IOP Institute of Physics

Institute of Physics (IOP) priorities for Spending Review 2021

Executive summary

Almost every modern-day technology has its origins in fundamental physics discoveries. From building particle detectors, sensors of all types and advanced satellite platforms to better understand our planet and the universe, to using new materials and nanotechnology to drive engineering advances, or developing new cancer diagnostics and treatments to improve outcomes for patients, UK physics has been indispensable to many of the world's most impactful and successful innovations.

Many of these applications have grown from the world-leading discovery science of the UK physics community, where the intellectual and technical leadership have delivered discoveries from the nature of fundamental particles to new materials. Physicists in the UK have played key roles in major discoveries from the Higgs boson to gravitational waves to graphene. This success and impact is a consequence of the UK's strong historical investment in physics and will only be sustained if funding is increased to levels that match or exceed international comparator nations.

A desire to explore the great open questions such as how the universe came into being and how the matter we are made from was created and, increasingly, a desire to apply such fundamental knowledge to tackle problems like climate change and improve people's lives inspires young people on journeys which lead to careers in STEM. Without the pull of this inspiring science there would be a reduced flow of talent into many of the sectors the UK relies on for physics inspired skills.

Investment in physics is a catalyst for innovation and growth. Physics-based businesses span sectors including manufacturing, energy and services, and contribute 10.6% of UK GDP, employing more than 2.7 million people (10% of total UK employment). More than 20% and perhaps as much as 30% of UK businesses' R&D takes place in industries that rely strongly on physics research. Given the right conditions, 59% of physics innovators in industry expect their R&D/innovation spending to increase over the next five years.

Many of these industries will have the biggest impact on the Government's net zero ambitions, meaning that additional support for physics R&D will accelerate progress towards the 2.4% R&D investment target and fuel the green industrial revolution.

Physics research, innovation, knowledge and skills can play a defining role in the realisation of the ambitions set out in the Government's Innovation Strategy and Plan for Growth – but only if they are nurtured and supported.

To become a science and innovation superpower the Government must:

1. Accelerate progress towards 2.4% and beyond to 3%
    a. Set a clear trajectory to reaching the £22 billion public R&D investment target by 2024/25, to accelerate progress towards the 2.4% target and avoid being left behind by international competitors.
    b. The uplift should be delivered in even increments over three years, rather than a more significant uplift towards the end, to incentivise businesses to increase R&D investment early in the UK's emergence from the Covid-19 pandemic.
    c. Increase support for physics-based business innovation with additional funding for early-stage R&D and development-stage activities, a focus on long-term funding schemes (supporting technology-driven, challenge-led and high-risk, high-reward research), and a more attractive tax environment to promote the commercialisation of new technologies, manufacturing and exports.

   d. Work with the IOP to create a roadmap of new technology sectors which draw on fundamental physics discoveries to emulate the development of the successful UK photonics and compound semiconductor sectors, secure the future development of the National Quantum Technologies Programme, and recognise the potential of emerging sectors such as metamaterials and spintronics.

2. Invest in world-leading university research
   a. Much of the work that underpins and will drive advances in the technology families which lie at the heart of the UK Innovation Strategy, has come from physics research in our universities. To realise the full benefits of these transformative technologies, our university physics research base needs to be world-leading and sustainable.
   b. Return QR funding to at least 2010 levels and increase the proportion of full economic costs recovered on all publicly-funded research grants, to sustain UK university research at the forefront of global science.

3. Strengthen the UK's international presence and partnerships
   a. Maintain a strong presence in international networks, infrastructures, partnerships and programmes, and remain open and attractive to talented researchers and innovators from overseas. This should include continued support for UK scientists to participate in international programmes in all physical science areas.
   b. Ringfence funding for association to Horizon Europe for the duration of the programme.
   c. Invest in new international collaboration channels, such as the proposed strategic partnership programme to develop physics capacity, including access to facilities, in sub-Saharan Africa.

4. Invest in research and innovation infrastructure
   a. Invest in and develop world-class domestic facilities to help the UK attract and develop talent, create strategic partnerships, grow inward investment in innovation, and strengthen national capability.
   b. Review future opportunities for UK physics facilities, drawing on expertise, advice and evidence from UKRI's infrastructure advisory committee and infrastructure review.

5. Place diversity and inclusion at the heart of UK science and innovation
   a. Prioritise the R&D People and Culture Strategy's ambitions to create a more inclusive research culture in which everyone can thrive, to drive future innovation, and ensure that research and innovation funding structures support this.
   b. Revise teachers' professional standards and ensure that teachers are trained to teach inclusively and tackle injustice, and direct Ofsted to place greater emphasis on inclusive teaching (as well as consistently consider teachers' subject-specific professional development) in school inspections, as set out in the IOP's Limit Less campaign.

6. Bolster provision of physics education and skills
   a. Invest £87 million over three years into an Office for Science Education Professional Development to address the specialist science teacher shortage. The Office should lead a world-class system of subject-specific CPD, to provide more confident, engaged teachers with the necessary subject knowledge, and learners with equity of access to quality education – ending wasteful and damaging teacher churn and building the skills we need to make the UK a science and innovation superpower.
   b. Work with the IOP, employers, education and training providers and funders to address the growing need for technical skills in physics- and engineering-based businesses: building the right skills via supporting initiatives such as the STFC Skills Factory proposal, and testing whether the new technical skills environment will provide an effective alternative to the academic education route, to create a more robust and diverse future skills supply.

1 Introduction: Physics, productivity and prosperity

Physics, as the science of matter and forces, provides a fundamental understanding of the universe and in turn creates innovation. Just as the development of many of the devices we rely on in our modern lives were, many of the key innovations we expect in the coming decades will be driven by physics. These include not only transformative new technologies such as quantum technologies including quantum sensors, cryptography and computing, advanced materials such as metamaterials and graphene, and zero-carbon energy generation using, for example, nuclear fusion, but also step-change improvements resulting from advances in laser-based photonic systems, next-generation multi-layer silicon devices, climate modelling and forecasting, cancer treatment, advanced robotics, miniaturisation, and extending the Internet of Things and management of large-scale data and data processing.

We increasingly depend on knowledge and skills from physics and other disciplines to address the challenges facing us, whether through diagnosis and treatment in healthcare, living more prosperously and sustainably, addressing inequities in access to water and food, meeting our energy needs or protecting our biodiversity. In all these ways, and others, physics has the potential to improve our lives, whilst also creating high-value jobs and generating economic growth.

As we emerge from the Covid-19 pandemic, the UK has an opportunity to harness the transformative potential of physics to drive economic growth, improve our health, increase standards of living and lead the way in the transition to a net zero world and a new green economy.

For these reasons and others, the importance of this Spending Review cannot be overstated. The Spending Review takes place against the backdrop of a strong initial recovery from the greatest economic shock in modern times, a world-wide climate emergency and the advent of a new industrial era, that will be dependent upon scientific discovery and technological innovation. In the same way that the post-war recovery heralded rapid and sustained improvements in quality of life, the post-pandemic era offers an opportunity for the UK to chart a sustainable route to a green recovery with the benefits of a more prosperous society and productive economy available to all.

