local to the host and not within the UK. Activities may promote a 'brain drain' of UK talent to the host. ■ Sovereign research applications including defence requiring ultrafast X-ray capability cannot be fulfilled without domestic infrastructure. ■ Maintaining the status quo forfeits opportunities to stimulate UK science and technology growth through strategic investment.
Opportunities	**Threats**
■ Potential funding could be allocated against other UK national priorities. This could be positively received, based on projected public spending pressures and public appetite for large-scale investment in UK science and scientific infrastructure. ■ UKRI can focus limited resources on strengthening UK user skills and access to existing international facilities through training, travel and other funding support mechanisms.	■ Limited access and influence concerning next-generation XFEL capability may erode the UK's global competitiveness in science and technology. ■ Without protected access, UK science and technology enabled by XFELs is vulnerable to external political and regulatory shifts. ■ UK-prioritised next-generation capabilities may not materialise due to external funding or strategic constraints. ■ Lack of investment reduces UK influence over strategic decisions shaping future XFEL capabilities. ■ Delaying a decision on a UK-based XFEL could result in a 10-15 year capability gap, undermining future strategic needs.

Table 7.1: SWOT analysis: no additional investment

Shared technical risk As applied to the technical challenges associated with those projects, UK expertise can help address R&D barriers which may prevent realisation of next-generation capability. The UK design team have enhanced their skills and experience as part of a three-year conceptual design project; these skills could be valuable to European XFEL and LCLS who must balance user operations with new design activities. Sharing the technical risk in this manner could increase the likelihood of an external upgrade project proceeding.

It is not clear if any in-kind contribution can result in some level of guaranteed access. For example, the UK 2% shareholding in European XFEL – itself based on an in-kind contribution to the construction phase – does not guarantee UK user access to the facility; this is solely judged on the scientific merit of proposals submitted. Likewise, the US 'Collaborative Access Team' (CAT) model, in which an external collaboration makes some form of contribution to ongoing operating costs, does not guarantee a specific level of access. Such contributions do however serve to influence the relevant bodies when beam-time is allocated, and may result in a higher level of access being awarded which exceeds the value of the contribution given.

In summary, an in-kind contribution would significantly strengthen the likelihood of UK users accessing next-generation XFEL capability. It would form the basis for influencing the scope and direction of an upgrade to align with UK next-generation requirements, and the value of that contribution could be used to negotiate improved access for UK researchers. More detailed consideration of any such agreement (etc.) is beyond the scope of this Options Analysis and would be the subject of a subsequent phase.

Any in-kind contribution would be directed at an existing area of UK expertise. This expertise could originate from national laboratories, academia and industry. It would likely be built upon existing structures and collaborations, and therefore the time required to ramp and prepare the relevant resources would be relatively short. The bodies involved – all of whom would most likely originate within the UK – would directly benefit from the investment during the 'construction' element of the activity (preparation and delivery of the contribution). The skills developed, as well as experience and reputation gained, could lead to further opportunities within this specific area; e.g., invited contributions, advisory roles/committees, etc., supporting other facility developments.

Although any contribution would likely be towards a specific deliverable, there is likely to be some transfer of broader technical expertise and experience from the host institution (and their partners) into the UK bodies involved. This knowledge and the experienced gained by working with international experts could provide longer-term benefits to UK institutions; e.g., large-scale scientific research infrastructure including ISIS and DLS.

Any contribution must fit within the project management and delivery frameworks of the external activity. These frameworks may impose limitations linked to delivery; e.g., employment of specific/preferred industry partners in the procurement and construction of specific systems. As such, the engagement of UK industry (and associated benefits) may be limited as compared to other UK institutions (etc.).

Assuming the contribution delivered leads to UK access, there would be benefits from the R&D activities performed, which would benefit from the facility capability as a whole and not just the specific area of the UK contribution.

