NEUTRON SCIENCE AND FACILITIES

A Strategic Review and Future Vision for Neutron Science in Italy
Report of the Advisory Panel

Società Italiana di Fisica

SoNS

AUTHORSHIP

The Italian Physical Society and SoNS have sole responsibility for the contents of this report, and the questions, findings, and recommendations within.

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Report of the Advisory Panel

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1. Foreword

In 2019 the Italian Physical Society (Società Italiana di Fisica SIF) and the SoNS (School of Neutron Scattering "Francesco Paolo Ricci" Association) have jointly commissioned a report concerning a strategy for neutron facilities in geographical Europe.

Founded in 1897 to advance and disseminate the knowledge of physics, the Italian Physical Society promotes, favours and safeguards the study and the progress of physics in Italy and worldwide. Since then, the Society has expanded, accompanied by the foundation in 1953, of the international School of Physics in Varenna (Lake Como), a School later named after Enrico Fermi. It has acquired a broader international dimension concerning its scientific, societal and publishing activities, and today is a leading organization of physicists in Italy with over 3000 members (senior, junior and students) in academia, national laboratories and industry.

Founded in 2003 to promote the training of young researchers in the field of neutron spectroscopy and associated techniques, the SoNS Association provides a service to scientists interested in the use of neutron techniques and their applications, promoting and managing multidisciplinary and thematic schools, workshops and events. Since 2014 the Erice School "Neutron Science and instrumentation", organised by SoNS, was established as one of the permanent Schools at the "Ettore Majorana" Foundation and Centre for Scientific Culture in Erice.

In 2016 SIF and SoNS signed a collaboration agreement to promote joint initiatives, such as the "Neutrons Matter" prize for young researchers, and the creation of joint committees for reviewing and addressing case studies.

At present, the access to neutron facilities enabling scientific research for Italian academics and industry is an important element of the Italian public research (MIUR and CNR) investments. These include, since 1985, the access to the world-class ISIS spallation neutron and muon source (owned and managed by the United Kingdom's Science and Technology Facilities Council (STFC), now part of United Kingdom Research Infrastructure (UKRI)) and, since 1998, to the world-class Institut Laue Langevin (ILL) research nuclear reactor (owned by the three founding countries France, Germany, and the United Kingdom, and governed by three associate institutions, one per founding country, in association with 10 Scientific Member countries, including Italy). Currently, the ILL and ISIS directors are chair and vice-chair, respectively, of the League of Advanced European Neutron Sources (LENS), which officially launched its activities on the 29th March 2019, to promote collaboration on neutron usage, technology development, innovation, data, education, and strategies. Since 2014, the Italian Government (through the Ministry of Education, Universities and Research – MIUR) is also funding and managing Italy's contributions to the new European Spallation Source (ESS) under construction in Sweden.

In response to concerns expressed by the Italian users' communities, namely that the neutron capacity available for Italian users across Europe was likely to be significantly reduced in the short to medium term, SIF and SoNS commissioned an advisory panel to carry out a strategic review, based on the analysis of the Italian neutron capacity and output, as well as on a survey probing various kinds of stakeholders to assess how current and future priorities can best be met.

Without losing sight of cost containment constraints, the panel focused on the need to ensure and optimise the access of Italian users to neutron sources in Europe until 2033. This report, presenting the panel considerations and providing realistic options for future planning, is intended as a contribution to the debate between physicists and multidisciplinary scientists working in areas where neutron scattering plays an important role.

The panel examined a variety of issues, including the current and future needs of neutrons for science and industry; the landscape of neutron facilities in Europe and worldwide; the complementary merits of spallation sources and nuclear reactors; and the economic motivations for maintaining and growing neutron science and its industrial applications.

SIF and SoNS welcome the panel's findings and recommendations set out in this report. The conclusion that Italy has gained an excellent position internationally in many areas of neutron and muon science and that actions need to be taken to secure this position into the next decade is acknowledged as an important factor to be considered for future decisions. In particular, the panel's view of the major role that these science areas can play in supporting many of the pillars of Italy's proposed new industrial strategy is persuasive.

The panel has developed several options for securing future access to neutron and muon sources, with differing mixes of access levels at ILL, ISIS and the ESS. These options represent a range of research capacity and cost outcomes for Italy.

Two clear conclusions emerge from the panel's analysis. Firstly, that securing a sustainable access to both ILL and ISIS facilities up to 2030 is the most important element in all the options considered. Secondly, that all options will involve negotiating with our international partners on the future possibilities for life extension at ILL until 2033, and Italy's level of involvement in scientific operations at ESS.

SIF and SoNS consider the panel's recommendations as a significant contribution to develop a strategy for future neutron and muon access for Italian researchers. The strategy will seek to achieve an optimal balance between managing costs and empowering the research communities to continue to achieve excellent outcomes for science, industry and society.

Luisa Cifarelli President SIF	Roberto Senesi President SoNS

2. Preface by the Panel Chair

Without a doubt, neutron scattering research is about to encounter interesting times. On one hand, Europe's bright, new spallation source is starting to take shape; on the other, two-thirds of Europe neutron scattering capacity is at risk within the next eight years. Further, the nature of European collaboration, going forward into the next decade, is also uncertain. It is clear, however, that a strong and well-equipped Italian neutron science programme is critical to play a leading role both within Europe and beyond.

Science is a superb way of transcending national boundaries and political circumstances. Italy can be proud of its pioneering contribution to neutron science, initiated in 1934 with Fermi's discovery "Radioactivity induced by neutron bombardment" (Appendix 1).

In 1985, Italy established the first International agreements with the ISIS pulsed neutron and muon source, administered and operated by the Science and Technology Facilities Council-STFC (previously SERC and CCLRC). In 1994 Italy established the first international agreement with the ILL Research Reactor user facility (in Grenoble, France). Both the ILL and ISIS agreements are currently in force and are examples of successful collaborations over the past twenty-five years (ILL) and thirty-five years (ISIS) [1].

This review demonstrates how Italy continues to exploit neutrons for high-impact science through its access to ILL, ISIS and other facilities across the world. In many cases, this is not only enabling world-leading science but, also, science that is delivering economic, health, and societal benefits. It is important to recognise the unique characteristics of neutrons, for example in revealing where the atoms are, how the atoms 'move' and their magnetic properties, providing unique insights, unavailable by other means. Many scientists worldwide use neutron scattering in combination with other investigative tools to build up a detailed multi-faceted picture of materials. Therefore, funding neutron science must be considered as a part of a complex array of research infrastructures devoted to the knowledge of our world.

This strategic review has examined how current reactor and spallation facilities, mainly ILL and ISIS, are used by Italian researchers, and what is needed to maintain and further expand the Italian role in neutron and muon science and applications. As we approach a period when older facilities are phasing out and new ones ramping up, significant gaps in facility access can have long-term effects on the science. Further, establishing a new 21^{st}- century facility like the new European Spallation Source (ESS) brings new challenges and a significant spike in funding requirements. How we may navigate through the significant drop in neutron availability and the realignment of international collaborations in the 2020's will be critical to the future of Italian science.

The next decade will be a time of significant change in the neutron landscape as a number of older sources reach the end of their operational life. This will certainly result in a reduction in available neutron capacity, so Italy needs to plan strategically to avoid a slowdown in its scientific advances.

Given these many variables, it is not possible to precisely map out how the global provision of neutron beams will work out, nor how international funding and partnerships will realign. Consequently, this review explores certain options and looks at the opportunities and risks that each of them presents. Two options are proposed for future access: a 'scientifically optimal' scenario in which funding is available to meet all the ambitions of the Italian neutron community, and a 'constrained' scenario based on a less optimistic funding environment. It is important to note that none of these guarantees maintaining the current number of beam days in the long term, and that all involve reprofiling in funding as changes occur. Central to all of these options is the need to maintain access to the world class ISIS and ILL facilities, which will remain internationally competitive and at capacity well beyond 2030. Access to these facilities will ensure that national scientific needs are met, give resilience to changes at other sources, and also provide a basis for building partnerships with existing and new collaborators across the world as the neutron landscape evolves. The ISIS spallation source and the ILL Reactor provide complementary capabilities and capacity, and both are needed to remain internationally competitive. After 2030, the ILL Reactor faces potential closure if a new protocol and extension to 2033 and beyond is not agreed.

Italy is one of the countries contributing (since 2014) to the construction of the new ESS long-pulse spallation source, which is expected to bring significant new (albeit yet unproven) capabilities in the future. The evolving landscape of neutron sources and new emerging user requirements will create the need for new funding and access models to broaden the user base and facilitate new partnerships and collaborations with industry and internationally.

In light of the significant changes taking place over the coming years, as older sources close and the ESS comes on line, we believe that there should be a further detailed evaluation of Italy's neutron requirements in the mid-2020's, coupled with periodic instrument reviews to ensure continuing value for money from the investments in neutron capacity and capability.

While the authors of this review are not completely certain about what the future will bring, we are sure that the provision of world-class neutron and muon facilities will play a key role within the palette of investigative tools that Italy needs. This report is supported by the whole review panel and we commend the findings and recommendations to SIF and SoNS.

Piero Baglioni

3. Executive summary

3.1. Key findings

Access to large-scale facilities in general and neutron sources in particular gives Italy unique opportunities in emerging areas of science and technology in which its community excels, and on which its industrial competitiveness and distinctive culture depends, for example, in the fields of materials engineering, food science, green economy, cultural heritage, etc.

We found that the Italian neutron community, estimated at about 800-1000 units including academics, researchers from national and international institutions and companies, is very active, diverse and well integrated both domestically and internationally. Its productivity, assessed by bibliometric indicators, compares favourably with that of similar communities worldwide. Most members of the community are regular and committed users of neutron facilities. There is also a strong engagement with the developments of neutron instrumentation jointly with technical and scientific partners at neutron facilities.

For the foreseeable future, Italy is well served by having access to both continuous and pulsed neutron beams at the ILL, ISIS and elsewhere, together with the complementary instrumentation optimized for each type of source. A clear outcome of the survey we conducted is that the majority of the Italian neutron scattering users think that their scientific needs in the next decade will be mainly covered by ILL and ISIS. The management boards of these facilities have recently provided reassurance to their stakeholders that there are no technical barriers to continuing operation beyond 2030.

If Italy is to extract the maximum benefit from its investment in ESS and in order to manage the transition towards full operational capabilities and capacity of the ESS, Italy should maintain or increase its present level of activity at existing neutron sources, and in particular at ISIS and the ILL. As the world leading facilities, ISIS and the ILL are crucially needed to support the future development of neutron science in Europe in general and Italy in particular.

It is essential to maintain a steady stream of new early-career researchers who will develop into future Italian users of ESS, when this source will come on line.

It is a current view in Europe and Asia that "to become and stay competitive, a high-technology economy requires access to the most modern research tools, including both synchrotron radiation and neutron scattering." The same reasoning applies to Italy.

3.2. Key recommendations

Maintaining the current level of access to ISIS and the ILL (as a minimum requirement), and ideally increasing the subscription level to match Italy's real usage, must be the cornerstone and absolute first priority of any prudent neutron strategy for the next decade.

The bilateral agreements that Italy has established with the STFC and the ILL are of mutual benefit for the Italian scientists and those of the other countries. Maintaining and strengthening these agreements during the transition period to a fully operational ESS is a key strategic priority.

It is imperative for Italy to remain coupled to the development of the ESS, and to influence its policies and instrumentation portfolio so they are most relevant to its needs.

Although a high level of involvement with the ESS is scientifically desirable, any realistic funding scenario will have to balance the requirement to maintain capacity at ISIS and the ILL – clearly the top priority – with our international obligations to the ESS projects and Italy's ambition to build a strong future presence at the new facility.

Italy must continue to collaborate with existing neutron facilities in the field of neutron instrumentation. If possible, the successful model of in-kind contributions to ISIS should also be extended to the ILL. Italy should continue to be involved in the technical design and development of 'alternative' neutron sources, including those driven by compact accelerators. The Italian neutron science community should be attentive to these developments, whilst maintaining a realistic outlook on their potential.

Italy needs to maintain close links with the overall landscape of the European neutron scattering facilities and foster a balanced program meeting the demand of its scientific community while optimizing access costs. In this respect, bilateral agreements with other neutron laboratories, such as the German Heinz Maier-Leibnitz Zentrum, are desirable, as they would provide an insurance policy against the unforeseen closure of a major facility.

Italy must implement an aggressive programme of outreach to strengthen the ties between neutron sources, universities and industry. Exchanging staff is an excellent way to inform and advise industries of the opportunities and the available means of access. In parallel, new access modes will need to be developed together with our partners at the ILL, ISIS and the ESS, to ensure that academic and industrial users can effectively exploit neutron techniques to address high priority science and technology challenges.

Italy's research plans should promote cross-fertilization initiatives between disciplines, such as large-scale, high-performance computing, '-omics' studies, artificial intelligence, cultural heritage, etc., which benefit from neutron scattering and other techniques.

Italy should foster collaborations between industry and academia, facilitating the access of high-tech companies to neutron scattering tools by promoting specific, industry-oriented training schemes. The panel recommends the creation of co-funded academia-industry PhD's positions for nurturing a new generation of neutron scientists, including instruments scientists at ILL, ISIS, and ESS, who would champion a fruitful synergy between neutrons, materials science, theory, and technological development.

Italy must nurture its talent base and continue to strengthen its training provisions with a variety of targeted programmes. A strategic initiative to recruit and the best and the brightest in neutron science, regardless of nationality, could be a game changer, enabling Italy to match or exceed the impact of its closest competitors.