The Government has recognised the importance of science and innovation to the country's future and has set out an ambitious prospectus. Between them, the Plan for Growth, Integrated Review, Innovation Strategy and R&D Roadmap explain how and why the Government intends to set the UK on the path to becoming a scientific superpower.

With ambitious goals come unprecedented opportunities. The Government must now unlock the resources needed to unleash a new wave of innovation and make sure everyone in every part of the UK can realise the full benefits of the societal and economic revolution and recovery that science can deliver.

2 The social and economic contribution of physics

Physics plays a fundamental role in the global economy. Since the dawn of modern physics in the early 20th century, ground-breaking physics research has set the direction and pace of social and economic progress. Almost every modern-day technology has its origins in fundamental physics discoveries. Whether it is designing new particle detectors or advanced satellite platforms to understand more about the fundamentals of our universe or to monitor the earth for environmental impacts, using innovations in new materials, the development of devices such as the liquid crystal display, nanotechnology and quantum applications in new and highly innovative engineering practice, or breaking new boundaries in cancer diagnosis and treatment and medical imaging (such as MRI), the UK has fostered and is widely recognised for some of the world’s most rich and successful innovations.

Medical physics has demonstrated its strength and potential to further contribute to the life sciences. Areas such as proton beam therapy, multispectral medical imaging technologies and related small-scale portable devices (which have also helped further develop robotic surgery) have all continued to demonstrate potential for further growth. One very current example is the use of the high-powered light-source technology at the Diamond Light Source facility to image the Covid-19 virus, helping to rapidly accelerate the development of new vaccines.[1]

Photonics has for many years been a UK strength and remains a hidden economic engine: in 2020, companies manufacturing and delivering services based on photonics technology in the UK produced £14.5 billion in output, employed nearly 80,000 people and contributed £6.5 billion of gross value added (GVA) to the UK economy.[2] As the technology continues to develop and demand increases across applications from food, health and communications, the UK photonics sector is expected to grow to a £16 billion industry by 2022.

Similarly, the compound semiconductor cluster, CSConnected, in South Wales is a world-leading centre of innovation, showcasing Wales's unique capability to be centre stage in the development of new and emerging technologies and strengthening the long-term economic prospects for the regional economy. A recent report by the Welsh Economy Research Unit at Cardiff University found that CSconnected firms and institutions directly supported £121 million of Welsh GVA in 2020.[3] In the final quarter of 2020, CSconnected firms and institutions accounted for an estimated 1,400 jobs, showing a stability of employment despite the challenging economic conditions during the global pandemic, and with output largely maintained at a time when there has been a 10% contraction in UK economic activity, the largest annual contraction on record.

The strategic growth of quantum technology as one of the extended Eight Great Technologies programme has paved the way for the UK to become a global leader in this sector which will have major implications from state-of-the-art measurement, secure communications and step changes in computing and calculation. The investment in low and high TRL (technology readiness level) programmes is a model for the support of turning discovery physics research into products. Quantum technology will touch all parts of life from medical imaging and advanced measurement of brain function through to defence and security. It is likely that quantum technology will grow into a major UK technology, industry and service sector.

Quantum physics is not alone in being an area of discovery science with strong translational potential and there needs to be a co-ordinated, strategic national approach to identifying and developing new fields that are ripe for translation. These objectives must be at the top of the agenda for the new National Science and Technology Council, Office for Science and Technology Strategy and Advanced Research and Invention Agency. Examples of such areas include metamaterials and spintronics. Metamaterials can play an increasingly critical role in delivering affordable, reliable and above all, green energy. Spintronics is one of the emerging fields for next-generation nanoelectronic devices to reduce their power consumption and increase their memory and processing capabilities. Mirroring the success of the photonics sector, there is enormous potential for these physics-based technologies to grow the UK economy and ensure resilience and diversity that extends beyond the current reliance on the service sector, playing an important role in meeting the UK's Net Zero ambitions.

Taken together, physics-based businesses make a substantial contribution to the UK economy, enhancing productivity, boosting economic growth and increasing prosperity. Spanning a diverse

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[1] Diamond Light Source. Research contribution on COVID-19 https://www.diamond.ac.uk/covid-19/for-public/diamonds-research-efforts.html

[2] Photonics Leadership Group (2021). Photonics grows to a £14.5 billion UK industry https://photonicsuk.org/photonics-grows-to-a-14-5-billion-uk-industry

[3] Welsh Economy Research Unit, Cardiff University (2021). Revised economic baseline: Compound Semiconductor Cluster in South Wales https://csconnected.com/wp-content/uploads/2021/04/20210422_CardiffUniversityreport_MaxMunday.pdf

range of sectors – including manufacturing, energy and services – it is estimated that physics-based businesses contribute 10.6% of GDP in the UK.[4] Physics-based businesses also directly employ more than 2.7 million people (in FTE terms), a 10% share of total employment in the UK, and this is set to grow in the coming years if current trends continue. The sector is highly productive, with each person employed in physics-based businesses contributing an average of £84,000 a year in value added.

In the years to come, we will depend even more on the knowledge and skills from physics and other disciplines to address the challenges facing us, whether through diagnosis and treatment in healthcare, living more prosperously and sustainably, addressing our energy needs or protecting our biodiversity. In all these ways, and others, physics has the potential to improve our lives.

3 Becoming a science and innovation superpower

The UK's track record in physics is remarkable. The historical leadership that the UK has been able to demonstrate in physics and foundational science will only be sustained if investment is at levels that match or exceed international comparator nations. We welcome that UKRI funding for physics research increased between 2010 and 2020 partly through establishment of the Industrial Strategy Challenge Fund and increases in funding for applied science. Commensurate increases in funding for foundational research are necessary if the UK is to sustain and grow the research fields and skills that will be needed to secure the UK's status as a science and innovation superpower.

A significant proportion of UK business R&D takes place in industries with high physics intensity (industries that rely strongly on physics research).[5] IOP estimates suggest that such industries account for more than 20% and perhaps as much as 30% of the R&D performed by UK businesses. These industries include some of those which will have the biggest impact on the Government's net zero ambitions (such as energy, automotive and aerospace), meaning that additional support for R&D in these sectors will have the dual benefits of accelerating progress towards the 2.4% and driving the innovation which will fuel the green economy.

Physics-based businesses will, therefore, play a defining role in the realisation of the ambitions set out in the Government's innovation strategy, the objective of which is to boost private sector investment by making innovation central to everything they do.

Physics-based businesses are innovators by nature and they plan to increase investment in research and innovation in the five years ahead. As evidenced by the CBI Economics report 'Paradigm Shift' commissioned by the IOP, business activities that we identify as built on physics skills and expertise are associated with high levels of innovation. Across the UK, physics-based firms are making innovation central to everything they do: actively investing in scientific discovery and technology, driven by the goal of developing new products or services and growing their businesses. 89% of physics innovators agreed that R&D/innovation is a strategic priority that is incorporated into their business plans. Given the right conditions, 59% of physics innovators expect their R&D/innovation spending to increase over the next five years relative to the previous five years, thereby accelerating progress towards the 2.4% target and unlocking associated economic and societal benefits.