The financial value of any in-kind contribution cannot be currently defined, although is unlikely to exceed $\sim$100 MGBP based on the current understanding of proposed facility upgrade plans. Such a contribution is likely to be delivered over $\sim$5 years, although this will vary with the specific facility/project in question. Any such investment could only be announced and delivered following confirmation of the upgrade activity, although could be confirmed in principle on that assumption.

It is not clear if it would also be associated (by necessity) with a long-term committent to facility operations costs.

From the perspective of this Options Analysis, even if an in-kind investment would only be made based upon certain conditions, there is still uncertainty in the realisation of those conditions – albeit these are reduced compared to the case of no additional investment. There may be (e.g.) political factors impacting the feasibility and timing of such an investment. These could be both positive (the investment could be announced as part of a broader bilateral agreement) and negative (political appetite for investment in a specific country could suddenly change). A SWOT summary describing the case of UK investment in existing infrastructure is presented in Table 7.2.

Strengths	**Weaknesses**
■ Enhances strategic influence over international XFEL upgrades. ■ Leverages areas of strength within UK national laboratories, academia and industry, including that developed through the UK XFEL conceptual design project. ■ Offers direct benefits to UK institutions charged with in-kind delivery, particularly during any construction phase. ■ Facilitates and strengthens international collaboration. ■ Delivery risk is owned primarily by the host facility.	■ No guaranteed access despite investment (c.f. UK shareholding in European XFEL). ■ Uncertainty in the realisation of proposed international upgrades, which may not fully meet UK requirements. ■ Engagement of UK industry potentially limited due to external project delivery frameworks. ■ Sovereign research applications including defence requiring ultrafast X-ray capability cannot be fulfilled without domestic infrastructure. ■ Complexity in negotiating access agreements and alignment with external timelines.
Opportunities	**Threats**
■ Potential to enable user access which exceeds the financial value of any investment. ■ Potential for long-term knowledge transfer and capability building between the UK and international partners. ■ Potential to increase likelihood and accelerate international projects through UK support including funding. ■ Improved UK reputation as a trusted partner may lead to invited contributions to other international activities. ■ Investment could be made a component of a broader bilateral agreement or strategic international partnership.	■ Internal and external political factors may affect feasibility or timing of investment. ■ Risk of residual misalignment with UK next-generation needs despite influence. ■ Dependence on external project success and timelines. ■ Financial value of investment currently unknown and to be subject to future negotiation, impacting planning processes. ■ Investment possibly associated with long-term operational cost commitments not yet clarified.

Table 7.2: SWOT analysis: investment to upgrade an existing international XFEL facility

Table 7.3 compares the case of no additional investment with investment in an existing XFEL facility. Both approaches are compatible with the objective of UK access to next-generation XFEL capability.

Without additional investment, the UK's strategic influence would remain as per existing channels, such as advisory roles held by members of the UK scientific community. In contrast, an in-kind investment would signal a clear national commitment to an international XFEL facility, enhancing the UK's influence on decision making and strengthen technical collaboration between the UK and that facility.

Guaranteed UK access to next-generation capability remains uncertain under current international access arrangements. However, an in-kind investment could significantly enhance the UK's

Criteria	Status quo	International upgrade	New facility
Strategic influence	Low	Moderate	High
UK access	Low	Moderate	High
Socioeconomic return	Low	Medium	Very High
Sovereign capability	Not supported	Not supported	Supported
Technical risk	None	Low	Moderate (shared)
Delivery risk	None	Medium	High
Financial risk	Low	Moderate	Very High

Table 7.3: Comparative analysis of UK investment models for access to next-generation capability (no additional investment, in-kind investment to upgrade an existing XFEL facility, construction of a new next-generation facility.)

position in annual beam-time allocations.

Demand for beam-time at international facilities currently exceeds supply, limiting UK participation. UK access could be improved by:

1. Negotiated access agreements that increase the number of hours allocated to UK researchers.
2. Facility upgrades that expand total beam-time capacity, in line with next-generation essential criteria.
3. Combined investment in both access agreements and next-generation facility upgrades.