Training the next generation of neutron scientists is clearly a strategic necessity for Italy, and is a pre-requisite to achieve a healthy return on the investment made with the ESS. Italian institutions and user organisations already organise a series of excellent training programmes and 'neutron schools'. An expansion of these provisions, targeting in particular the scientific areas where Italy has historically not been strong, should be made a priority for the next decade.

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4. Introduction

Since the time of their discovery by Chadwick [2] and their first applications by Fermi [3-4], neutrons are employed in numerous scientific and technological/industrial fields, thanks to their ability to “see” in a unique way “where atoms are” and “what atoms do” [5].

Small, laboratory-scale neutron sources do not exist except at very low neutron flux levels. As a result, neutron research relies on the availability of large-scale facilities. These are typically based on fission research reactors (such as at ILL) and accelerator-driven spallation sources.

Why are neutrons such a strategic sector for Italy? Neutron scattering techniques provide powerful tools for studying the properties of matter, with profound implications for the development of basic knowledge and technological progress. In fact, the abilities of neutrons to reveal the structure and dynamics of matter at the atomic level, to distinguish the isotopes of the same element and to measure with extreme precision the static and dynamic magnetism, have transformed them into a privileged probe for research areas ranging from the physics of condensed matter to the biology of soft matter. More generally, neutrons play a prominent role in the compartment of large Research Infrastructures (RI), together with synchrotrons, free electron lasers and advanced light sources. The strategic management of these RI generates a constant flow of expertise towards other scientific and technological fields – a synergy that could represent the fulcrum of the country's future industrial strategy in sectors such as advanced materials, additive manufacturing (3D printing), low carbon dioxide energy technologies, the digital economy, the

Figure 1: ILL research reactor (left), ISIS spallation neutron and muon source (right)

pharmaceutical and biomedical industries [6, 7, 8]. In the last thirty years, Italy has made significant investments in ISIS and ILL [Annex I], both being listed in the 97 global and priority Research Infrastructures (RI) in the PNIR (Research Infrastructures National Plan 2014-2020) [9]. The neutron community is well integrated within the international context and, through proactive engagement with technical and scientific partners, generates scientific results, economic impact and significant international recognition [8]. Moreover, the management of a ‘virtual neutron RI’ in Italy, borne out of necessity, is exercised in an international and multilateral framework, and is therefore strategic by definition.

4.1. Brief description of the ILL, ISIS and the ESS in the context of this review

The ILL, founded in 1967, is one of the world-leading neutron research institutions, and operates a 58 MW reactor situated on the Polygone Scientifique in Grenoble, France. This is specially designed to deliver high brightness, channelling a high flux of neutrons to 40 state-of-the-art instruments. The ILL is owned by France, Germany and the United Kingdom, and managed in partnership with Italy and 9 other European countries. As a user facility, the ILL makes its instrumentation and expertise available to visiting scientists from all over the world. Every year, approximately 1400 scientists from over 40 countries visit the ILL and perform 700 experiments selected by a scientific review committee. Research at ILL focuses primarily on fundamental science in a variety of fields: condensed matter physics, chemistry, biology, nuclear physics, materials science, etc.

ISIS, a world-leading spallation neutron and muon source, is based on an 800 MeV proton synchrotron, and is in operation since 1984 on the Harwell Campus (Oxfordshire, UK). The facility, funded by the UK Government and managed by STFC, annually supports a national and international community of about 2,500 scientists from 32 countries, from academia and industry, who use a suite of 27 neutron instruments and 5 muon instruments. The science programme spans a wide range of disciplines, from magnetism to cultural heritage, engineering, food science, chemistry and environmental science. From the outset ISIS demonstrated to the global scientific community the feasibility and benefits of using a spallation source for the production of neutrons for science (Appendix 5), and, to date, it remains one of the most productive and technically advanced neutron sources in the world. The facility was originally expected to have an operational life of some 20 years (1985 to 2005), but its success prompted further government investments and significant refurbishments, including the construction of a second target station (TS2) that began operation in 2008. The UK is considering an additional major upgrade of ISIS to MW-class operation in a short pulse mode, intended to advance the facility and extend the life of ISIS beyond 2033.

Access to the ILL and ISIS enables scientists to study materials at the atomic level, using a suite of instruments. Research is undertaken in a wide variety of subjects. The benefits of neutron scattering, coupled with the strengths of the facilities, have been responsible for the emergence of a world-class research programmes in participating institutions, covering topics at the forefront of physics, chemistry, materials science, earth science, engineering, biology and more.

In addition to its existing world-class facilities, the neutron research community in Europe is presented with the exciting prospect of a brand-new neutron source – the European Spallation Source (ESS), which is currently being built in Lund (Sweden). The ESS is a long-pulse spallation source – a relatively new concept with the potential to deliver much higher neutron fluxes compared to existing sources, especially in the 'cold neutron' range, which is essential for applications such as magnetism and biology. This would enable an entirely new class of experiments, not currently possible elsewhere, to be performed at the ESS. The construction for the ESS began in 2014, and the first user experiments are expected for 2024. The instrument construction programme will take place in phases: an initial set of 15 instruments is included in the construction budget. Expansion of the suite up to 22 instruments is anticipated, and the facility is designed to accommodate even more in the future.

However, the exciting opportunities afforded by the ESS also come with many challenges. All neutron sources are complex facilities, and their construction, commissioning and operation require a great deal of highly specific expertise, which is not easily found elsewhere. Therefore, new neutron facilities face a very steep learning curve towards reaching their scientific potential, following their initial commissioning. This is particularly true for the ESS, since it is a new type of neutron source built in a 'green field' site. Previous studies (see Figure 4 in [10]) have found it may take as much as ten years for new facilities to reach a steady state in terms of outputs. Managing the transition of the ESS through its commissioning phase and towards full capacity, whilst maintaining a vibrant neutron research community in Europe, is a major challenge. Reviews similar to ours, conducted in other countries, have concluded that this transition can only be managed by sustaining the operations of ISIS and the ILL at the current level [7].

This review found that there is a continuing need for neutron science as part of a broader portfolio of complementary research techniques, and emphasises the economic and social impact of research with neutron, delivered at both reactors and spallation sources.

Central to the panel's approach to carrying out this strategic review has been the recognition that *any analysis and recommendation must be based on the scientific needs and priorities for Italy*. This report sets out the panel's findings, conclusions and recommendations. The panel has reviewed and assessed the evidence for continuing to support and fund access to neutron (and muon) techniques in important science areas, and the prospect of generating beneficial economic, societal and knowledge outcomes for the next 20 years (Appendix 1).

Given the cost of the facilities, it is important to justify the role that neutron science plays in the advancement of knowledge and the generation of impact, ensuring that the right level of access is provided, in the understanding that maintaining a neutron scattering community *per se* cannot be assumed *a priori*. The advisory panel membership and terms of reference are set out in Appendix 3.

4.2. Context of the review

Approximately 80% of the current Italian use of neutrons is at ILL or ISIS (see Figure 1). This strategic review has therefore focussed on how Italy can make best use of the capacity and capabilities that these two existing sources and the future ESS can provide. It needs to be recognised that Italy has signed a bilateral agreement with STFC for the ISIS spallation source, and that the operation of the ILL and the establishment of operations at the ESS are managed within intergovernmental agreements in which Italy participates. The other neutron facilities used by Italian researchers in the last ten years, as detailed in Table 3 and Figure 20, are:

ANSTO, Australia	BER-II, Germany	BNC, Hungary	DELFT, the Netherlands	FRM II, Germany
GELINA, Belgium	HFIR, USA	J-PARC, Japan	LANSCE, USA	LLB, France
NIST, USA	SNS, USA	SINQ, Switzerland		

In the majority of case, there are reciprocal arrangements in place which allow small amounts of time on these sources to be available to Italian users at no cost. Any extended use has to be paid for from the researcher's funds or by industry, if the latter plans to make a commercial use of the beamtime.

An important issue for the present review is the projected evolution of the neutrons availability over the next ten to thirteen-years, which is the time frame we considered. In the next few years, a number of reactor sources in Europe (and elsewhere) will definitely or most probably be closing in response to factors including increased operating costs, facility lifetime limits, more stringent safety requirements and fuel supply restrictions. A study commissioned in 2016 by the European Strategy Forum on Research Infrastructures (ESFRI) analysed this in detail [6]. The ESFRI report (Section 11,

Figure 9) demonstrated that, even in the 'Best Case' scenario, there will be a 'neutron drought' with about 40% fall in capacity, impacting all users of European facilities.

We have re-examined the outcome of the ESFRI report, three years after it was released, and found that the present prospects for neutron access in Europe are *significantly degraded*, even compared to the ESFRI worst-case scenario, mainly due to delays in the ESS transition towards operation. In addition to being a source of significant concerns, we consider this circumstance as a potential opportunity, since it will act as a stimulus to drive innovation. The strategic review has looked for such opportunities in developing the recommendations in this report.

4.3. Properties of the neutron probe and their complementarity with other probes

Neutrons are abundant in nature. Along with protons and electrons, they form the basic building blocks of the material world. Neutrons are tightly bound together with protons in the nucleus at the centre of an atom.

The unique properties of neutrons (and muons) have made them an increasingly popular and important probe for experiments addressing not only fundamental properties of materials at the nanoscale but also innovation-related issues addressing major societal concerns (see Appendix 2).

In a neutron scattering experiment, a neutron beam traveling through the sample under investigation provides the capability to "see" inside it as a magnifying glass, revealing the relative positions of atoms and unveiling the details of their motion. In that gaze lies a deep insight into the physical, chemical or biological properties of materials.

Having no electric charge, neutrons can penetrate materials far deeper than other probes such as electrons or x-rays. This is because they interact with atomic nuclei via a force that is strong but very short-ranged, typically acting over a distance 100,000 times smaller than that between atoms. Therefore, while traveling inside materials, neutron essentially 'see' an empty space. Neutrons also carry a magnetic moment, meaning that they behave has a nanoscopic compass needle able to interact with the magnetic field created inside the material by the atomic electrons. This second neutron-matter interaction mechanism is much weaker than the nuclear one, but gives rise to a long-range force whose effects are comparable in intensity with those produced by the strong but short-ranged neutron-nucleus force.

The fact that neutrons are only weakly scattered by matter has two consequences. On one side, this is an advantage, as it allows one using simple mathematical treatments for the interpretation of the experiments. On the other hand, this means that only a small fraction of the neutrons impinging on the sample may be scattered.

Combined with the fact that neutron sources are intrinsically weak (up to 10^{13}-10^{14} times less brilliant than for instance state-of-the-art synchrotron radiation sources), this means that neutron scattering techniques are signal-limited. However, neutrons are able to see matter in a way that is very different from other probes and unveils properties that other techniques cannot disclose. In this sense, they can be considered as a necessary tool to complete the information provided by other techniques, such as x-ray scattering, electron microscopy and nuclear magnetic resonance. These are blind with respect to some properties that are nevertheless crucial for the discovery of new phenomena. A variety of neutron instruments can be designed, each of which tailored to resolve specific details of the scattering and at the same time maintaining sufficient scattered neutron intensity for a meaningful measurement.

In spite of its unique advantages, neutron scattering is only one of many other techniques available for probing the structures and dynamics of materials to fully understand their wide range of properties at the nanoscale. These different methods, including x-ray scattering, electron microscopy and nuclear magnetic resonance (NMR), used to probe material structure provide complementary information to neutron probe because the nature of the interactions between these probes and the sample are different [6]

5. Neutrons for research

In this section, we present a series of applications of neutron techniques for research. These examples are not intended to represent a fully comprehensive review, but are chosen to demonstrate the capabilities and contributions of neutron scattering in different research areas.

The themes we have selected are also well aligned with the published PNR (Piano Nazionale della Ricerca – National Research Plan), which describes the future industrial strategy for Italy, and confirms the strategic importance of the research and its applications. Further examples of applications highlights and a summary of the impact of individual neutron facilities are given in Sections 9.1.3 and 9.1.4.

Highlighting Information technology

Information technology and electronics are hugely important to the economy of a country and to our everyday lives. From the early studies of simple anti-ferromagnetism [5] to the extremely complicated 3D, multilayer or surface magnetic structures in today's devices, neutron science continues to play a crucial role for the development of modern digital requirements, enabling new basic components for future information technology infrastructures.

Magnetic Electronics. Neutron scattering and muon spectroscopy are two of the most powerful tools to study magnetism. The majority of our present understanding of modern magnetism is based on neutron scattering studies. Particular outstanding recent examples are studies of antiferromagnetic layered structures for spintronics applications, engineered structures based on CuMnAs thin films, in-field and zero-field cooled chiral magnetic structures, and tuneable magneto-structural phase transitions.