Put simply, of those companies that are doing physics, most are innovating, and those that are doing the most high-intensity physics tend to be innovating more. Investment in physics continues to be a demonstrable catalyst for innovation and growth.

[4] CEBR (2021). Physics and the Economy (UK). Publication pending. Data from 2019.

[5] The IOP determined the physics intensity of industries by analysing the publicly-funded, privately-conducted research projects for all businesses in a given industry. Those industries with high levels of physics research overall were categorised as high physics intensity industries.

However, the report identifies challenges that innovating businesses face in securing investment, accessing skills, and collaboration – areas where government support is needed to enhance capability and economic return. It identifies regional variations that show that not all parts of the UK are benefitting equally. And although the UK is a world-leader in research and idea generation, supported by globally renowned universities which attract the best talent from around the world, it simply does not do enough R&D by any international comparative measure, and it lags behind on successful commercialisation of ideas. Importantly, we need to do more to retain innovation and IP in the UK to benefit from the huge growth potential and the related inward investment.

The UK can do better. To do so, the nation requires an ambitious R&D roadmap so physics-based businesses can thrive and play their part in unlocking the benefits that physics can offer society and the economy.

The Spending Review is a pivotal moment for the Government to ensure the necessary investment and the right conditions are in place for UK physics research and innovation to flourish.

3.1 Accelerate progress towards 2.4% and beyond to 3%

The UK has a world-leading and highly productive research base. However, the UK invests relatively little in R&D by international standards. Over the past three decades, the UK's R&D intensity has remained consistently between around 1.5% and 1.7% of GDP, well below the current OECD average of 2.5%.[6] Global competitors, such as Germany, Japan, South Korea and the US, are already investing more than 3% of their GDP in R&D and are pulling further ahead, with international expenditure growing more strongly in recent years than at any point since the mid-1980s.[7]

The Government has previously committed to increasing R&D investment to 2.4% of GDP by 2027, and to 3% in the longer term, to bring the UK in line with its competitors and cement its status as a science superpower. The latest data published by the Office for National Statistics[8] shows that the UK's R&D expenditure rose to 1.74% of GDP in 2019, up slightly from 1.72% in 2018. This represents the seventh consecutive annual increase in R&D intensity, which is positive progress, but the pace and scale of investment must increase significantly if the UK is to reach the 2.4% target.

The current low level of R&D investment limits the UK's ability to develop and build on scientific discoveries and innovations, which are vitally important in raising productivity, prosperity and long-term economic growth. The UK STEM community has the talent, skills and knowledge to capitalise on R&D investment and fuel technological, social and economic change. The need for investment has become all the more significant as we turn to technology, knowledge, skills, and innovation to support economic recovery from the impacts of Covid-19.

The Government must set out a clear trajectory to reaching the £22 billion public R&D investment target by 2024/25, as committed to in the 2020 Spring Budget, to accelerate progress towards the 2.4% target and avoid the UK being left behind by international competitors.

The need for additional investment is urgent. The uplift should be delivered in even increments over the three-year period, rather than through a more significant uplift towards the end, to boost businesses' confidence and incentivise them to increase investment in R&D early in the UK's emergence from the Covid-19 pandemic. Evidence suggests that £1 of public R&D investment stimulates between £1.96 and £2.34 of private R&D investment in the long run, with the majority of

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[6] OECD. Main Science and Technology Indicators [accessed 9 September 2021] https://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB

[7] OECD (2021). OECD Main Science and Technology Indicators: Highlights on R&D expenditure https://www.oecd.org/sti/msti-highlights-march-2021.pdf

[8] Office for National Statistics (2021). Gross domestic expenditure on research and development, UK: 2019 https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2019

private investment crowded in five years after the public investment.[9] Increased public investment is therefore needed now to maximise the amount of private R&D investment leveraged by 2027 and beyond. The CBI asserts that 'increasing direct investment to £22 billion by 24/25 would leverage sufficient business investment to reach the 2.4% of GDP target in 2027.'

3.2 Invest in world-leading university research

From subatomic particles to the most distant objects in the universe, physics enables our understanding of the world around us and contributes to the improvement of our everyday lives.

The mobile phone is an exemplar of the role of (often seemingly unrelated) advances in discovery physics and maths research in sparking innovation which delivers breakthrough technologies and creates new markets and industries. Work by Maxwell and Hertz on electromagnetism in the late 19th century, along with more recent developments in information theory, semiconductor physics and microelectronics, all played an enabling role in the development by industry of one of the most transformative products of the modern age.[10] Even Einstein's theories of special and general relativity, viewed for many years as having little practical application, are essential to the accuracy of the GPS that determines our phones' locations and underpins around 7% of UK GDP.[11]

UK universities' physics departments have played an indispensable role in many of the developments outlined in section 2, and their outputs – fundamental knowledge, novel insights and highly skilled, adaptable people – will also be needed for the future technological advances that will drive the UK's economic engine and shape the society we live in. (Further examples of the impact generated from UK university physics research can be found in the appendix.)

The Government's Innovation Strategy describes 'seven technology families of UK strength and opportunity' which, if harnessed, can help us to tackle large-scale, complex societal challenges and 'shape our lives in the decades ahead'. These technologies are:

- Advanced Materials and Manufacturing
- AI, Digital and Advanced Computing
- Bioinformatics and Genomics
- Engineering Biology
- Electronics, Photonics and Quantum
- Energy and Environment Technologies
- Robotics and Smart Machines

Much of the work that has underpinned advances in these fields, and in challenge-led innovation such as that supported by the Industrial Strategy Challenge Fund, has come from the physics research base in our universities. Indeed, the bearing of physics on these complex challenges is well illustrated by the fact that Innovate UK is now the single largest source of physics research grant funding in the UK.[12] To make sure the UK is able to continue driving these and other transformative developments, and to realise the full societal and economic benefits, our university physics research base needs to remain world-leading. That means strengthening our research and innovation ecosystem and building more productive ties between universities, research institutes, businesses

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[9] Department for Business, Energy & Industrial Strategy (2020). BEIS Research Paper Number 2020/010: The relationship between public and private R&D funding https://www.gov.uk/government/publications/research-and-development-relationship-between-public-and-private-funding

[10] Neuvo (2008). Industry needs universities and vice versa. *The University in the Market* https://research.aalto.fi/en/publications/industry-needs-universities-and-vice-versa

[11] Oxford Economics (2012). The economic impact of physics research in the UK: Satellite Navigation Case Study https://stfc.ukri.org/files/satellite-navigation-case-study/#:~:text=Based%20on%20GPS%20(Global%20Positioning,or%20about%20%C2%A3100%20billion

[12] IOP analysis of UKRI data

and government. Most crucial, however, is the need to put research funding for physics on a sustainable footing.