A proposed next-generation upgrade – a second fan at European XFEL – could raise the number of accessible FEL sources from three currently to ten, tripling available beam-time.

An in-kind investment that boosts both UK access and facility capability would create headroom for community growth. It would also relax the scale of any access agreement; for example, an agreement to fix 2024 levels (11.6 %) combined with a second fan would still provide headroom.

Compared to European XFEL, data on UK access (proposal success rates, etc.) to LCLS is more limited. UK researchers were 4.5 % of all users in the period 2021-2024, and 3 % of users in 2024 alone. This level of access as compared to European XFEL may be due to multiple factors, for example a smaller proposal acceptance rate (greater competition), fewer applications involving UK researchers, higher costs associated with travel and location, or all of the above; the data required to make a conclusion is not available.

The same principles to the analysis to European XFEL would however apply; an in-kind investment, combining an access agreement with support for an next-generation upgrade, would be expected to surpass UK requirements and provide headroom for the community to grow. Projections performed for LCLS-X anticipate a factor 4.5 increase in available beam-time hours achieved by increasing from 2 to 10 FELs [29]. An access agreement with LCLS may encourage the UK community to propose more experiments at LCLS (e.g., addressing any hesitancy due to geographic location) and boost overall access in the short term. While still speculative, it is therefore not unreasonable for an in-kind investment in LCLS-X could have proportionally a larger impact on UK access.

The arguments above are based on several assumptions. A more robust assessment – incorporating detailed user data – will be required to provide a clearer understanding of the UK's access challenges. Facilities contacted as part of this project indicate variation in the way user data is recorded, making a broader analysis challenging. Any future study would need to engage and actively support the relevant user offices to achieve its goals.

The majority of the technical risk associated with a facility upgrade will lie with the host institution, with the UK picking up specific technical components as in-kind contributions. These would likely be directed towards areas of existing UK expertise, appealing more to international partners while reducing the risk of delivery.

Neither investment model supports sectors requiring secure environments for performing classified research. Such work demands full operational control and stringent security protocols which are not possible with international facilities – even with additional UK investment.

Although its value cannot be currently defined, an in-kind investment up to potentially $\sim$100 MGBP represents a moderate financial commitment. This value would be in addition to ongoing contributions to existing facilities, such as European XFEL operational costs, which would continue regardless of new investment.

Improving UK access to next-generation capability should be a key consideration. If enhanced access is a national priority, an in-kind investment potentially offers a viable path forward. If current access levels are deemed sufficient – which contradicts the findings of the Science and Technology Case – the case for taking up additional financial risk is weaker. The broader political and economic context should also influence any decision.

Given this context, a progressive approach as illustrated in Figure 7.1 may be preferable. This would allow the UK to build influence incrementally, while allowing a major investment to be timed with external factors such as bilateral agreements or major demonstrations of next-generation capabilities at other XFEL facilities. Such a strategy would balance opportunity with risk in an uncertain environment.

Diversification of an investment between multiple facilities could ensure access to the unique capabilities developed by **both** European XFEL and LCLS. It could also increase the overall capacity available to UK researchers, by overcoming limits to what might be acceptable at either one of these facilities.

7.3.3 Investment to create a new facility

Investing to establish a new UK-based XFEL facility represents a transformative step beyond the options previously discussed, which are effectively access models linked to existing infrastructure including associated upgrades. Such an investment would create a major new research infrastructure – potentially on the scale of a national laboratory – which would be a flagship scientific facility within the broader international landscape, bringing with it all the wider socio-economic benefits that comes with new national infrastructure.