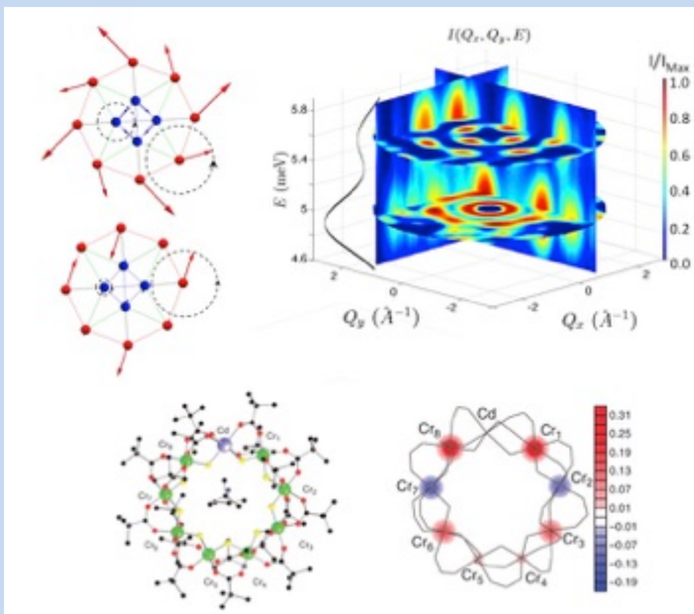
Neutron scattering studies of magnetic moments down to the atomic level (Panel 5.1) has driven the discoveries of new magnetic phenomena and the corresponding applications. In the case of Information Technology (IT), the discovery of giant magneto-resistance has been the first application of spintronics [11,12] – an emerging technology that employs electron spins rather than charges to transmit information. This, together with the development of high-performance permanent magnets, has enabled important advances in areas such as hard drive technology, magnetic-field sensors and transistors, such as those used inside desktop and laptop computers. In the last five years this has driven a 40-fold increase in data storage density with multi-billion-euro industrial market. The current challenge is to be able to obtain a layer-by-layer understanding of the chemical and magnetic structure, connecting the fundamental physics of spintronic materials with their actual behaviour. Spintronics and magnet technology has further potential to deliver a variety of novel applications in IT, the motor industry and health care.

Protecting aircraft and space systems from cosmic rays. The ChipIR beamline at ISIS was designed and built within the framework of Italy-STFC agreement for the period 2008-2014 (section 9.2 2008-2014). This instrument has been developed to mimic fast neutron damage to electronic systems caused by cosmic rays. The design and construction effort of ChipIR involved industry-driven collaborations in Italy and the UK to produce a facility that is now able to "certify" devices and systems, addressing a major economic issue related to rare but possible catastrophic failures of safety-critical IT systems due to cosmic rays, for example in avionics or in space. With increasing dependence on automated and autonomous systems – e.g. driverless cars – this issue is becoming more and more important. A team of scientists, led by University of Padua, has used the ChipIR wide-beam facility to irradiate a NAND Floating Gate Memories, at radiation levels equivalent or greater than a Carrington event [13], verifying equipment SEE tolerance [Simone Gerardin *et al., Transactions on Device and Materials Reliability* **12**, 437, (2012)]. Currently, ChipIR allows companies to test complete electronic equipment and microchips at an accelerated rate, whilst performing *in* situ monitoring and testing. This is a crucial step in developing strategies to mitigate the potentially catastrophic effects of radiation on control circuits [14, 15].

Panel 5.1 -Looking inside Single-Molecule Magnets

The Big Data and Artificial Intelligence revolutions require pushing the envelope of data storage technology. Single-molecule magnets, i.e. molecules containing clusters of strongly interacting magnetic ions, could offer a way to increase data storage density dramatically. For this to happen, however, these molecules have to be understood at the atomic level.

The Italian community is at the international forefront in the use of neutrons for the study of single-molecule magnets. Experiments performed at ISIS and the ILL measured the probability that a neutron, while moving through the sample, is scattered from its initial state to one with different energy and velocity. Thanks to these experiments, the magnetic moments on each ion in antiferromagnetic rings have been quantitatively measured for the first time – a breakthrough for experimental spintronics. Tatiana Guidi, one of the lead authors, says: "*In future Information Technology, we want to go ever smaller. Finite spin chains represent the smallest level on which we can exploit magnetic material for quantum communications*".



Top panel. Precession pattern of individual manganese spins in an excited level of the archetypal Mn12 single molecule magnet (*Top centre*). The twelve arrows in the molecule scheme represent the magnetic moments of the Mn ions, executing a precession motion about the z direction in a given excited state. The picture is obtained from neutron scattering probability maps (*top right*) measured at ISIS with the LET (from [1]).

Bottom panel: Spin density distribution maps obtained by the refinement of polarized neutron diffraction data collected with the D3 instrument at ILL for a ring-shaped Cr8Cd molecule (*bottom left*, from [2]).

[1] A. Chiesa et al., *Phys Rev. Lett.* **119**, 217202 (2017), DOI: 0.1103/PhysRevLett.119.217202.

[2] T. Guidi, et al. *Nat. Commun*. **6**, 7061 (2015), DOI: 10.1038/ncomms806

"These high energy neutrons and protons are problematic because they interact with semiconductor material – on the ground or aboard aircraft –where they give rise to lower energy protons nuclear recoils and other secondary charged particles. These deposit a small amount of electronic charge causing SEE's"

`Royal Academy of Engineering, Extreme space weather: impacts on engineered systems and infrastructures'

Highlighting Manufacturing and Industry

Millions of tons of material are processed around the world to manufacture a great range of products that we need in everyday life. Neutrons are increasingly being used to study all sorts of products, from soaps, cosmetics and drugs through to cars, planes and industrial solvent. For example, engineers employ neutrons to evaluate the stresses and performance of structural objects, from aerospace components including engines and helicopter blades, through new automobile technologies and components, to major steel structures in the energy industry, such as pipelines or railways, to lifetime issues in major structures like bridges and tunnels.

Energy-efficient mass production of key industrial chemicals is founded on basic knowledge of molecular interactions. A small piece of molecular knowledge from neutron scattering can contribute to improving the efficiency, quality and price of industrial products.

The main methods used in engineering are neutron imaging (the neutron analogue of X-ray radiography) and neutron strain scanning. In the former, a shadow image is measured, just as in a hospital X-ray, or a complete tomographic reconstruction is made (like a CT-scan) (Panel 5.2). The latter exploit the sensitivity of neutron diffraction to the presence of strains in an object, material or ancient artefacts, which manifest themselves as shifts in the Bragg diffraction peak positions. If three perpendicular strains are measured, the full 3-D strain tensor can be extracted, and this can be done on 1mm^3 scale, scanning through an object or device.

"Residual stress measurements using neutron scattering are unique tools for researching and developing existing and novel material manufacturing and to allow processes and products to be engineered."

Sesto Viticoli (Vice President Associazione Italiana Ricerca Industriale)

Neutron imaging is especially sensitive to water damage or corrosion, and to the presence of voids or cracks in components. There is also very significant activity worldwide using neutrons to measure stresses around welds, and in novel composite structural materials. One of the most exciting new areas is that of 3-D printing (or additive manufacturing), which can be thought of as a "continuous weld", at least when used for metals (like titanium, stainless steel, aluminium alloys and so on.) Exploiting these tools and expertise, engineers will be able to design lighter, cheaper and stronger components for many applications across industry.

Similar techniques can also be employed to obtain a fundamental understanding of the early history of the Solar System, or to study important historical artefacts, as shown in the two final examples.

Stress field distribution in automotive gears. Automotive gears are mechanical components requiring a hardening process of the surface of the gear teeth to improve wear behaviour. Thermal or mechanical treatments are applied to the specimen to obtain the required hardening. These treatments, however, induce high residual stress field in the components. The triaxial stress field in two steel automotive gears was measured at LLB (France) using the G5.2 two-axis diffractometer with a position sensitive XY detector. Measurements along the three principal directions, at different depths from the surface of the throat between adjacent teeth, allowed the profile of the strains to be determined as a function of depth [M. Ceretti, R. Magli, D. Vangi, *Materials Science Forum*, **321**, 732, (2000)].

Investigation of Residual Stress Distribution in Wheel Rims Using Neutron Diffraction. The main objective of this research, led by T.E.E.S. srl Technology Equipment & Engineering Solution, CNR-IFP Milan, Universities of Milano Bicocca and Rome Tor Vergata, was to apply non-destructive neutron diffraction methods to measure residual stress distribution of the wheel rim quantitatively in as-manufactured conditions. Damage accumulation due to fatigue significantly reduces the safety of railway vehicles. Shattered wheel rim failures are the result of fatigue cracks, which propagate roughly parallel to the wheel tread surface. Large stresses, most likely due to wheel/rail impact or material discontinuity, is responsible for the initiation of shattered

Panel 5.2 - Neutron imaging study dives deep into pearls.

Although our fascination with these precious gems has spanned millennia, we spare little thought for how they are formed. The beauty of pearls is correlated to surface features, for example the colour, the lustre, and the overtone; all these properties are due to the bio-mineral structure of pearls. Energy-selective neutron imaging – a non-destructive neutron technique – has been used to study the inner morphology of the pearl. Despite the very complex nature of the samples to be investigated, a team from Universities of Cosenza and Milano Bicocca have been able to obtain a tomographic reconstruction of a pearl, using the IMAT beamline at ISIS [*1*]. It was possible to show numerous features of the pearl inside its bulk and derive a 3D volume rendering (Figure 1). The latter exhibits an empty core, characteristic of the "soufflé" pearls.

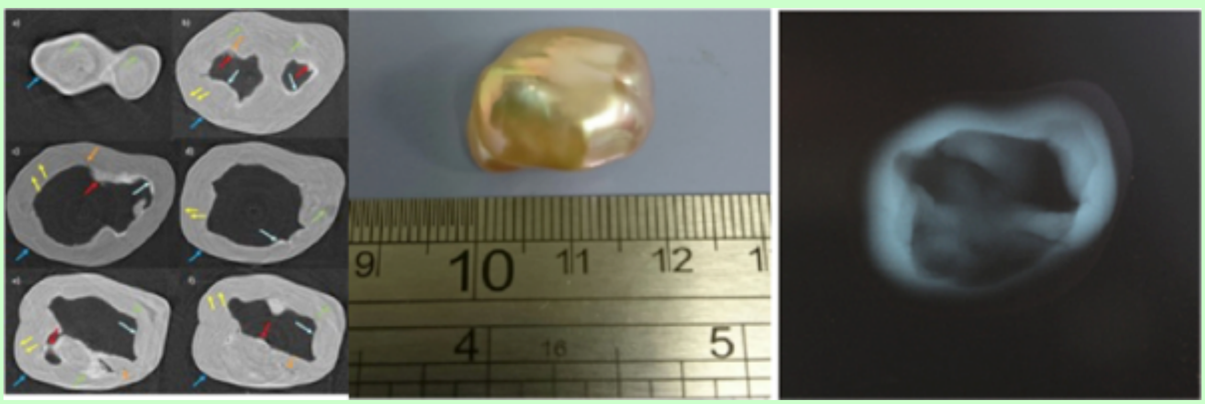


Figure 1

Despite their well-known tiny aspect, each pearl hides tons of peculiarities in its morphology, as well as in its atomic composition, some of which cannot be detected using the standard x-ray technology. Cold neutron pulses available at the IMAT beamline may reveal such "cool" secrets"

Giuseppe Vitucci, University of Milano Bicocca

[1] Giuseppe Vitucci et al., Microchemical Journal ***137****, 473-479 (2018),* DOI: 10.1016/j.microc.2017.12.00

rims. Voids and inclusions of sufficient size within the stress field will also lead to wheel failure. Significant improvements have been made in recent years to prevent shattered rim failures. The 'new-generation' wheels have a better resistance to shattered rim failures, due to the fact that the circumferential residual stress on the tread of a new wheel must be compressive to comply with requirements of international standard EN 13262. However, this does not necessarily apply to millions of 'old' wheels that are still currently in use. Prior to the use of neutron methods, most residual stress measurements are carried out either using destructive methods (such as slitting or hole drilling), or using quantitative ultrasound methods, which, however, only yield the *average* stress across the whole section [Marco Alessandroni, *et al.* Materials Science Forum, Volume 681, 522 (2011), DOI:10.4028/www.scientific.net/MSF.681.522].

Non-Destructive investigations of iron meteorites using neutron diffraction. Scientists, from CNR-ISC Florence, University of Florence, Museo di Storia Naturale, Università degli Studi di Firenze and Museo di Scienze Planetarie-Fondazione di Prato, used neutron diffraction to study iron meteorites non-destructively, revealing the conditions during the early formation of the solar system. The INES beamline at ISIS was used to study a collection of nine iron meteorite samples of different chemical groups, obtaining insights into their crystallite size, texture and internal strain. The samples showed varying texture, which could be related to the conditions during crystallization. The Engin-X beamline at ISIS was used to examine the stresses within several samples from different meteorites. The high resolution diffraction patterns obtained on Engin-X demonstrates that one of the meteorites contained two types of stresses – the 'type-I' stress across large crystal domains, and the 'type-II' stress across small crystal domains. Two other meteorites only contained type-II stresses [Stefano Caporali *et al. Planetary and Space Science*, **153**, 72-78 (2018), DOI: 10.1016/j.pss.2017.12.015; Francesco Grazzi *et al., Minerals* **2018**, *8*(1), 19; DOI:10.3390/min8010019].

Neutrons probe ancient metal reinforcement from one of the largest cathedrals in the world. One of the largest-scale examples of gothic architecture is Milan's Cathedral (the 'Duomo di Milano'), which attracts around 5 million visitors every year. This prominent feature on the Milanese skyline is one of the largest churches in the world, and had a very long and complex construction history, which started in 1386 and lasted more than five centuries. The Duomo is also a major feat of engineering: towering more than 100 metres above ground, its structure supports a number of heavy architectural features including 325,000 tonnes of statues. In 2012, the replacement of a broken tie rod in the cathedral presented a rare opportunity to study a piece of history of this building, sparking a flurry of research. Researchers from University of Milano Bicocca, Politecnico di Milano and CNR-IFP Milan have used neutrons to perform non-destructive characterization and an *in-situ* identification of local defects of this ancient tie rod support and other samples from the Cathedral. The results provided an independent and unique assessment and validation of structural models and of novel on-site monitoring techniques – something that would not be possible with any other conventional non-destructive technique. [Daniela Di Martino, *JINST* **13** C05009 (2018), DOI:10.1088/1748-0221/13/05/C05009].