Both elements of the UK's dual support system – the block grant largely comprising quality-related (QR) funding and Research Council funding to support specific research projects and programmes – provide essential support to the world-leading research that takes place in UK universities.

The long-term, flexible nature of QR funding enables universities to act strategically, explore new and high-risk avenues of research that underpin future innovation, and pursue excellence in line with their institution's and local strengths. Without QR funding, the UK would not have had innovations and discoveries such as graphene, genomics, opto-electronics, and new tests and treatments for everything from bowel disease to diabetes, dementia and cancer.[13] However, analysis from the Russell Group reveals there has been a 14% real-terms decline in QR across the higher education sector in England between 2010/11 and 2020/21, and that the balance of funding between QR and Research Council funding has fallen from 80p in the pound in 2007 to 50p in the pound in 2018.

To sustain UK university research at the forefront of global science, the Government – working in partnership with UKRI – needs to address the decline in the value of QR funding and return support to at least 2010 levels. As additional investment is made as part of reaching the target of 2.4% of GDP, a more sustainable balance between QR and Research Council funding will allow universities to continue to forge new partnerships with business and industry, invest in the talent pipeline, build research capacity and use R&D to power future economic growth.

In addition, research in the UK's universities is currently funded at levels below the full cost of performing that research, with the total deficit for research activity in universities in England and Northern Ireland reaching more than £4 billion in 2019/20.[14] In particular, universities only recovered 71% of the full economic costs (FEC) of research funded by the Research Councils, substantially less than the 80% committed to. This deficit requires universities to cross-subsidise research from other income-generating activities and leads to an unsustainable system in which research capacity is dependent on factors, such as tuition fee income from overseas students, which have been negatively impacted by the Covid-19 pandemic and which vary between institutions.[15]

The Government should increase the proportion of FEC recovered on all publicly-funded research grants to safeguard the sustainability of the world-leading research that takes place within the higher education sector and ensure long-term capacity exists in all universities, in all parts of the UK, to deliver an increase in research activity.

3.3 Boost support for business R&D

Physics innovation, while economically beneficial, can at early stages be costly and risky and can entail development times that are longer than for other technology areas. This gives rise to complex financing needs that must be sustained over time. Costs and finance pressures are most acute at the manufacturing stage of the R&D/innovation journey.

Currently, the UK invests little (compared with other nations) in the development aspect of R&D, with support at intermediate technology readiness levels (TRLs) lacking. This limits the likelihood that new knowledge will be transformed into products and services which create impact, benefit society and provide a financial return on R&D investment.

[13] Russell Group (2021). Underpinning our world-class research base – the importance of QR funding https://www.russellgroup.ac.uk/policy/policy-documents/underpinning-our-world-class-research-base-the-importance-of-qr/
[14] Office for Students (2021). Annual TRAC 2019-20 https://www.officeforstudents.org.uk/publications/annual-trac-2019-20/
[15] HEPI (2021). Regional policy and R&D: evidence, experiments and expectations https://www.hepi.ac.uk/2021/05/13/regional-policy-and-rd-evidence-experiments-and-expectations/

These challenges were confirmed by the recent survey undertaken by CBI Economics on behalf of the IOP, which found that:

- Half of physics innovators said the most significant challenges they face when undertaking R&D/innovation are the direct costs (50%) and potential costs/finance risks (46%)
- Cost pressures are greatest during large-scale prototyping (40% of physics innovators) and production/scaling up stages (40%), the latter also reflecting the phase when it is most difficult to secure funding (40%).

Short-term funding has also been identified by IOP members as a challenge for larger or more technical projects. In such cases, problems can arise when short-term funding runs out with research still incomplete. This is particularly the case in less developed research areas which may also need longer-term funding to reach the point of commercialisation.

Amid pressures on public finances and corporate cash balances following the Covid-19 pandemic, creating the right conditions for all businesses to innovate and giving them the confidence to do so can help unlock future investment.

Firms have told us that the right support from government and public investment stimulates R&D activity that would not have otherwise occurred:

- 64% of UK physics innovators that had received public funding for R&D/innovation said that it fills a financing gap without which the activity would not take place
- 53% of UK physics innovators said public funding supported the development of products/services that otherwise may not have been produced.

The Government must increase support for business R&D and funding for development-stage activities, to support later stage technologies and facilitate commercialisation. A focus on long-term funding schemes (supporting a mix of technology-driven, challenge-led and high-risk, high-reward research) and a more attractive tax environment can also help promote the commercialisation of new technologies, helping support manufacturing and exports in the UK in a way that builds strategic advantage. In particular:

- 67% of physics innovators in the UK said greater access to direct funding for early-stage R&D could encourage more R&D/innovation activity in the next five years
- 61% of physics innovators in the UK said long-term funding schemes could encourage more R&D/innovation activity in the next five years
- 59% of UK physics innovators believed that a more attractive tax rate for R&D would support greater activity in the UK.

Increasingly, mission- and challenge-led innovation is fundamental to UK physics – delivery of the Industrial Strategy Challenge Fund, for example, has been powered by physics innovators across the country. The R&D ecosystem is broad and complex, and mission- and challenge-led innovation is vital to bring together cross-disciplinary researchers and innovators to help solve some of our biggest challenges, such as achieving net zero. Continued investment in mission- and challenge-led innovation, alongside support for discovery research, is needed in areas that will build strategic advantage.

In particular, in the face of unparalleled challenges posed by climate change, and the high potential for paradigm-shifting innovation on the boundaries between disciplines, Government should support development of mission and challenge incentives across the landscape around transformative cross-disciplinary solutions relating to energy and climate change, including exemplars within UKRI and government departments, new elements to the infrastructure such as ARIA, and third sector exemplars such as Nesta, with a key focus on the role of physics in both understanding the problem and identifying potential solutions. This should include focus on high-risk, high-reward technology innovation, such as space solutions, synthetic biology and materials science, as well as discovery research that advances our understanding which will lead to next-generation energy devices. As part of this, international collaborations that support strategic advantage should be sought.

4 Invest in people for a sustainable post-Covid recovery

Science and innovation are fundamental to prosperity and productivity, addressing challenges facing the economy – but they are also important to all of us as a society. Their benefits can have an impact on everybody, allowing us to build a not only a more sustainable world but a fairer world. We want to see every person throughout the country benefitting in some way from advances in science and technology.

Furthermore, as recognised by the R&D People and Culture Strategy, people are at the heart of R&D and to realising ambitions for the UK to be a global science and innovation superpower. To unleash a new wave of UK innovation, we must unleash a new wave of talent: attracting, developing and retaining diverse people with the right skills, in an environment in which everyone can realise their full potential.

We need to make it as easy – and attractive – as possible for the results of our research and innovation system to be translated into better jobs, better products, better services, and a better quality of life for more people, all over the UK. For this, we'll need to develop new models of training and skills that allow more, and more diverse, people to benefit from and participate in a more vibrant knowledge economy.