The value of research infrastructure to the UK is expressed in the 2020 UKRI Infrastructure Roadmap [16]:

> "*...research productivity and inward investment are founded on the availability of internationally competitive, high-quality infrastructure. Access to world-leading infrastructures supports research and innovation activity at all scales, from individual investigators to large multinational collaborations. They act as a magnet to international talent and users, contribute to local and national economies, and generate knowledge and capability critical to UK policy, security and wellbeing. Many link to the development of key sectors of the economy, including those supported through Sector Deals as part of the Industrial Strategy. Others perform vital functions for government policy-makers including statutory functions, informing public policy, improving public services and supporting resilience and response to emergencies.*"

In summary, a UK-based XFEL would deliver benefits beyond that delivered through the scientific research enabled, including:

- Economic and regional development
- Skills and talent development/retention
- National resilience and security
- Strategic autonomy control

A domestic facility would give the UK majority control over its capability, delivery, and operations including access model – primarily at the expense of high technical and financial risk. As outlined in **??**, the entry point for a new national facility would likely be greater than 1000 MGBP and shared with international partners. The delivery of this investment would likely span multiple government terms.

A new facility fundamentally achieves all of the project objectives:

- The capability of the facility would be completely tailored against all UK science and technology requirements criteria, as defined by the Science and Technology Case.
- Establishing a UK-based XFEL facility is anticipated to serve as a major catalyst for UK researchers. Drawing on usage patterns observed at XFEL international facilities, it is expected that they will engage with the facility at scale and form the majority of its user base. This concentrated engagement would reinforce the UK's leadership in ultrafast science and innovation, perpetuating further community growth.
- As the host nation, the UK would have majority control over the delivery, with flexibility in scaling to adapt to future national priorities. This is facilitated by the phased approach as outlined in **??**.

Defence and security sectors require guaranteed access to the most advanced measurement methodologies. In order for these agencies to exploit it, a new facility would need to be designed to include a secure data pipeline and dedicated access channels. This was identified as a priority by attendees from relevant UK agencies at the UK XFEL Defence Town Hall, who also highlighted such access is impossible to implement at international facilities.

The design of a new facility with next-generation capability would need to overcome major technical challenges, examples of which are listed in Table 7.4. Their resolution would be the subject of a technical design phase. Several of these challenges are under active investigation internationally, presenting the UK with a strategic opportunity to engage partners in joint problem solving for mutual benefit.

Delivering a new XFEL facility in the UK will require a coordinated national effort, drawing on expertise from national laboratories, academia and industry. This mobilisation of skills and resources would represent a significant increase on current levels. An appropriate strategy to achieve this would be the focus of a future technical design phase. This phase itself would require an escalation of available effort across a range of disciplines. As a project of international significance, it should expect to attract world-leading talent to the UK.

The construction and operation of a UK-based facility will be governed by a complex landscape of legal and regulatory factors. Research activities would need to comply with UK patenting law (and protections), health and safety laws, employment laws and fiscal regulations. Vice-versa, UK researchers performing research abroad will be subject to regulatory and institutional frameworks local to the relevant facility. Differences in intellectual property regulations and GDPR could

Technology challenge	**International activity**
Reliable operation of high repetition rate (1 MHz) electron linac	Significant investigation already underway, based upon comparable performance requirements at LCLS-II now, and LCLS-II-HE and SHINE in future
Simultaneous operation of multiple (optimised) FELs from same linac	European XFEL currently operates 3 FELs in parallel. LCLS-II-HE and SHINE currently plan to operate 2 FELs in parallel. High-order multiplexing is the subject of proposed activities including a European XFEL second fan and LCLS-X
Transform-limited pulse generation across a range of X-ray photon energies	Investigations underway in specific photon energy ranges and specific techniques. Investigation of HB-SASE concept at SwissFEL at low repetition rate. Wide-spread application across a broad tuning range could be investigated in proposed activities for LCLS-X. Specialised consideration required to applicability of techniques at high (100 kHz) repetition rate
Dual photoinjector operation for optimised FEL performance	Limited precedent, with no major comparable activity underway. Possible subject of future investigation for European XFEL, but unclear if fundamentally required to achieve their strategic objectives
High power beam dump and radiation protection for 1 MHz operation	Very limited precedent. Some discussion of proposed designs for SHINE and LCLS-II, but those facilities are currently proceeding with order-of-magnitude lower power designs

Table 7.4: Major technology challenges associated with a next-generation facility, and international precedent (including planned activities).

be important in cases where industry is collaborating with academia and linked to sensitive commercial outcomes or information.