"A deep characterization of this metallic reinforcement is greatly relevant; it's not only an opportunity for us to study a sample of medieval technology but a chance for us to investigate a structural element that remained in full operation for more than 600 years"

Daniela Di Martino, University of Milano Bicocca

Highlighting Medicine and Health

While neutrons have a rather niche role in structural biology, making particular use of selective deuteration in conjunction with small-angle scattering or reflectometry, they play a much more significant role in the wider field of health technologies. The ability of neutron scattering to determine molecular structures accurately allows the behaviour of proteins, enzyme and cell membranes, food and nutrition to be understood and characterized, leading to improved medical devices. The interactions between pharmaceuticals and biological molecules can be studied and benchmarked with computer simulations. Scientists apply a "materials-science" approach to proteins

(Panel 5.3), food, wine and agriculture, and answer questions that arise in processing and in the use/disposal of waste streams.

The impact of neutrons on health and life sciences extends from the stabilization of antibody formulations, new tumour-specific contrasts agent for medical diagnostics, new drugs for boron neutron capture therapy (a non-invasive therapeutic approach for treating locally invasive malignant tumours such as primary brain tumours, recurrent head/neck cancer, and cutaneous and extracutaneous melanomas), to the improvement of dental cement for tooth reconstruction, yielding stronger and more enduring teeth.

Panel 5.3 - *A common critical dynamic regime for proteins upon melting*

Proteins are molecular nano-machines that carry out essential metabolic processes in living organisms. Full knowledge of their structure and dynamics in their native, transition, intermediate and denatured states is a key goal of life and physical sciences. Here, a team led by researchers, from CNR Messina and Universities of Verona, Pisa and Perugia, show that the amplitude of local fluctuations of a model protein in the presence of different environments rescales to the same value when approaching its unfolding temperature, meaning that these machines can sustain up to a certain level of internal flexibility before abandoning their native structure and functionality.

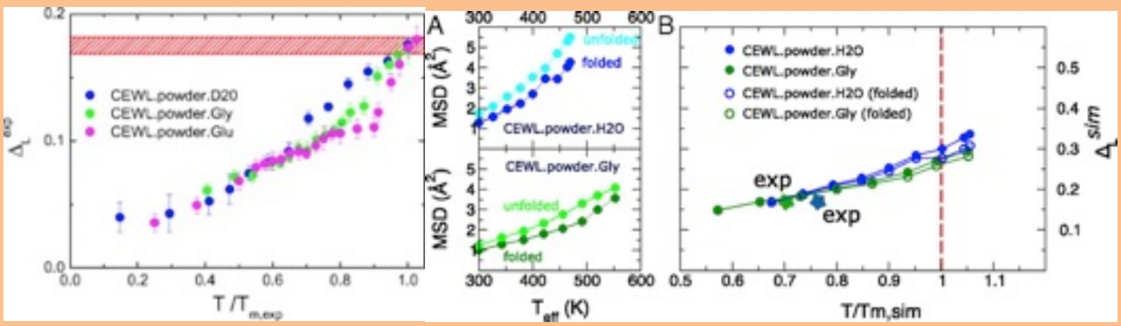


Figure. An example from the IN13 Backscattering Spectrometer at the ILL.

Left: Scaling law of protein fast fluctuations by Elastic Incoherent Neutron Scattering. Shown is the experimental Lindemann parameter for lysozyme (CEWL = chicken egg-white lysozyme) in the presence of different environments as a function of the reduced temperature $T/T_{m,exp}$. The red hatched area highlights the region of critical hydrogen mean-square displacements, corresponding to the protein melting in the different environments.

Right: Scaling law of protein fast fluctuations by simulations. (*A*) Mean-Square Displacement (MSD) from molecular dynamics trajectories started from folded and unfolded configurations of CEWL in the presence of water and glycerol. The data for the unfolded state are obtained as the average over four independent runs initiated from different configurations of the unfolded CEWL extracted from the REST2 enhanced sampling. (*B*) Lindemann parameter obtained by combining the folded and unfolded states MSD, MSD=f·MSDf+(1–f)MSDuMSD=f·MSDf+(1–f)MSDu, with ff the fraction of folded states. In the same graph we report the folded-state contributions. The coloured stars indicate the experimental points for the two systems.

[1] Marina Katava *et al.*, *Proc. Nat. Acad. Sci.* **114** (35), 9361–9366 (2017), DOI: 10.1073/pnas.1707357114

Studying drying processes using acoustic levitation. The so-called 'drying phase' is the last stage in various manufacturing processes, and has a critical influence on the quality of the final products, which could be improved by better understanding the biophysical mechanisms involved in the drying process. The first measurements of protein solutions using acoustic levitation were performed at ILL using small angle neutron and X-ray scattering, employing the small-momentum-transfer diffractometer with variable vertical focusing D16 and the small-angle scattering diffractometer D33 at the ILL, as well as the small-angle X-ray scattering diffractometer SWING at SOLEIL [Credits: Viviana Cristiglio *et al., Biochimica et Biophysica Acta*, **1861**, Part B, 3693-3699 (2017), DOI:/10.1016/j.bbagen.2016.04.026]. In this work, acoustic levitation was combined for the first time with small-angle neutron scattering and associated with small-angle X-ray scattering, to probe large-scale structural fluctuations and interactions of lysozyme (model protein) in aqueous solution as a function of the concentration in drying conditions.

New insights into the Alzheimer's β-peptides interaction with membrane rafts were provided by neutron reflectivity. In 2013, the UN published a report estimating that, by 2050, over 20% of the world's population will be 65 or older. Advances in medicine and the increase in global living standards mean that the human race is living longer than ever before. An ageing population implies a higher rate of diagnosis of age-related illnesses such as Alzheimer's. In 2015, 46.8 million people were living with dementia, costing the world economy over $800 billion. With an estimated 131.5 million Alzheimer's sufferers by 2050, understanding Alzheimer's is more important than ever. The idea that Aβ oligomeric species play a fundamental role in the development of Alzheimer disease is widely accepted, and is attributed to their membrane-active features. In a recent study, a team of scientists applied the neutron reflectometry technique, using the vertical-sample reflectometer D17 at ILL, to examine the interaction of Aβ with a single asymmetric complex membrane, containing cholesterol and monosialoganglioside GM1 [Valeria Rondelli *et al Scientific Reports* **6**, 20997 (2016)].

Drug delivery stays on target: a tiny, injectable ball to carry a drug designed to treat a specific diseased tissue. Compared to radiotherapy, which can have a negative side effect on healthy organs, targeted drug delivery has the potential advantage of treating only the diseased tissue. The challenge, however, is how best to deliver a drug, such as a DNA fragment used in gene therapy, to the unhealthy organ. One possible solution is to base the transport system around a biocompatible polymer. Using neutrons, a team from the University of Rome Tor Vergata is working at ISIS to study the efficacy of drug delivery vehicles constructed using bio-compatible polymers [Shivkumar V. Ghugare *et al.,* J. Physical Chemistry – **B 114**, 10285 (2010); Shivkumar V. Ghugare, *et al.* Soft Matter **8**, 2494 (2012)].

Going to the extreme. Most life on Earth is believed to exist in near-surface environments under relatively mild conditions of temperature, pressure, pH, salinity etc. This view, however, is changing, following the discovery of several 'extremophile' organisms that prefer environments based on high or low T, extreme chemistries, or very high pressures. Extremophiles can thrive in some of the most extreme environments, for example, around boiling deep-sea vents, deep under desert rocks or in some very salty or aggressive places such as animal intestines. Some bacteria are able to withstand both heat and cold, whilst facing even more extreme kinds of high pressure. Studies of high-pressure dynamic effects in living organisms are required to understand Earth's deep biosphere and to develop new biotechnology applications. Understanding the ultimate pressure for survival of organisms is critical for food sterilization and agricultural products conservation technologies. A team of scientists led by Fabrizia Foglia used quasi-elastic neutron scattering at ISIS to study the diffusion of water across biological membranes under high pressure, observing how the membranes react to this extreme environment. [Fabrizia Foglia *et al., Scientific reports* **6,** 18862 (2016)]

"*Piezophillic organisms are extraordinary because they can function and survive under extreme pressure conditions. For example, some bacteria have been found to survive up to 110MPa in deep sea floor environments. It is critically important that we can understand how bacterial life can function under such* *extreme conditions as these, and to do this we are studying the membrane structure of live bacteria under high pressure."*

Fabrizia Foglia, University College London

Highlighting Energy

One of the main challenges in the coming years is the change in mix of energy technologies in all countries, as we move away from fossil fuels towards renewables and energy storage. Neutrons are an excellent tool for all manner of problems in energy, mainly because of the neutron's sensitivity to light elements like hydrogen, lithium and oxygen. Thus, research programmes to discover lightweight materials that can effectively and safely store and transport hydrogen rely heavily on neutron scattering (Panel 5.4). Neutrons also help in understanding the formation of clathrates (i.e. gas hydrates), which can be detrimental for gas pipelines, thus saving approximately about 500M€ per year worldwide. At the same time, the concentration of natural gas in this peculiar solid at room temperature can boost its use as fuel for long-distance transport.

Among the most exciting emerging technologies are lithium-ion batteries and fuel cells, the latter relying on hydrogen storage. Neutrons are widely used to characterise new battery materials and optimize *in operando* performance of entire batteries: new materials for rechargeable lithium battery have been characterized and improved, thanks to the detailed knowledge acquired through neutron diffraction experiments. The method is sensitive to both cathodes and anodes, and sometimes to the electrolyte as well. In the case of hydrogen storage, both neutron diffraction and quasi-elastic neutron scattering are used to understand where the hydrogen locates in storage materials, and how strongly it is bound. Neutrons are used in many other ways to improve the performances of fuel cells – from optimizing the membranes to understanding the flow of fluids in real fuel cells.

Neutron scattering is still widely used for traditional energy technologies, for example to study the porosity of coals, coke (for the steel industry) and the sedimentary rocks that form oil and gas reservoirs, as well as potential CO_2 sequestration sites. Neutron techniques are also widely used for optimizing structural components in both conventional and nuclear thermal power stations, for instance to examine repairs of steam turbine blades, and in optimizing welds in natural-gas pipelines, or for nuclear reactors.

Neutron study of microstructural evolution during the aging of pyrolysis oils from biomass. Using small-angle neutron scattering (SANS), a team of scientists led by University of Florence performed the first microstructural characterization of pyrolysis oils obtained from biomass. Bio crude oils (BCOs) are good candidates as substitutes for mineral oils as fuels. BCOs are nanostructured fluids constituted by a complex continuous phase and nanoparticles mainly formed by the association of units of pyrolytic lignins. Over time, the aggregation of these units produces branched structures with fractal dimension D_f between 1.4 and 1.5, which are responsible for BCO aging. SANS results fully support the so-called thermal ejection theory, accounting for the mechanism of formation of the lignin fraction in oils obtained from fast pyrolysis of biomass [Emiliano Fratini, *et al*, *Langmuir,* **22**, 1 (2006)].

Neutrons reveal 'quantum tunnelling' on graphene. Graphene is known as the world's thinnest material due to its stable 2D structure. Each sheet is only one carbon atom thick, allowing each atom to engage in a chemical reaction from both sides. Graphene flakes can have a very large proportion of edge atoms, with specific chemical reactivity. In addition, chemically active voids created by missing atoms are abundant defects in graphene sheets. A team from University of Parma studied structural defects of graphene sheets and edges, using the three-axis spectrometer IN1-

Panel 5.4 - Neutrons reveal secret to sweetness

Scientists used neutron diffraction to study hydrogen bonding between monosaccharides and water to investigate the link between hydration and sweetness. Glucose and mannose have a different degree of sweetness, a feature which implies different affinity to the sweet taste receptor: while the receptor structure is still undefined, there are several geometrical models for their binding mechanism. A detailed study of the hydration structure of sugars with known degree of sweetness provided unprecedented information on the accuracy of such models. A team from University of Rome Tre, performing a neutron diffraction study on the hydration of glucose and mannose, was able to show that both α- and β-glucose form strong hydrogen bonds with water, and that the steric hindrance of their first hydration shell matches the receptor geometrical model. The α-anomer of mannose has a similar, well-defined first hydration shell, but with fewer and weaker hydrogen bonds compared to glucose. Conversely, the hydration shell of β-mannose (reported as bitter) does not match the receptor geometrical model (Figure 1).

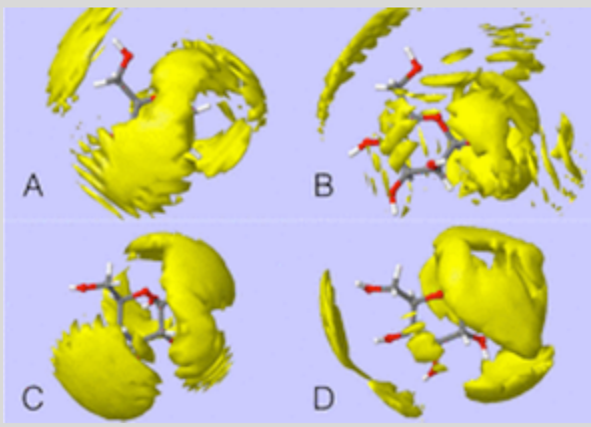


Figure 1. In In The likely hydration of mannose and glucose is shown in 3D, in terms of SDFs (spatial density functions). Panels A, B, C, and D refer to α- and β-a nomers of mannose and glucose, respectively. The isosurfaces are shown at a fractional level of 0.04, within distance of 10 Å from the origin of the reference frame, sitting on the O1 atoms. These findings suggest a link between the hydration shell of sugars and their degree of sweetness. The results suggest that in addition to mannose being less sweet, it likely binds with a lower affinity to the TIR2+T1R3 receptors

[1] F. Bruni *et al., J. Phys. Chem. Lett.*, **9** (13), 3667–3672 (2018).
[2] N. H. Rhys, F. Bruni, *et a l., J. Phys. Chem. B*, **121** (33), 7771–7776, (2017)].