4.1 Bolster provision of physics education and skills

The UK's economic recovery and future prosperity is dependent upon people in all parts of the country having the knowledge and skills needed to realise their full potential in productive employment. Education and training in physics open doors to fulfilling careers across a range of critical industries, from engineering and construction, to health and science, to digital and finance – around 1 in 20 jobs in the UK make use of physics-related knowledge and skills.[16] Demand for physics-related skills is large enough to be significant, and underpin high-value jobs and industries, in every part of the UK, with the highest concentration of jobs in Scotland, followed by South West England, then the East Midlands and East of England. With demand for physics-related skills growing and now in excess of pre-pandemic levels, investment in physics education and training is needed to drive economic growth in every region and nation of the UK and secure a more prosperous, sustainable future.

In addition to their broad utility across the economy, physics-related knowledge and skills have a critical role to play in fuelling technological innovation and addressing some of the most pressing challenges facing society, such as achieving the net zero emissions target. However, skills shortages threaten to derail plans to increase investment in physics-based R&D/innovation, causing delays to projects, missed targets and missed opportunities. In our survey of physics-based businesses, 66% of physics innovators reported suspending or delaying R&D/innovation activities in the past five years because of skills shortages; only 11% of innovators faced no difficulties recruiting.

So, for the UK to fully seize the opportunities offered by increased investment in R&D, and build a more innovative economy, we need an equally dramatic increase in the scale and diversity of the R&D workforce to fuel scientific progress. Additional investment in science education and training is needed to boost students' attainment and progression at school and upskill those already in employment.

[16] Upcoming IOP-commissioned research on physics skills in the workforce

Significant disparities in educational outcomes exist across the regions of the UK and between students with different demographic and socio-economic backgrounds, and these have been exposed and accentuated by the Covid-19 pandemic. Tackling these inequalities is critical to the Government's plans to boost productivity and 'level up' the economy, as disparities in educational attainment are known to be the greatest drivers of regional variation in productivity.[17]

The Government must ensure that high-quality physics teaching and training is available everywhere and for everyone – including by addressing shortages of teachers with a science background at primary schools and of specialist physics teachers in secondary and further education. Availability of a diversity of physics education and training pathways, at all skill levels and in all parts of the UK, will be essential to supporting employers' access to the skills they need and to opening up opportunities for productive careers to all.

In particular, the Government must place greater emphasis on addressing the growing level 4-6 technical skills shortages in physics- and engineering-based businesses: building the right skills, and testing whether the new technical skills environment will provide a genuine alternative to the academic education route, to create a more robust and diverse future skills supply.

The growing STEM skills shortage is already costing businesses £1.5 billion a year in recruitment, temporary staffing, inflated salaries and additional training costs.[18]

Our own study of physics in the workforce shows that more than half of the jobs which demand physics knowledge and skills are in roles which typically don't require a degree. Physical scientists and science production technicians are seeing some of the fastest growth (40 per cent and 35 per cent respectively, from 2010 to 2020). As an example, the number of science, engineering and production technicians (SOC 311) has grown by 43% between 2005 and 2020,[19] and demand is only likely to grow as a result of increased R&D investment.

To help address the growing need for technical skills, the Government should support and build on initiatives like the Science and Technology Facilities Council's (STFC) proposed Skills Factory that will offer 300 technical trainee placements a year from school leavers to returners. STFC plan to offer one-, two- and four-year schemes providing industrial experience, professional accreditation credits and apprenticeship qualifications. They will help drive diversity by asking all trainees to contribute 10 days of school and community engagement per year. As part of the technical training programme, trainees will be offered placements with SMEs and other R&D facilities to gain a breadth of experience and maximise the likelihood of job offers by giving them sought-after skills.

Initiatives like this – that not only develop more skilled people, but establish a better flow of skilled people between business, academia and national facilities – if funded at appropriate scale to meet growing demand from businesses, will make a valuable contribution to meeting the significant and growing need for technical skills among employers right across the economy, and ultimately building a nation that can deliver on the science superpower ambition.

4.2 Invest in world-class teaching

Great education systems are built on great teachers. Teaching quality has been shown to be the single most important school-related factor in determining student outcomes, in terms of improved

[17] CBI (2017). Unlocking regional growth https://www.cbi.org.uk/media/1170/cbi-unlocking-regional-growth.pdf
[18] STEM Learning (2018). Skills shortage costing STEM sector £1.5bn https://www.stem.org.uk/news-and-views/news/skills-shortage-costing-stem-sector-15bn
[19] IOP analysis of Office for National Statistics' Annual Population Survey https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/methodologies/annualpopulationsurveyapsqmi

attainment and progression rates,[20,21] and particularly for those from disadvantaged backgrounds.[22] Targeting investment at ensuring all students have access to high-quality subject teachers is therefore an effective and cost-efficient way of improving educational outcomes, particularly as the Government seeks to minimise the negative impacts of Covid-19 on students' prospects and existing disparities in our education system.

The development of excellent teachers is a career-long process requiring high-quality, subject-specific professional learning which starts in initial teacher training (ITT), is built upon early in their careers and continues throughout their professional lives. A common feature of the world's best education systems is substantial investment in teachers' continuing professional development (CPD),[23] but levels of investment and participation in CPD are relatively low in the UK.[24] In addition, while some excellent subject-specific CPD programmes exist, CPD opportunities for teachers are currently disconnected, piecemeal, difficult to navigate and too often of poor quality.

As outlined in the IOP's Subjects Matter report[25], we recommend the Government invests in a world-class system of subject-specific CPD for teachers, to provide them with the necessary subject knowledge quickly and efficiently and build a more confident, engaged teaching profession. In the 2021 Spending Review, we recommend the Government invests £87 million over three years to establish a national system of subject-specific CPD for teachers in the sciences, overseen by a newly-established Office for Science Education Professional Development. We envision the system in the sciences acting as a pathfinder towards a longer-term vision in which a national system of subject-specific CPD exists for all teachers in all subjects.

The Office would draw on subject experts, multiple CPD providers, and existing standards and frameworks to build a systematic approach to subject-specific CPD that gives teachers choice and ownership, provides assurance of quality, stimulates innovation and engenders a culture of professional learning in all schools.

By increasing the number of teachers with excellent subject knowledge, the proposed system would ensure all students have access to high-quality science teaching, irrespective of their household income or where they live, and increase the numbers progressing to study the sciences post-16, providing vital support to the Government's ambitions for the UK to be a science superpower and for people in all parts of the UK to have access to productive employment.