Environmental factors will play a critical role in both the construction and long-term operation of a new facility. These include:

- Development of a greenfield site and associated planning procedures, which could be subject to changes during construction and operational phases.
- Impact on energy use from domestic variations in energy costs and access to the national grid.
- Carbon costs associated with international travel, which apply equally to UK researchers attending an international facility, and international users attending a UK facility.

The development of a UK-based facility presents a unique opportunity to generate socioeconomic benefits impacting multiple sectors. These benefits and the associated Theory of Change (TOC) model for a new facility is compared against other options in the UK XFEL socioeconomic report. Key conclusions from this report are summarised below:

1. **Investing in a new UK-based facility is expected to deliver greater benefits to the UK than international access models.** This is primarily driven by the UK's ability to retain full control of strategic inputs and activities during project delivery. However, this approach would require higher levels of investment from the UK government.
2. **A UK-based facility would have multiple impact pathways which extend well beyond infrastructure (build and maintenance) and R&D.** They include financial management, workforce development, business and sector development, collaboration, and public engagement.
3. **Strategic coordination of investment across these impact pathways can amplify benefits and create systemic value.** This should take into account various options including the timing of activities (e.g., early engagement with industry, workforce training) and the choice of the facility's location within the UK, which is yet to be decided.
4. **Rates of return on investment would *likely* be higher for UK-based infrastructure than international infrastructure**, based on evidence identified from previous infrastructure developments (e.g., Diamond Light Source). However, further investigation and evidence is required to establish clear estimated (or comparative) rates on return; this should be performed as part of any future business case.

A summary of the strengths, weaknesses, opportunities and threats for investment in a new next-generation XFEL facility is provided in Table 7.5.

Evaluating the case for investing in a new UK-based XFEL facility, versus investment in existing international infrastructure, is challenging. The financial disparity between options is substantial: international options would likely be associated with an investment of up to ∼100 MGBP, whereas a new facility would exceed 1000 MGBP. Crucially, both the benefits and risks of each option scale with investment level.

The international options listed primarily represent enhanced access models for UK researchers. In contrast, creation of a new facility represents a strategic investment in national capability, sovereignty, and UK society more broadly. The socioeconomic impact pathways differ, with factors such as financial management, workforce development, business and sector development – all

Strengths	**Weaknesses**
■ The UK would retain majority control over the facility's capability, delivery, operations and user access models. ■ The capability of the facility would be fully aligned against all UK science and technology requirements, including the essential criteria listed. ■ A UK-based facility would host sovereign research activities in support of defence and national security interests, for which secure access – which cannot be guaranteed at overseas facilities – is essential. ■ The socioeconomic return to the UK would be maximised as compared to other investment options, by giving the UK full control over strategic inputs and activities during project delivery. ■ Impact would be realised across diverse pathways, including in non-research driven domains (e.g. financial management, workforce development, business innovation, public engagement) of relevance to the UK's Modern Industrial Strategy. ■ The construction and operation of the new facility are likely to attract global talent to the UK, enhancing its reputation as a scientific superpower. ■ Data produced by a new national facility – which would be one of the largest data 'factories' in the world – could be leveraged as an asset in support of economic growth.	■ A new facility would be a multi-billion pound investment and committent running over multiple government terms. ■ The UK would bear the majority of delivery risk and need to navigate complex UK legal, environmental and planning frameworks to ensure construction of the facility. ■ Coordination of international partner contributions to the facility (including construction and user operations) will be complex and involve significant stakeholder engagement. ■ The UK would be responsible for resolving major technical challenges associated with next-generation capability (Table 7.4).
Opportunities	**Threats**
■ Global partners can be engaged against technical, financial and in-kind contributions, strengthening UK-international scientific collaboration. ■ Strategic coordination of investment across impact pathways could amplify socioeconomic benefits, with site selection offering a targeted means to augment regional growth. ■ A phased delivery model as proposed would allow the facility to adapt to evolving national priorities and incorporate technology advances in XFEL capability. ■ Rates of return on investment are likely higher for UK-based infrastructure as compared to international investments, however further investigation is required to confirm this. ■ A new facility would be of the scale of a national laboratory and represent an opportunity to stimulate science, technology and innovation developments around a new hub.	■ Public spending pressures and political shifts throughout decade-spanning delivery may impact project continuity and support. ■ While international partnerships are expected, the scale and timing of their contributions is not known and may result in delays or higher costs to the UK. ■ A Phased delivery model introduces cost inefficiencies due to inflation, staff retention and focus, along with potential disruptions to user operations. ■ Advances at international facilities such as European XFEL, LCLS (LCLS-X) and SHINE may compete for UK users and diminish the strategic relevance of a UK facility. ■ Successful delivery would require complex coordination of contributions from across academia, industry and government. ■ Varying environmental factors could emerge and impact construction and operations phases, including regulations determining greenfield site development and energy sourcing.