LAGRANGE at ILL, and discovered that these play a vital role in carbon chemistry and physics, as they alter the chemical reactivity of graphene. In fact, chemical reactions have repeatedly been shown to be favoured at these defect sites [Chiara Cavallari *et al*., *Phys. Chem. Chem. Phys.* **18** 24820 (2016), DOI: 10.1039/C6CP04727K].

Panel 5.5 - Neutrons for Arts and Heritage

Neutrons are an ideal tool for non-destructive analyses of precious artefacts and can unveil the secrets of their manufacture, whatever delicate the investigated items are. The Italian Neutron Experimental Station (INES) at ISIS offers an ideal environment to perform archaeometric studies. It exploits the power of neutron diffraction to identify the chemical phases that form the investigated object, usually a fine-grained polyphase material. Sophisticated analyses allow the determination of specific features, such as the size of the grains forming the materials and their preferred orientation distributions (texture), which are fingerprints of the methods used to create the artefact. This provides unique information to archaeologists and art historians on the civilization to which the object belongs. A team of scientists from CNR Florence from have used this experimental method to study the manufacturing techniques of ancient Japanese and Indian swords forged in historical periods ranging from the 10th to the 19th centuries (Figure 1). Besides providing quantitative analyses of the materials used to produce the blades, the results highlight the geographic differences in forging traditions and the time evolution of the manufacturing techniques. In other studies, despite the alterations due to the long burial period, experiments at INES allowed a team of scientists, from CNR, Museo Archeologico di Torino, University of Padova and Turin, to estimate the silver content in ancient coins from the late III to the I century BC.

As a final example, we cite measurements carried out by a team of University of Sassari, CNR and Soprintendenza per i Beni Archeologici per le province di Cagliari e Oristano, on a Nuragic bronze statuette found in an Etruscan tomb in Vetulonia (Italy) and dated no later than the second half of the seventh century BC. Quantitative information on phase composition and microstructure gathered from neutron diffraction data has given a unique insight on the conservation status, the casting technique, and the manufacturing complexity of this unusual figurine of high artistic value.

Figure 1. Examples of artefacts analysed with the INES instrument at ISIS.

Top: Indian sword (tulwar) with a hilt of central/northern Indian type, and a curved blade probably of the late 18th/19th century [1]. **Bottom left**: Victoriatus silver coin issued during the Roman Republic from about 221 BC to 170 BC [2] **Bottom right:** Picture of the bronze boat model from Vetulonia, Italy, (courtesy of F. Lo Schiavo) [3].

[1] Francesco Grazzi *et al*., *Microchem. Journal*, **125,** 273 (2016); DOI : 10.1016/j.microc.2015.11.035
[2] Pierluigi Debernardi, *et al*., *Archaeological and Anthropological Sciences* **10,** 1585-1602 (2018). DOI: 10.1007/s12520-017-0464-y
[3] Antonio Brunetti *et al., Archaeological and Anthrop. Sciences* **10**, 1-6, (2018), DOI: 10.1007/s12520-018-0731-6

Highlighting Heritage Science

Increasingly, neutrons are being employed to assess and understand objects of great historical significance and cultural heritage (Panel 5.5). Italy has been a world leader in this application, with many studies of interesting objects from antiquity, through the Renaissance to the modern era. All manners of important objects have been studied by museums, art galleries, universities and private collectors: from Egyptian mummies, to paintings, through metal objects like coins or ancient swords, to classical musical instruments.

Neutrons are especially effective for understanding manufacturing methods, for detecting the presence of water, oils or other organic materials and for understanding the mode of action of advanced nanostructured fluid, which are employed for the removal of contaminants from the surface of frescos, paintings, etc. Moreover, neutron imaging enables non-destructive studies of the inner structure of bulky archaeological samples.

Neutron techniques used to study 1400 BC grave goods from an Egyptian tomb. Over 100 years since its discovery in 1906 by the archaeologist Ernesto Schiaparelli, artefacts from the Egyptian grave goods of Kha and Merit, preserved at the Museo Egizio in Turin, were studied in 2018 by an international collaboration of scientists from Centro Fermi, CNR-IPCF Messina, Universities of Rome Tor Vergata, Milano Bicocca. Using cutting-edge neutron technology at ISIS, the team unravelled the secrets of the tomb and its contents through non-invasively investigations of two artefacts from the tomb of 'Kha and Merit'. The experiments were performed using neutron tomography on the IMAT and Engin-X beamlines, through a combination of non-destructive and non-invasive neutron and gamma techniques (namely neutron imaging, neutron diffraction and prompt gamma activation analysis). The results provide unprecedented morphological reconstructions of the inner parts of the two alabaster and metallic vases and their isotopic and phase composition, thereby extending our knowledge of the hitherto unknown content of the vases and their functions. The images unveil the presence of a truncated-cone plug under the linen sheet; in the inner part of the alabaster vase, the absorption coefficient revealed the presence of an organic compound, which could be as a mixture of oils and wax. Calculations of the neutron linear attenuation coefficient of a mixture of typical animal and vegetal organic compounds are fully consistent with this hypothesis [Giulia Festa *et al.*, *Angewandte Chemie* 130, 7497-7501 (2018), DOI: 10.1002/ange.201713043].

6. Neutrons for industry

Almost all the transformative changes in our society, such as the revolutions in transport, in medicine and in production techniques, the development of information technology, the birth of the Internet and the constant increase in average life expectancy, have their origin in the understanding and exploitation of physics and material chemistry. Over the past 40 years, the intense neutron beams produced by continuous or pulsed sources and the properties of the neutron probe in the interaction with matter have been used to drive an intense research activity on materials and to understand their physical and chemical properties on an atomic scale. No longer a technique reserved exclusively to physicists, neutron and muon probes now embrace fields of applications ranging from engineering to medicine, archaeology and zoology [6].

Neutron scattering provides essential information to solve problems of direct industrial relevance, enabling innovation in many sectors. As an essential component of studies leading to the development of novel materials, neutron scattering plays an important role in Europe's innovation capacity. Neutron research has a deep impact on industrial branches ranging from aerospace and automotive, agriculture and food, health care and pharmaceutical, chemical and energy, materials engineering and information technology.

As neutrons penetrate easily in most materials, non-destructive investigations of large samples can be done without special preparations, revealing structural characteristics at the microscopic scale, mapping chemical phase inhomogeneity and residual stresses, or producing 3D images of the inner parts of an operating machine.

The possibility, for instance, to investigate *in operando* a lithium battery, a hydrogen fuel cell, or even an internal combustion engine, is extremely valuable for developing devices with higher performance, lower cost, and increased life span.

Thanks to the high sensitivity to protons and the capacity to clearly distinguish protons and deuterons, neutron scattering is particularly powerful in the study of organic and biological systems. Selected components of complex molecules can in fact be highlighted by *isotopic labelling*, *i.e.* by substituting hydrogen with deuterium atoms (a variant of hydrogen with identical chemical properties but with a nucleus twice as heavy). This facilitates the acquisition of structural and dynamical information associated with biological functions, helping the development of new drugs and therapeutic approaches.

Industrial researchers extensively use neutron diffraction to reveal, for instance, microstructural changes in gas turbine blades at temperature and stress operating conditions, or to obtain key information for additive manufacturing (3D printing) or for the synthesis of novel super-alloys with improved mechanical resilience. Information gained from neutron scattering is used to improve the quality and price of engine and structural components for cars and airplanes. Mapping the internal stress distribution in aircraft parts or in nuclear power plant components after manufacturing allows engineers to assess the integrity of welds and optimize the manufacturing process for getting safer parts at lower price.

In the bio-medical field, small-angle neutron scattering studies underpin the development of biomaterials, for example, enabling the 3D printing of artificial tissue-like structures for regenerative medicine, whilst the ability of neutron diffraction to localize hydrogen atoms and characterize hydrogen bonding networks helps the development of durable bio-compatible cements. Neutrons are also essential for the *green chemistry* industry, for instance for producing environmentally friendly detergents, safer solvents, or cosmetics.

The pharma-industry is using neutron scattering to better understand the transport of complex molecules from one cell to the other and the interaction of pharmaceuticals with biological molecules, accelerating the finding of novel drugs to treat diseases such as Alzheimer's.

Besides neutron scattering, a key contribution provided by neutron sources is medical isotope production. Materials temporarily exposed to the neutron flux undergo nuclear transformations and isotopes are formed. For instance, gamma emitters such as molybdenum-99/technetium-99 for diagnostic imaging, or beta and alpha emitters such as lutetium-177 and actinium-225 for therapies are mainly produced in nuclear reactors. Europe is currently the largest producer of medical isotopes in the world. The European Commission's High Flux Reactor operated by NRG in Petten (the Netherland) currently accounts for more than 25% of the global capacity for medical radioisotope, closely followed by the BR2 reactor in Mol (Belgium).

7. The neutron facility landscape

The most common methods of making neutron beams for material research are *nuclear fission* using uranium fuel in a reactor, and *spallation*, where a high-powered particle accelerator fires a particle beam into a metal target to release neutrons. The energy of the neutrons produced by these methods is initially very high, so neutrons need to be 'moderated' (slowed down) to become useful in most applications. Once moderated, individual neutrons become identical regardless of the way they were initially produced; however, each type of neutron source has practical advantages and limitations. For example, in the last forty years, techniques to exploit the time structure of pulsed spallation neutron sources have been developed, yielding important scientific results. The structure of the data collected at pulsed neutron sources is different from that obtained in research reactor due to the time dependence of their neutron scattering spectra. This makes pulsed neutron instrumentation at the two types of sources highly complementary.

As we have seen in the previous section, research at neutron sources not only leads to scientific advances and discoveries, but is also essential to the development of applied technologies and industrial uses. Thus, access to a diverse suite of neutron sources and instruments is an indicator of a country's scientific competitiveness and economic vitality. Laboratory-scale neutron sources do not exist except at very low neutron flux levels (see Appendix C for information on 'alternative' neutron sources). As a result, research in neutron science relies on the availability of large-scale facilities. These are typically based on fission research reactors (such as at ILL) and accelerator-driven spallation sources (such as ISIS).

Europe is continuing to hold a dominant position in neutron scattering science worldwide, as measured by capabilities, capacity to support users, and scientific output. European laboratories operate two world-leading facilities: the Institut Laue-Langevin research reactor in France and the ISIS pulsed and muon source in the United Kingdom, as well as a variety of other sources.

7.1. Research reactors

For many decades, a network of nuclear fission reactors, dedicated primarily to research and isotope production, has provided for the needs of the European health services and the European neutron science ecosystem [6,10]. These research reactors are simpler than power reactors and operate at lower temperatures, needing less fuel, and producing lower quantities of fission products as the fuel is used up. One of their principal applications is to serve as intense sources of neutrons. In these sources, neutrons are naturally moderated around room temperature, while the most advanced source use a system of moderators at different temperatures to change the neutron energies. Neutron guides are used to direct neutrons to the instrument beamlines far away from the source.

In addition to the world-leading ILL reactor, another example of a modern, world-class, reactor-based facility in Europe is the Forschungs-Neutronenquelle Heinz Maier-Leibnitz-II reactor (FRM-II) in Garching, a 20 MW research reactor at the Technical University of Munich that began operation in 2005. FRM-II features cold neutron (<0.025 eV energy) fluxes comparable to that of the ILL.

Outside Europe, the best-known reactor-based neutron sources are: the NIST Centre for Neutron Research (NIST, Gaithersburg, USA), the High-Flux Isotope Reactor (Oak Ridge, USA), the OPAL Research Reactor (ANSTO, Sydney, Australia), the HANARO Research Reactor (KAERI, Daejeon, South Korea), the JRR-3M Research Reactor (JAEA, Tokai, Japan) and the China Mianyang

Research Reactor. In addition, the 60-MW China Advanced Research Reactor (CIAE, Beijing, China) is also just starting operations.

Nuclear-reactor neutron sources reached technological maturity in the 1970's. In order to improve their performance, designers turned to the use of highly enriched uranium (HEU) fuel. This choice implies a threat of misuse of fissile materials, and HEU vulnerability remains a concern at civilian sites with inadequate security. For this reason, a considerable international effort is taking place to convert research reactors to low enriched uranium, which will however degrade their performance in terms of neutron flux. The construction of new civilian research reactors that use HEU fuel is no longer a viable option in Western countries. Old reactors shutting down after having reached their planned operation life will not be replaced by similar facilities.

7.2. Spallation neutron sources

Spallation sources are an attractive alternative to reactors for producing neutrons with high efficiency. In comparison with reactors, a spallation source produces ten times more neutrons per unit of generated heat (the energy developed per useful neutron in a spallation source is typically of about 20 MeV whereas in a reactor it is of about 180 MeV).