High-quality CPD has also been shown to improve teacher retention.[26] By keeping teachers in the profession for longer, a national system of subject-specific CPD would help to address the lack of specialist science teachers in our schools, a problem which disproportionately impacts disadvantaged students and has led to 70% of A-level physics students in England coming from just 30% of schools, as well as reduce the costs of recruitment and ITT – modelling suggests that even a modest 1.5 percentage point increase in the teacher retention rate would directly save at least £126

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[20] RAND (2019). Teachers matter: understanding teachers' impact on student achievement https://www.rand.org/pubs/research_reports/RR4312.html
[21] Hanushek (2011). The economic value of higher teacher quality https://www.nber.org/papers/w16606
[22] Education Endowment Foundation (2017). The attainment gap https://educationendowmentfoundation.org.uk/public/files/Annual_Reports/EEF_Attainment_Gap_Report_2018.pdf
[23] See, for example: Barber & Mourshed (2007). How the world's best-performing schools systems come out on top. McKinsey & Company https://www.mckinsey.com/industries/social-sector/our-insights/how-the-worlds-best-performing-school-systems-come-out-on-top; Schleicher (2018). How to build a 21st-century school system. OECD https://www.oecd-ilibrary.org/education/world-class_9789264300002-en;jsessionid=dmkhnT9bWAPoBSEQbSK4BG3Q.ip-10-240-5-24
[24] Department for Education (2019). The Teaching and Learning International Survey (TALIS) 2018 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/809738/TALIS_2018_research_brief.pdf
[25] IOP (2020). Subjects Matter https://www.iop.org/sites/default/files/2020-12/Subjects-Matter-IOP-December-2020.pdf
[26] Fletcher-Wood & Zuccolo (2020). The effects of high-quality professional development on teachers and students. Education Policy Institute https://epi.org.uk/publications-and-research/effects-high-quality-professional-development/

million per year.[27] In addition, by providing assurance of the quality of CPD, the system would ensure more effective use of the £260 million schools in England spend on teacher development each year.

To effect wholesale improvements to teaching quality, a culture must be fostered in which all schools prioritise subject-specific CPD and senior leaders recognise their role in enabling teachers to realise their entitlement to and responsibility for improving their subject knowledge for teaching. Ofsted should strengthen its education inspection framework to ensure it is consistently evaluating schools' focus on the continued development of staff's subject knowledge.

4.3 Place diversity and inclusion at the heart of the UK's science and innovation ecosystem

STEM, and particularly physics, thrives on creativity and imagination. Diversity of thought comes from diversity of background, but our community is not as diverse as it could and should be. To drive innovation, to tackle the global challenges we face as a society like climate change, and to create a fair and sustainable future, everyone's voices will need to be heard.

IOP data shows that in the physics sector there are too few women; too few Black people, especially of Black Caribbean descent; too few people with disabilities; too few LGBT+ people; and too few people from less well off or disadvantaged backgrounds. As an example, women account for 50% of all apprentices in the UK; however, in 2018/19, only 10% of STEM apprenticeships were started by women.[28]

The IOP has been driving equality, diversity and inclusion (EDI) in physics as part of the wider STEM community since 2004, and this is a core pillar of the IOP Strategy, 'Unlocking the Future'. We want to build a thriving, diverse physics community and play our part in solving the STEM skills shortage by ensuring that people, no matter their background or where they live, have access to world class physics education and training.

The IOP's Limit Less campaign seeks to remedy the underrepresentation of certain groups studying physics, or beginning a physics-based apprenticeship, from age 16. Its focus is on ensuring that those who influence the subject choice and career decisions of young people do not perpetuate misconceived ideas about what physics is, and who is suitable to do physics, but instead promote the benefits of physics to all young people. The IOP is calling on the Government to:

- Revise professional standards for teachers to set out an expectation that teachers will address injustice in their professional practice and actively dismantle any sexism, racism, homophobia, ableism and classism from their own work and their schools'.
- Ensure that all teachers are trained to teach inclusively and to tackle injustice so that they can achieve these robust standards. This should be in both their initial teacher education and their continuing professional learning and development.
- Direct Ofsted to place greater emphasis on the importance of inclusive teaching and schools' efforts to address injustice.
- Mandate nurseries and schools to develop whole-school equity action plans that:
    - are informed by ongoing data and evidence collection including students' choices.
    - promote equity and equality for young people in underserved groups.

The IOP calls for investment to improve EDI in physics, from prioritising the R&D People and Culture Strategy's ambitions to create a more inclusive research culture, to boosting diversity in STEM roles in the media to give young people role models to aspire to.

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[27] Based on IOP analysis – full details available on request
[28] IOP (2020). Limit Less https://www.iop.org/sites/default/files/2020-11/IOP-Limit-Less-report-2020-Nov.pdf

Direct action to boost uptake of physics and science subjects among young people from underrepresented groups will be a key step to ensure all young people have access to world-class physics education and training. This should include targeted investment in schools in underserved and deprived areas – for example, as above, 70% of A-level physics students in England come from just 30% of schools, and a student in the most deprived quintile is three times less likely to take A-level physics than one in the least deprived quintile. The effects of the Covid-19 pandemic have particularly increased socio-economic inequalities in education and skills.[29] The huge disruption to schooling has affected all children, particularly those from poorer families, with long-term effects on their educational progression and labour market performance. Investment is now needed to make sure the system does not exacerbate these inequalities even further.

5 Strengthen the UK's international presence and partnerships

Science is a global endeavour. The UK's physics and wider scientific communities are dependent upon international networks, infrastructures, partnerships and programmes. A strong international presence must be maintained, if we are to remain in the vanguard of scientific discovery and innovation.

Openness to talent and ideas has allowed the UK to build such strong international ties, valuable and productive research collaborations and world-class shared infrastructure. The Government must both maintain existing, and develop new, international collaboration channels, to catalyse the movement of people between countries, sectors and roles, and facilitate knowledge exchange. Opportunities for in-person collaboration and international travel have been significantly curtailed since the start of the global pandemic and this has had a negative impact on research and researchers, especially those at early and mid-stages of their careers. Steps to make collaboration and international mobility easier will greatly enhance the prospects of those who have already embarked on a research career and may help to attract and retain more people in the research community.

The UK is a member of a number of significant international physics programmes, which are essential to UK physicists' leadership and influence within global science, and provide valuable opportunities to contribute equipment, instrumentation and other technologies to the development of the experimental facilities. Continued support for physicists' participation in major international programmes is essential to the UK cementing its status as a science superpower.

Long-term science relationships between countries offer important scientific, strategic and, sometimes, political benefits. Some challenges are too big, complex or costly for one country or community to tackle alone so long-term, large-scale collaborative research programmes offer advantages of scale, efficiency and cost (e.g. ITER). These relationships often benefit from long-term, stable funding commitments from partners meaning that more risks can be taken. Long-term commitments also allow for the development and maintenance of valuable technical skills and knowledge, which benefit partner nations.

Scientific relationships (formal or informal) can also play a critical role in international relations, supporting traditional diplomacy or negotiations and, in some cases, substituting for them. For example, 'science diplomacy' has been a mainstay in the politics and international governance of atomic weapons and, in different forms, biodiversity, climate change and chemical, biological and toxin weapons.