Table 7.5: SWOT analysis: investment to create a new national XFEL facility

important to the UK government's Modern Industrial Strategy – not as relevant to the international options.

The option to invest in a new next-generation XFEL facility is compared against the status quo and international upgrade options in Table 7.3.

7.3.4 Combined approaches

Greater benefits can be potentially achieved by combining investment in a new facility with an investment in an existing facility.

An investment could be divided between a potential next-generation facility (e.g., European XFEL, LCLS) and another which, while not immediately compatible with the essential criteria, would provide complimentary and coherent benefits. An investment in a facility such as FERMI could, for example, provide immediate access to transform-limited pulses (EC-II) at soft X-rays and allow researchers to build expertise prior to experiments at European XFEL/LCLS-X.

An alternative investment strategy could involve a dual approach, combining the development of a new UK-based XFEL facility with strategic engagement in an existing international facility. For instance, the UK might construct Phase 1 (**??**) of a next-generation facility focused on lower photon energies, while concurrently investing in a high-energy, hard X-ray facility such as the European XFEL or LCLS-X. This approach could be formalised through a collaboration agreement, enabling UK researchers to access the facility best suited to their scientific needs. It would enhance overall capacity and capability available to the UK research community, optimise the return on investment, and reinforce the UK's leadership within the global XFEL landscape.

A joint investment would involve multiple negotiations which could be complicated by the relationship between stakeholders. While challenging to manage, this approach could accelerate benefits realisation in the event one project is delayed or is subject to changes in scope (see risks, Table 7.2).

Supporting the creation of a new facility through investment in an existing facility has several major benefits:

1. Depending on the construction timescale of a new facility compared to planned developments, it could accelerate access to next-generation capability. Timely access would strengthen and develop the UK user base in preparation of access to a new facility.
2. An investment in an existing facility could be strategically made to complement – but not duplicate – the capability of an existing facility. This would broaden the resources available to UK researchers. It could also enable shared access models, in which the community is directed to the facility which is best aligned in capability, promoting growth at both locations.
3. An in-kind investment towards an existing facility would promote collaboration, knowledge sharing and skills development in a wide range of areas. Assuming compatible timelines, this could de-risk a major technical challenge or serve as a prototyping phase for a new facility build. It would also help establish a trusted collaborative platform on which future facility developments can be built, and lessons-learned shared.
4. These benefits could be realised at an additional $\sim$5-10 % of the total project cost of a new facility, and – if aligned appropriately – could be comparable in value to major technical risks.

For these additional benefits to be realised, scope and delivery must be strategically aligned and actively managed. For example, it is important that the capability of a UK facility is appropriately positioned within the existing and planned international landscape. Effective working relationships must be built and maintained with prospective stakeholders during all phases of a new facility build, and any joint activities appropriately timed so that they can benefit that build.

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