During the past 40 years, there has been a continuous growth in interest for this technology, and spallation neutron sources and instrumentation have been developed to the point of equalling or surpassing the performances of reactors in many subfields of neutron science. Spallation neutron facilities are based on a high-current proton accelerator in the GeV region. The high-intensity proton beam is directed towards a heavy-metal target (nowadays typically tantalum-clad tungsten or mercury), producing high-energy neutrons by spallation. If the purpose of the source is to produce neutrons for scattering or spectroscopy, the target is coupled to a series of moderators at different temperatures through a complex arrangement of neutron reflectors. The intense neutron beams provided by these facilities are either continuous (SINQ) (see A2.2.3) or pulsed (all the others – see Appendix A2.2.4 and A2.2.5). In short-pulse spallation sources, the final stage of the accelerator is a rapid-cycling synchrotron or a storage ring, which produces proton pulses of a few ns, leading to bursts of moderated neutrons in the range from 10 μs to several 100s of μs, depending on the wavelength and the type of moderator. In long-pulse or continuous spallation sources, the linear accelerator (linac) is directly coupled to the target, producing pulses in the ms range (see below).

The UK was the first country in the world to build a high-power, short-pulse spallation neutron source (ISIS) at the Rutherford Appleton Laboratory (1984). The Swiss Spallation Neutron Source (SINQ) at the Paul Scherrer Institut (PSI) near Zurich (1996), which provides a continuous source of neutrons, was the world's first spallation source to operate in excess of 1 MW, using a proton beam on a liquid metal target. The European Spallation Source (ESS), currently under construction in Sweden, is a high-power long-pulse spallation source, with a linac capable of producing power up to 5 MW.

Outside Europe, the most important spallation neutron sources are: the 1.4 MW Spallation Neutron Source (Oak Ridge, USA), the J-PARC 1-MW spallation source (Tokai, Japan), and the 140 kW China Spallation Neutron Source.

7.3. The ESS and the long-pulse spallation source concept

The ESS has had a very long gestation period, dating back to the last decade of the 20th century. Originally conceived as a short-pulse spallation source like ISIS and the SNS, but with much higher power (5 MW) and two target stations, the design of the ESS evolved overtime, mainly due to cost considerations and the difficulty of designing a target that could handle extremely intense bursts of protons. In 2003, a new design was put forward, in which the proton pulses from the linac would be fed directly to the target, removing the complexity and cost associated with the proton storage rings. Direct linac pulses would be in the 2-3 ms range, which would simplify the target design, and enable the construction of more efficient moderators, especially for long-wavelengths 'cold' neutrons. One potential drawback of this design is that the duration of the moderated neutron bursts would be 10 to 100 times longer than for a short-pulse version, which is not suitable for all neutron science applications. Consequently, many instruments would require 'shaping' of the neutron pulses, using devices (known as 'choppers') that often need to be located very close to the target/moderator assembly, and therefore in a high-radiation area. Some of the beamlines also need to be extremely long – up to 300m. Nevertheless, the long-pulse design was adopted for the ESS, although the linac power was later reduced from 5 MW to 2 MW (with the possibility of future upgrades). Construction commenced in 2014, and the ESS is expected to become operational in 2023-2024, with the user programme commencing shortly afterwards.

Initial estimates, later corroborated by numerical simulations, indicated that the ESS at 5 MW should produce time-average neutron fluxes comparable to the ILL, with peak fluxes (closely related to instrument performances) being as much as 30 times the ILL in certain neutron wavelength ranges. Although this is extremely appealing, one should not underestimate the enormous technical and scientific challenges faced by the ESS in its efforts to bring multiple instruments (15 instruments are funded as part of the construction costs) into the user programme on a highly ambitious schedule. ESS instruments are for the most part of novel design, are very complex and have critical components in high radiation areas. In order to bring about a successful user programme, the ESS has to deliver not only the neutron source and instrument suite, but also the scientific and technical support, the software and hardware for data collection and analysis, the sample environment, and, last but not least, the collective engagement of the user community.

There is absolutely no doubt that the ESS will enable users to perform many experiments that were not previously possible; the Italian neutron community is well aware of this and shares the excitement of many colleagues around Europe. Although the final outcome is not in question, there is also awareness of the many challenges ESS has to face, and the very real potential that things may not go according to plan. Asking 'what ifs' and gauging the potential consequences of delays or initial difficulties with one or more components of this very complex operation is both natural and prudent. One of the goals of this review has been therefore to survey the current views of the Italian community towards ESS, and to assess the financial and programmatic implications of various risk mitigation strategies that might be put in place.

8. Costs of neutron sources and societal benefits

Costs of neutron sources have been extracted from a recent investigation coordinated by the Neutron Landscape Group [6] and mainly conducted on European large-scale facilities. These values comparable to those obtained for neutron facilities in the United States [8]. In our case only the top four neutron facilities that are expected to operate in the next coming years in Europe have been considered (i.e. ILL, ISS, FRM-II and SINQ). From the above-mentioned documents, the gross descriptors accounting for the expenses associated to a neutron source are the following:

- Average cost to operate a neutron source for one day ~ 320 k€ to 1,000 k€
- One published paper cost (excluding users cost) ~ 196 k€
- Cost to operate one instrument for one day[1] ~ 12.6 k€

Interestingly if we considering the cost per instrument-day (12.6 k€) for ILL and ISIS, the figures for the two types of neutron sources (neutron reactor and spallation) do not appear to be significantly different, even though a slightly higher cost is encountered in the case of spallation source. This is in line with the fact that annual costs are mainly influenced by staff numbers and that the cost of the fuel cycle of a research reactor is balanced by electricity and target costs for a spallation source [16]

Table 1: Instrument days, operational costs, replacement value and publication outcomes for the top four neutron scattering facilities in Europe along with forecast values associated to ESS. At present, the cost per instrument day for ESS is high, because the number of instruments is lower than a source of its power could sustain. Sources: ESFRI report "Neutron scattering facilities in Europe" (published in 2016) [6]

Facility	Instrument days	Operational cost M€$_{2014}$	Cost per instrument-day k€$_{2014}$	Replacement value M€$_{2014}$	Referred papers p.a. (rough estimation)	Cost per publication k€$_{2014}$
ILL	8000	95	11.9	2000	600	158
ISIS	3720	62	16.7*	800	450	138
FRM-II	6000	55	9.2	600	215	256
SINQ	2405	30	12.5	750	130	231
Total	20125	242	12.6	4150	1395	196
ESS$_{2028}$	3960	140	35.3	1847	-	-

*Note that the operational cost per instrument-day for ISIS is abnormally high because of its restricted operational regime.

[1] This is an approximate value for an existing facility, such as ISIS and the ILL, operating with a full complement of instruments. During the transition phase to its full capacity (which may last more than one decade), a new facility such as ESS will be much more expensive.

The average cost to operate a neutron source for one day (~ 320 k€) is not really indicative per se, since other factors like the number of instruments running at the same time and the corresponding total number of publications must be considered to correctly rescale the gross cost.

Interestingly, the cost per publication seems to be the best indicator of the 'true' the operational cost and the real productivity of research conducted at large scale facilities. In this respect, ILL and ISIS (158 and 138 k€ per publication) perform much better that FRM-II and SINQ (256 and 231 k€ per publication) demonstrating that larger neutron sources (with an optimized number of instruments and instrument days) are more productive. Moreover, spallation sources seem to have a higher publication rate per operating day with respect to neutron reactors as it can be easily evinced by comparing ISIS with FRM-II. In this case, ISIS and FRM-II have the same number of instruments and about the same operational cost, while the cost per publication at ISIS (138 k€) is almost half the value obtained for FRM-II (256 k€).

Considering that several of the current sources are approaching the end of their expected lifetimes, the economic balance must take into consideration the cost of decommissioning. This cost has been estimated to be 246 M€ for ILL, 246 M€ for FRM-II and 173 M€ for ESS considering administrative procedures, complete decontamination, demolition of the buildings, storage of radioactive waste, etc. as required by EU rules for nuclear facilities [6]. Relatively low-power, high-brilliance sources such as ISIS have a significant cost advantage in this respect, since they produce far less active waste and hardly any long-lived isotopes. In the case of ISIS, assuming that the Rutherford Appleton Laboratory would continue to do the same sorts of science, and that it will be therefore able to store the radioactive material until it has decayed enough to be disposable as normal waste (~20 years), the cost estimate for decommissioning could even drop to values around 30 M€.

Nevertheless, the typical cost of decommissioning estimated for neutron facilities ranges in the order of 200–300 M€, for both reactors and spallation sources either in Europe or United States [8].

After underlining the high cost of neutron sources for the society it is important to stress the enormous outcomes and benefit that neutron research has on everyday life. Examples span from energy, industry and materials, information technology and big data management, health and life, environment and cultural heritage [17].

On the basis of the examples we have presented in sections 5 and 0, it is clear that neutron science and technology has and will have an essential role in the advancement of the society both from a cultural and economic point of view.

9. The Italian neutron community

9.1. A bibliographic portrait of the Italian neutron community: 2008 to 2018

9.1.1. Introduction and methodology

In this section, we attempt to provide a reliable portrait of the Italian neutron science in the past decade, based on bibliographic information and data provided by neutron facilities. It is a well-known fact that sector surveys based on bibliographic searches are not very reliable, because search patterns implemented by scientific citation indexing services suffer from poor specificity. Nevertheless, we have attempted to provide a bibliographic 'snapshot' of the Italian neutron production in the period 2008-2018 and to compare it with that of other communities and with the neutron community worldwide. The search strategy that we have implemented on Web of Science is described in some detail in Appendix 7. A few key aspects of this strategy are described here below:

- Our basic strategy was to search for all publications that referred to neutrons in the title, abstract or keywords and to exclude publications in sectors that are not relevant for this review, such as particle physics, astronomy etc[2]. However, our search also includes papers that make use of neutron results rather than describing an experiment (for example, theory papers). We believe that this is an acceptable way to capture the impact of neutron science on the Italian community.
- We have excluded review papers, because they tend to skew the citation statistics.
- We have attempted to assess the relative impact of different large-scale facilities on the Italian neutron production by classifying the Italian publications that have a facility-based co-author. We have established that only ~50% of neutron papers cite a facility-based co-author [6], but we have no reason to believe that this figure should vary widely for different facilities.

We have also complemented the bibliographic information with access data provided by ISIS and the ILL – the two facilities that provide the vast majority of the Italian neutron capacity.

9.1.2. Output and bibliometric impact

The publication output from our bibliographic search and the associated bibliometric data are reported in Table 2. In the period under consideration, Italy generated approximately 5% of the world's output in neutron science. The Italian output is approximately 30% of each of the 'big three' European players (UK, France and Germany, all of which host neutron facilities), but compares very favourably with many other communities – for example it is 30% greater than that of the ESS hosts (Sweden and Denmark combined). The impact of the Italian neutron science, crudely measured by the number of citations per paper, is also well within the world-wide standard (for example, it is significantly higher than of Japan). The fact that this 'impact factor' is not as high as that of facility hosts (including relatively small countries such as Switzerland or Australia) is a clear testimony of the importance of a national source in producing the very top-tier neutron science.

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[2] For the Italian community, we have achieved specificity > 97%, i.e., at most 3% of our hits are in irrelevant subjects. However, there is no way to ensure that the relevant publications actually contain a description of an experiment performed at a neutron facility.

9.1.3. Research areas

The output of our bibliographic searches is classified by subject, either based on Research Areas (such as physics, chemistry etc., see Figure 2) or on the more detailed WoS categories (see Figure 3).

Table 2: Bibliometric indicators for publications related to neutron science in Italy and world-wide for the period 2008-2018 (source: Web of Science). The search parameter and criteria are described in Appendix 7.

Country	Total pubs	Pubs per year (average)	H-index	Average citations per item
Italy	**2053**	**187**	**61**	**13.93**
UK	5475	498	96	16.32
France	7065	642	96	15.68
Germany	6626	602	97	17.11
Sweden + Denmark	1588	144	63	15.37
Spain	1786	162	70	14.75
Switzerland	2137	194	75	17.59
EEA	18,485	1680	139	16.26
USA	11,434	1039	153	20.84
Japan	4405	400	82	13.33
Australia	1883	171	64	15.61
China	3831	348	78	12.73
Korea	1229	112	49	13.41
India	2233	203	54	11.61
Russia	3156	287	53	8.49
Rest of World	3789	344	64	9.52
World combined	*39,582*	*3598*	190	15.27

Based on both criteria, the distributions of the Italian and Worldwide outputs are rather similar, but one can notice that research areas related to chemistry in general and physical chemistry in particular are comparatively more popular in Italy than elsewhere. While Italy is perhaps not quite in the same class as other leading high-technology countries with their own domestic neutron sources (Switzerland, Germany France, UK, and the USA), it compares quite well with those that do not have a domestic neutron source (Sweden, Denmark, Spain). In terms of impact (as measured by citations per paper), Italy is performing at a significantly higher level than most of the high-technology countries outside Europe, even if they have their own domestic neutron source (Japan, Korea, China, India, Russia)

This trend becomes even clearer if one considers the detailed infographics provided by the ILL for the distribution of beamtime proposals (Figures 4 and 5). Compared with the 'big three', Italy proposes fewer magnetism experiments and more liquid and glasses experiments as a percentage of the total. The comparative under-representation of important neutron science areas such as magnetism and superconductivity in the Italian science portfolio has deep historical roots, and is also related to the lack of a national facility, since the majority of neutron specialists and instrument scientists have a physics background. Papers in these 'core' areas also tend to draw a large share of citations, partly explaining the citation data discussed in the previous section. Nevertheless, one positive aspect is that the Italian neutron portfolio is highly interdisciplinary, and draws strength from many different science areas in both physical sciences and life sciences.