[29] IFS (2020). Inequalities in education, skills, and incomes in the UK: The implications of the COVID-19 pandemic BN-Inequalities-in-education-skills-and-incomes-in-the-UK-the-implications-of-the-COVID-19-pandemic.pdf (ifs.org.uk)

5.1 Attract global talent

Innovation thrives on diversity, meaning our research and innovation system must be open to those with valuable knowledge, expertise and experience from all backgrounds. The UK physics community is enriched by talented people from all over the world, with its world-leading academic institutions continuing to attract global talent – from 2012/13 to 2018/19, the proportion of university physics staff from outside the UK increased from 31% to 37%.[30]

Recent research from the Higher Education Policy Institute and Universities UK International found that just one year's intake of incoming international students is worth £29 billion to the UK economy.[31] The contribution of international students to the economy means that every part of the UK is financially better off because of them. And that is without considering other important benefits, such as the longer-term investment, business and trade links from hosting international students in the UK; the soft diplomatic power exerted by the UK on an international stage as a result of the networks built up during their stays; and the wider cultural and societal impacts associated with a more diverse population.

The UK government's new Research and Development People and Culture Strategy is a welcome first step towards making the research community more open, inclusive and transparent and rightly recognises the need to attract global talent. However, additional action is needed to make the UK the destination of choice – for example, significant concerns remain over the affordability of the UK visa system (with upfront costs up to six times higher than the average of leading science nations[32]), and the IOP would like to see a significant reduction in the costs for international researchers and innovators and their families, to ensure the UK is an attractive option.

5.2 Support UK/EU collaboration

As historical partners and neighbours, the UK and the EU share many of the same domestic and global challenges, from climate change to the fourth industrial revolution. From its time as a member state, the UK has a rich history of sharing resources and ideas with EU partners, to create impactful collaboration and outcomes.

The IOP has strongly advocated for the UK's continued participation in EU science funding programmes.[33,34,35] We therefore welcome the UK's membership of Horizon Europe as an Associate Member,[36] which will grant UK researchers access to the European Research Council (ERC), the Marie Curie-Skłodowska Actions, the six 'Global Challenges' clusters and missions, the partnerships, and the European Institute of Innovation and Technology. These programmes are important resources for the UK physics community.

However the UK's membership costs for the programme have been dedicated on a year-by-year basis, and the fee has come from the UK's public research budget.[37] Concerns have been raised as to how this fee will be paid, and a payment plan should be published to protect the association status.

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[30] IOP (2021). Physics staff in UK universities: data brief. Based on data gathered and licenced by the Higher Education Statistics Authority (HESA) [available on request]
[31] HEPI and UUKi (2021). The costs and benefits of international higher education students to the UK economy https://www.hepi.ac.uk/wp-content/uploads/2021/09/Summary-Report.pdf
[32] Royal Society (2019). UK science and immigration: why the UK needs an internationally competitive visa offer https://royalsociety.org/-/media/policy/Publications/2019/international-visa-systems-explainer-july-2019.pdf
[33] IOP (2019). IOP Submission to Sir Adrian Smith's review of future frameworks for international collaboration on research and innovation. https://www.iop.org/sites/default/files/2019-10/Sub-Adrian-Smith-review-collab-res-innovate.pdf
[34] IOP (2019). Physics following a 'no deal' Brexit https://www.iop.org/sites/default/files/2019-09/physics-following-no-deal-brexit.pdf
[35] IOP (2020). IOP Submission to the 2020 Comprehensive Spending Review https://www.iop.org/sites/default/files/2020-09/IOP-Comprehensive-Spending-Review-submission-FINAL.pdf
[36] IOP (2021). IOP analysis of and response to the 2021 Budget https://www.iop.org/sites/default/files/2021-03/IOP-response-to-Budget-2021.pdf
[37] Department for Business, Energy and Industrial Strategy (2021). £250 million additional funding to boost collaboration and protect ongoing research https://www.gov.uk/government/news/250-million-additional-funding-to-boost-collaboration-and-protect-ongoing-research

The IOP is calling for details on the cost breakdown for association to Horizon Europe, and for HM Treasury to act upon its commitments by ringfencing funding for association to Horizon Europe for the duration of the programme.

5.3 Invest in new international collaboration channels

International collaborations and partnerships are likely to play an even greater part in finding solutions to the biggest challenges faced by society, such as those identified in the Government's 'Plan for Growth'. The UK has the opportunity to partner with countries around the world in new and exciting ways, and benefit from new opportunities and networks.

An example of the kind of new collaboration which could be developed has been proposed by the IOP to the Department for Business, Energy and Industrial Strategy (BEIS). The IOP has invited BEIS to invest in the development and implementation of a strategic partnership programme to develop physics capacity, including access to facilities, in sub-Saharan Africa (SSA), strengthen the region's physics talent pipeline, and facilitate stronger equitable research and innovation linkages across SSA and with the UK.

With a £50 million investment over five years, the Africa-UK Physics Partnership Programme can be a productive and effective partnership between the UK and SSA centred on global challenges-oriented physics research and innovation (primarily focussed on climate, weather management and energy), aligned with the Global Challenges Research Fund, Ayrton Fund and other BEIS investments, and implemented with the support of established UK and African partners. At the same time, this programme would help the Government achieve a number of its stated strategic priorities, from the R&D Roadmap ambitions to strengthen R&D partnerships with emerging and developing countries, to securing the UK's place at the forefront of discovery and innovation. The programme's support for inclusivity, and in particular for encouraging girls to pursue physics, is also well aligned with the Foreign, Commonwealth and Development Office's ambitions to support girls' education in low and lower middle-income countries.[38]

6 Invest in research and innovation infrastructure

Investment in international projects and collaborations needs to be complemented by investment in domestic facilities and programmes. This ensures UK researchers (whether from universities, business or government) have access to world-class scientific resources, while also positioning the UK as a location and partner of choice for leading-edge R&D to international researchers and investors.

The value of investment in our national infrastructure has been very evident during the Covid-19 pandemic. Historic and new investment enabled us to develop testing technologies, such as PCR, LAMP and lateral flow, which protected our hospitals and care homes, and broke chains of transmission to reduce the R value. Our world-leading ability to track the evolving threat of new variants likewise relies on the strength of our research and facilities in genomic sequencing.

Having a national large-scale physics facility is a key ingredient of 'science superpower' status and is an asset that nations compete for. Nations compete both for the demonstration of capability that hosting a flagship international science infrastructure indicates, and the concurrent benefits in terms of the attraction of high-quality intellect, the clustering of technology businesses and the associated GVA and jobs. The ISIS Neutron and Muon Source and Diamond Light Source are examples of strategically significant domestic physics facilities that support important and high-quality (often-multidisciplinary) science but also rely on and support an extended supply chain and highly trained

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[38] Foreign, Commonwealth and Development Office (2021). Every girl goes to school, stays safe, and learns: 5 years of global action 2021 to 2026 https://www.gov.uk/government/publications/every-girl-goes-to-school-stays-safe-and-learns-5-years-of-global-action-2021-to-2026

workforce. If the UK is to build on the underlying excellence of physics as a discovery science in the UK then a review of future opportunities for UK physics facilities is required. Any major investment strategy or programme should draw on expertise, advice and evidence from UKRI's infrastructure advisory committee and infrastructure review.

There should be continued development of existing facilities and their capabilities, to ensure the UK remains a centre for world-class science. Facilities such as Diamond Light Source, the Central Laser Facility, the ISIS Neutron and Muon Source (all based at the Harwell Research Campus), the Daresbury Laboratory, and other facilities highlighted in STFC's Delivery Plan[39] should be considered for further development.

In the past, science and innovation strategies have not fully acknowledged or encompassed the richness and diversity of the UK research and innovation landscape. Many of the UK's research institutions and facilities (including PSREs) have significant world standing but not all have benefitted from previous strategies or investment. The value of such facilities to physics-based businesses was evident in our recent innovation survey which shows that innovators frequently rely on partnerships with other businesses or universities to access the facilities and equipment they need to undertake R&D/ innovation.

But for a significant minority of businesses, a lack of access to suitable facilities and equipment can be a barrier to R&D/innovation activity. 16% of physics innovators believe a lack of suitable facilities or equipment limits their ability to undertake R&D/innovation activity, with 26% pointing to a lack of suitable buildings or space and 20% citing a lack of physical testing equipment. There may be scope to increase collaboration further, particularly with public research institutions and public/private innovation partnerships, which can help support late-stage development activities such as testing and demonstration.

Targeted investment in facilities can have specific scientific benefits but can also create significant spill-over benefits ranging from regional or national economic impacts (such as job creation) to the increased demand for specific skills, training or education to very direct benefits arising from application. For example, investment in new reactors for producing radioactive isotopes could give rise to many significant benefits, not least minimising the risk of a potentially serious shortage in the supply of radioisotopes. These have many useful applications including medicine (for use as a radiation source to treat cancer patients) and diagnostics, as well as research on metabolic processes. Radioactive isotopes also have many industrial applications, such as measuring the thickness and strength of metal or plastic sheets, as well as being used as compact sources of electrical power.

Additional investment in world leading research facilities and infrastructure will also signal to our partners that the UK is open for business and ready to embrace the opportunities of a changing world. For example, investment in a world-leading X-ray free electron laser (XFEL) facility would provide the UK with a world-leading capability to address scientific and societal challenges, such as combating viral pandemics and attaining carbon neutrality and sustainability and would also attract leading researchers and innovators from across the globe.

7 Appendix: Examples of impact

The following examples, based on impact case studies submitted to the 2014 Research Excellence Framework, illustrate the breadth of impact arising from UK physics research:

- Physicists at the University of Nottingham were instrumental in the development of MRI, one of the most important breakthroughs in medical science that has since transformed

[39] STFC Delivery Plan, at: https://stfc.ukri.org/files/delivery-plan-2019/

diagnostic medicine. With funding from the Medical Research Council, the world's first whole body scanner was designed by Sir Peter Mansfield and his team in the School of Physics and Astronomy in the late 1970s. Since then, physicists at Nottingham have played a central role in MRI's successful application at higher field strengths, which improves the quality of clinical diagnostic scans, as well as its extension to the field of functional MRI. Over the last REF period (Jan 2008-Jul 2013), as a result of their work, it is estimated that 30-40 million high-field patient examinations were performed, and at least $5 billion dollars was invested in high-field scanners globally.[40]

- Photonics research in the Department of Physics at the University of Strathclyde, partly supported by EPSRC, has led to the creation of innovative laser companies in Glasgow serving global markets. Between 2008 and 2013, Coherent Scotland and M Squared Lasers created an estimated 600 person years of employment and £135 million of sales from products underpinned by research undertaken at Strathclyde. Glasgow is now one of the leading European centres for innovative laser manufacturing.[41]
- Physics and physicists are playing a vital role in the development of advanced materials, such as 2D and metamaterials, which will transform the sustainability and productivity of our society. The isolation of graphene by Prof Andre Geim and Prof Kostya Novoselov during 'Friday night experiments'[42] at the University of Manchester led to nearly 8000 industrial patents between 2008 and 2012, over $200 million of commercial investment, and companies such as IBM and Samsung actively developing graphene-based technologies.[43] Physicists from UK universities and research institutes also developed the CASTEP software, which uses quantum mechanics to determine a range of properties of materials. As of late 2012, total sales of the software exceeded $30m and it had been employed by over 800 companies across the automotive, electronics and pharmaceutical industries - for example, by Toyota to design new battery materials and electrodes to improve the performance of electric cars; by Sony to integrate organic electronic materials for light-weight flexible displays; and by Johnson-Matthey to develop new catalysts for hydrogen-powered fuel cells.[44]
- Methods and techniques developed by physicists to describe physical phenomena are helping unlock the full benefits of the fourth industrial revolution through their contribution to advancements in artificial intelligence and data processing. For example, researchers at the University of Kent supported by EPSRC used techniques originally developed to analyse impact craters to revolutionise the way that facial composites are created.[45] The resulting facial recognition suite (EFIT-V) is now used by more than 90% of police forces in the UK and has been sold to 16 countries around the world, including the US, Canada, Australia, Chile, South Africa and Sweden.[46] The improved images have led to identification rates jumping from 5% to 55%.
- Discovery research into the workings of the universe plays a vital role in inspiring the next generation of skilled researchers, technologists and innovators, as well as in generating

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[40] REF 2014 impact case study: Catalysing the Clinical Application of High-Field Magnetic Resonance Imaging (MRI) https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=32737
[41] REF 2014 impact case study: Creation of a cluster of innovative laser companies serving global markets https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=42304
[42] Geim and Novoselov hosted regular 'Friday night experiments' where they would try out experimental science that wasn't necessarily linked to their day jobs. See: University of Manchester, Discovery of graphene https://www.graphene.manchester.ac.uk/learn/discovery-of-graphene/
[43] REF 2014 impact case study: The impact of the production and characterisation of graphene https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=28174
[44] REF 2014 impact case study: PHYS05 - Materials modelling using ab-initio electronic structure calculations https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=43437
[45] REF 2014 impact case study: EFIT-V Facial Recognition Software https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=1956
[46] University of Kent (2014). Research impact - Facial recognition https://www.kent.ac.uk/news/science/4575/research-impact-facial-recognition

economic and societal impact in unexpected ways. Physicists at the University of Leicester, for example, are using detectors originally designed for major international space observatories to develop the next generation of medical imaging instruments to improve patient outcomes in ophthalmology and cancer diagnosis.[47]

8 The Institute of Physics (IOP)

The Institute of Physics is the professional and learned society for physics in the UK and Ireland, inspiring people to develop their knowledge, understanding and enjoyment of physics.

We work with a range of partners to support and develop the teaching of physics in schools; we encourage innovation, growth and productivity in business, including addressing significant skills shortages; and we provide evidence-based advice and support to governments in the UK and Ireland.

Our members come from across the physics community, whether in industry, academia, the classroom, technician roles or in training programmes as an apprentice or a student. However our reach goes well beyond our membership to all who have an interest in physics and the contribution it makes to our culture, our society and the economy.

We are a world-leading science publisher and we are proud to be a trusted and valued voice for the physics community.

[47] REF 2014 impact case study: From space science to medicine; the application of novel sensor technologies in healthcare https://impact.ref.ac.uk/casestudies/CaseStudy.aspx?Id=41132