9.1.4. Impact of individual facilities

The ILL and ISIS neutron facilities have created substantial long-term impact. From the original vision over 30 years ago, both facilities have become one of Europe's major scientific achievements and have changed the way the world views neutron scattering. ILL and ISIS have delivered major social and economic benefit for France and the UK as well as other European economies. We estimated the relative contribution of each neutron facility to the Italian neutron science output based on the number of papers with facility-based co-authors, as discussed in the introduction, and is reported in Figure 6. The pie chart clearly highlights the reliance of the Italian neutron community on ISIS and the ILL (with 60% of these papers being with ISIS or ILL co-authors). Indeed, the access statistics for ILL (Figure 7) and ISIS (Figure 8) indicate that the Italian beamtime requests to both facilities are well in excess of the quota corresponding to the Italian financial contribution (Figures 6 and 7). Although it is impossible to be certain, it seems likely that in both cases the Italian success rate has been 'renormalised' to match more closely the Italian contribution[3]. This observation, if corroborated, would speak in favour of an *increase* of the Italian contribution to both facilities.

9.2. Skills and training

The ILL and ISIS facilities provide each year a significant level of 'on-the-job' training for 800-1200 students, PhDs and early-career researchers, (of which 40-60 are Italians), all of whom will later go on to work in academia and industry. The PhD student program contains an element of facility development - for example development of equipment, software or experimental processes. Studentships have an ILL or ISIS supervisor and a university supervisor who work in partnership throughout the student's project. Indeed, although most of these students, post-docs and early-career researchers are neutron users, a significant fraction is involved in building new

[3] For the 5 years 2009 - 2013, the Italian financial participation to the ILL was 3.5%, while the average number of allocated beam days per year (233) was higher than the contractual number (196), corresponding to 5-6%.

instruments and instrument upgrades and, in some cases, delivers operational support for other users of the neutron facilities.

Neutron research programmes offered each year help training people in skills that are highly regarded by industry, particularly in the manufacturing and digital technologies sectors. This is because neutron facilities 'campuses' provide an excellent environment to develop new skills for visiting students and early career researchers. Training programmes for new facility staff (both scientific and technical) have a particularly large element of technological skills development. Many of the students and staff members at facilities and visiting research groups will transfer to industry at some point in their careers, producing a flow of skills from the research community into the private sector, with the added benefit of helping to strengthen the engagement of industry in neutron applications. Whilst staff transfer from research to industry is of direct benefit to the wider economy, maintaining the skills base and expertise in the facilities and the research programmes drives a continuing need to train new technicians, engineers and scientists.

9.3. Neutron instrumentation development

Since 1985, teams of Italian scientists and engineers have designed and realized several neutron beamlines in joint collaborations with instrument scientists and engineers from ILL and ISIS, within the bilateral agreements in force with both facilities [1].

Many components of these beamlines were constructed in Italy and then transported, installed and commissioned at ILL and ISIS by small experimental teams based at CNR and Universities. A list of these *Italian instruments* is given below:

- Neutron Beamline PRISMA I, neutron 1985-1995, installed at ISIS
- Neutron Beamline PRISMA II, 1995-1997, installed at ISIS
- Neutron Beamlines PRISMA III and PRISMA IV, 1997-1999, installed at ISIS
- Muon Beamline EMU, 1990-1995, installed at ISIS
- XENNI and TECHNI, projects to develop neutron detectors, 1996-1998 (European Projects within FP4 and FP5), for ILL and ISIS
- Neutron Beamline TOSCA, 1994-2002, installed at ISIS
- Neutron Beamline VESUVIO, 1996-2001, installed at ISIS
- Muon Beamline DIZITAL, 1998-2002, installed at ISIS
- Neutron Beamline IN13, 1998-2004, installed at ILL
- Neutron Beamline BRISP, 1998-2005, installed at ILL
- Muon Beamline SLOWMU, 2000-2004, installed at ISIS
- Neutron Beamline INES, 2000-2004, installed at ISIS
- Neutron Beamline e.VERDI, 2001-2006, installed at ISIS
- Neutron Beamlines TOSCA Phase I and Phase II, 2002-2004, installed at ISIS
- Neutron Beamline NIMROD, 2004-2008, installed at ISIS

- Ancient Charm, a project to develop neutron instrumentation for 3D imaging with eV neutrons in science and engineering in Arts Heritage and Archaeology 2005-2009 (European Projects within FP6), installed at ISIS
- Neutron Beamline CHIPIR, 2008-2014, installed at ISIS
- Neutron Beamline IMAT, 2008-2014, installed at ISIS

A selected list of industries and small and medium enterprises which collaborated in the design, construction and experimental tests at ILL and ISIS is presented below:

Controlli e Microsistemi s.r.l., Rome	PRISMA
EURO-ELLE, Florence	INES
LOTO, Florence	TOSCA and INES
Officine Verdelli, Florence	BRISP, TOSCA and INES
R.M.P., Acilia, Rome	VESUVIO, e.VERDI
SIMIC S.p.A, Camerana (Cuneo)	NIMROD and BRISP
V. C. S. (Parma)	TOSCA
ST Microelectronics	CHIPIR
T.E.E.S s.r.l, Acelia, Rome	VESUVIO, ZOOM, CHIPIR
Thales Alenia Space Italia S.p.A.	VESUVIO, CHIPIR
CAEN S.p.A.	Nuclear components
TNX S.r.l.	Portable X-Ray diffraction and fluorescence
EFFE ENGINEERING S.r.l.	Shot peening, hot polishing
TRATER S.r.l.	Industrial heat treatments
MELONI TECNO-HANDLING S.r.l.	Transport systems (cranes and bridge crane) and storage, also for nuclear plants
SCANDURA & FEM S.r.l	Measurement instrumentation and generation of reference signals
SAEPI S.r.l.	Construction of large storage and pressure tanks
SIMAS S.p.A,	Production of seamless pipes and fittings
BASSI LUIGI & C. S.p.A.	Production of special fittings, bends, skids, and manifolds and pressure vessels (tanks and heat exchangers) for the nuclear sector
AMETEK S.r.l.	Radiation detection and testing systems
EL.SE. S.r.l.	Design, construction and installation of electronic instrumentation for nuclear plants
DOLLI CESARE	Design, construction and installation of soundproofing systems and safety of machine

	tools
COMECER S.r.l.	Equipment for handling of radioactive material and waste, operator safety.
GNR S.r.l.	Production of complete analysis systems (eg optical emission spectrometers, diffractometers, X-ray fluorescence)
STUDIO ROGANTE	Decommissioning consultancies.

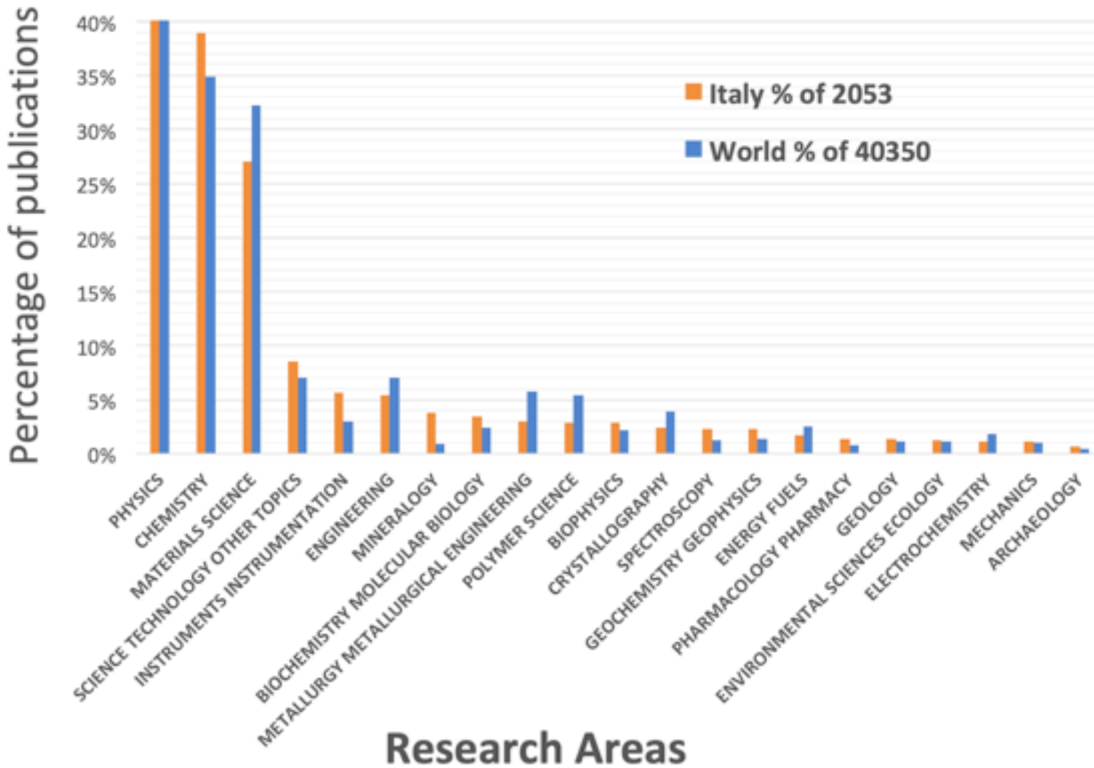

Figure 2: Percentage of Italian (orange) and world (blue) neutron publications in each of the most popular Research Areas. Source: WoS.

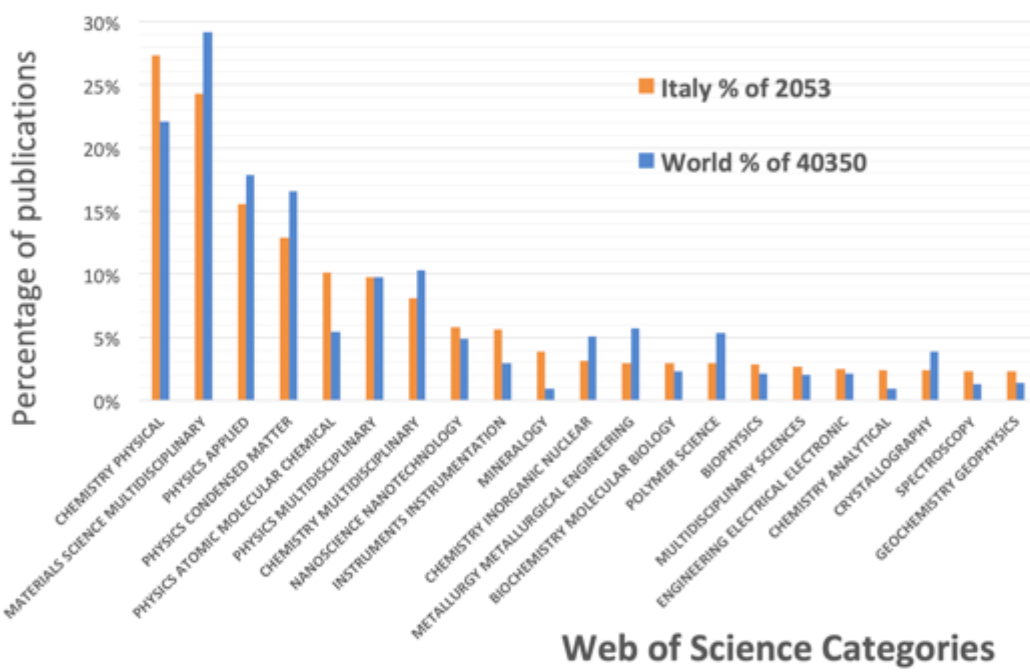

Figure 3: Percentage of Italian (orange) and world (blue) neutron publications in each of the most popular Web of Science categories. Source: WOS.

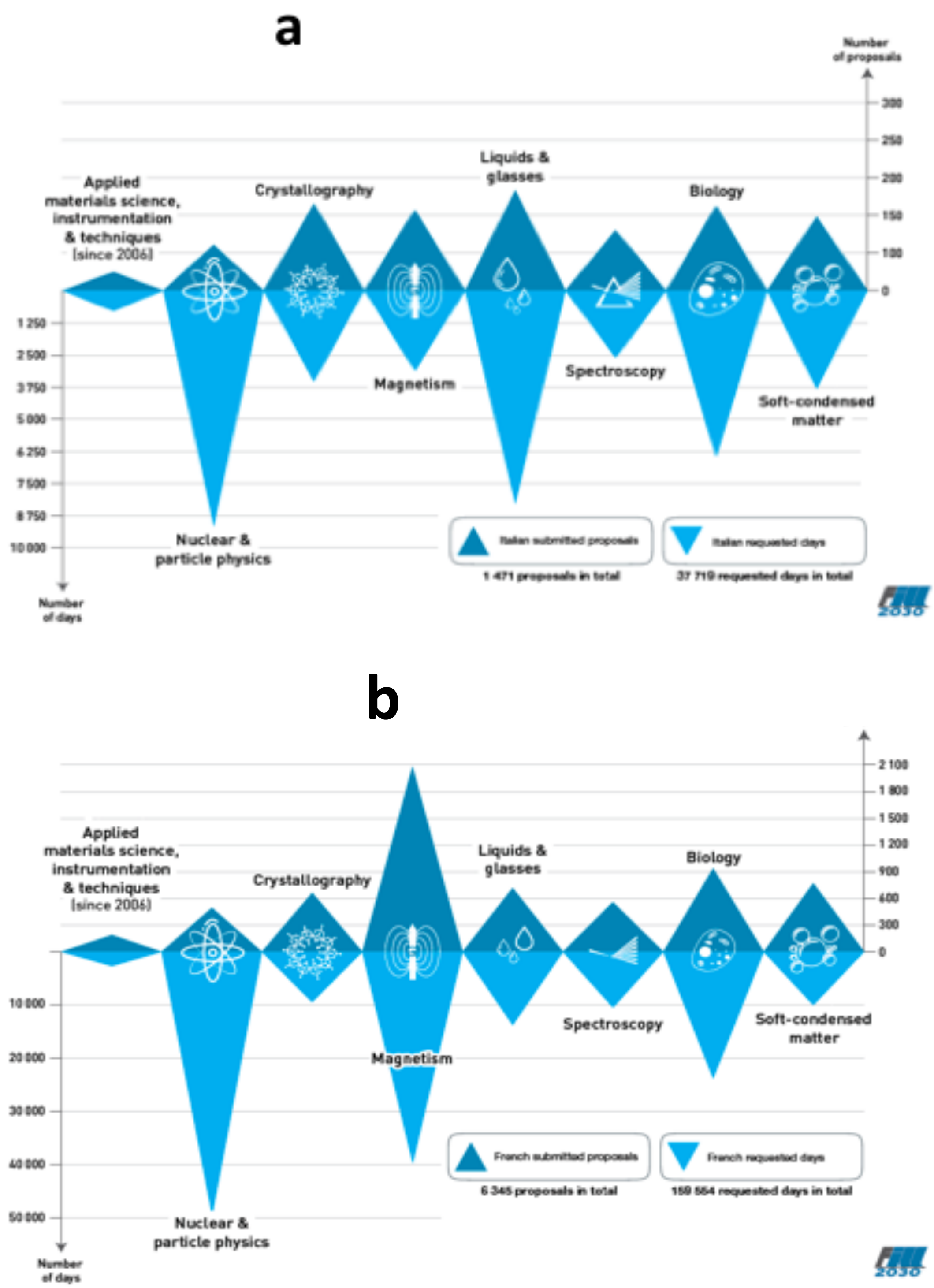

Figure 4: Disciplines distribution of the beamtime request at the ILL by Italy (a) and France (b). Source: ILL.

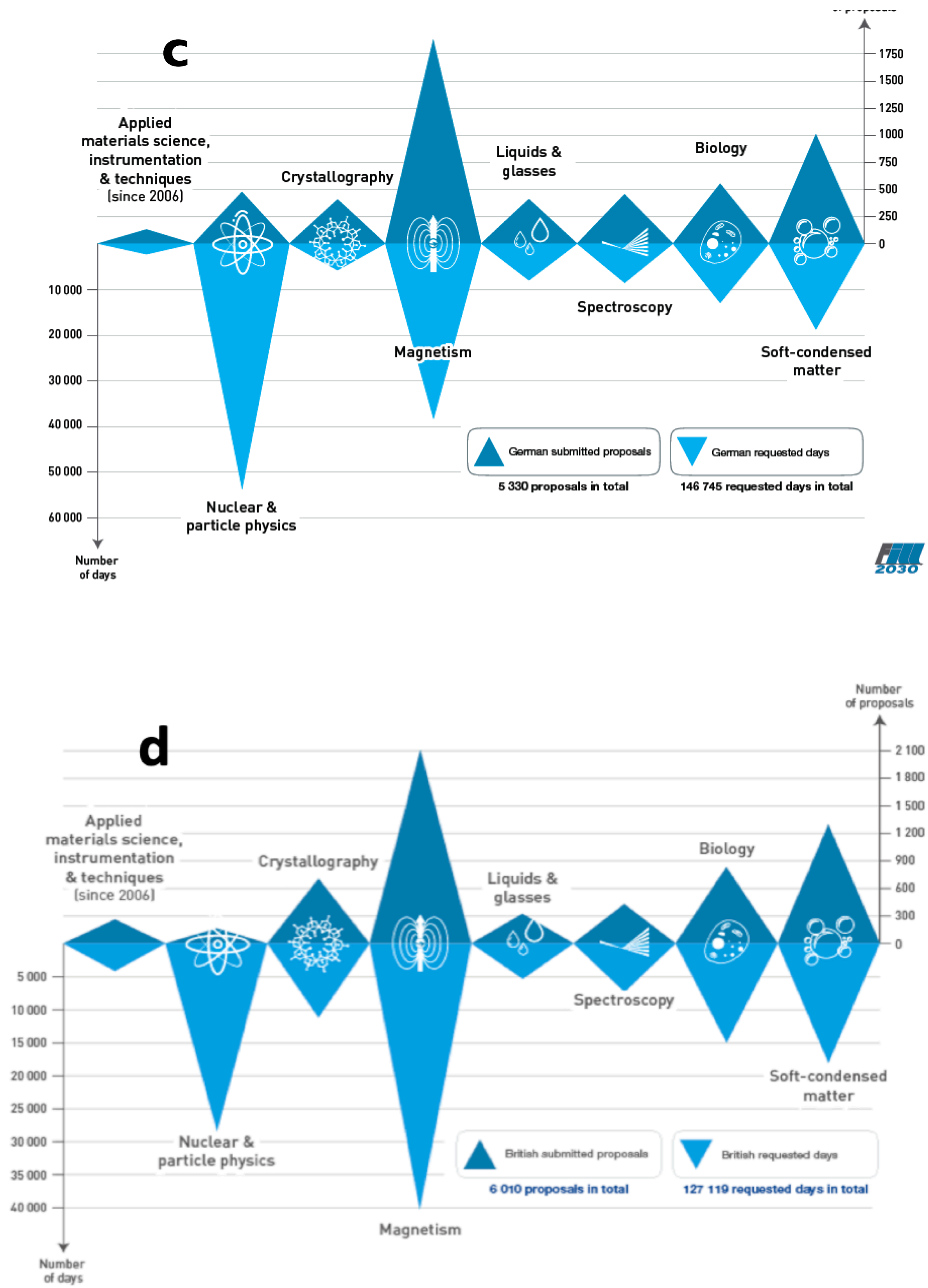

Figure 5: Disciplines distribution of the beamtime request at the ILL by Germany (c) and the UK (d). Source: ILL.

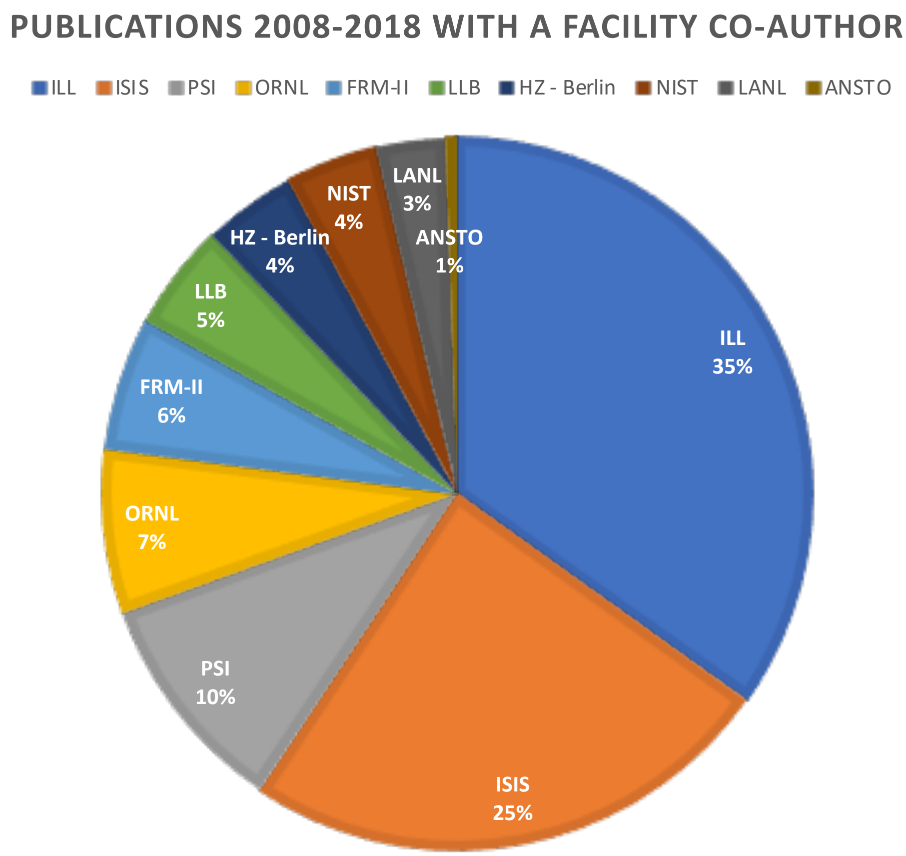

Figure 6: Distribution of Italian neutron publications with an identified co-author based at a large-scale facility. The ILL is the only facility for which we could obtain the total number of Italian publications (464 in the period 2008-2017). The co-author citation rate based on these data is 53%.

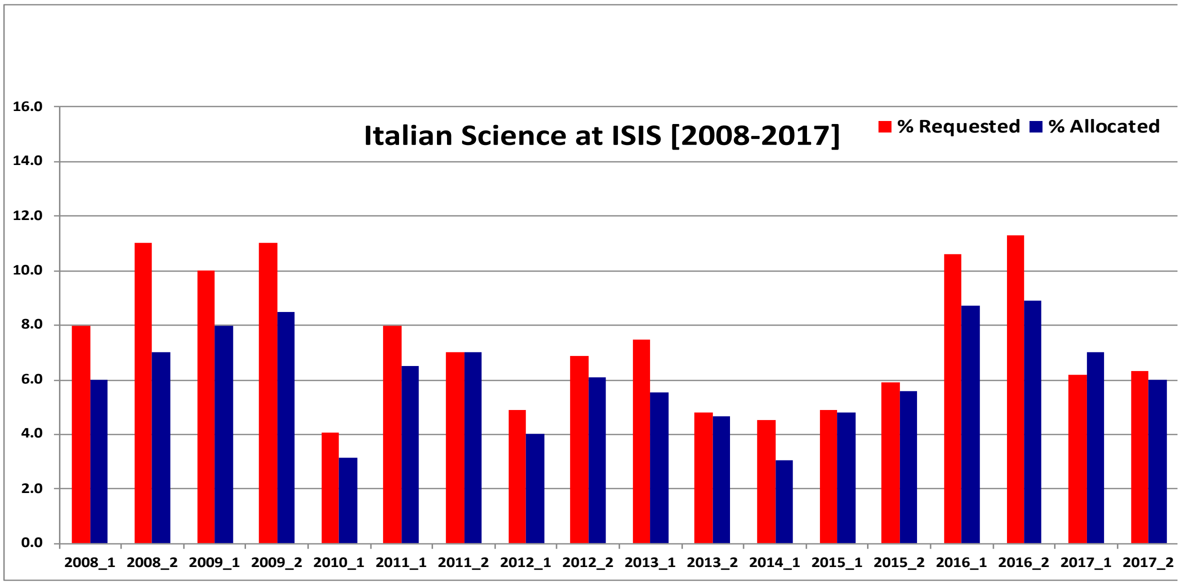

Figure 7: Percentage of ISIS beamtime requested by (red) and allocated to (blue) to Italian proposal in each beam allocation period since 2008. The data include muon instruments. Source: ISIS.

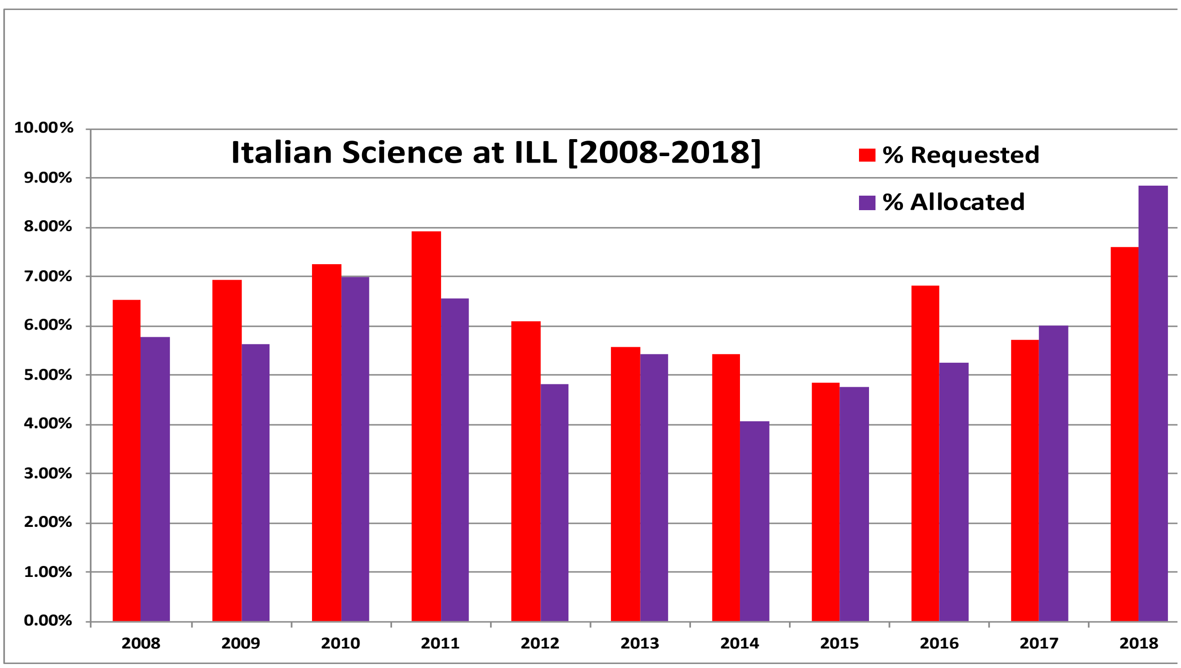

Figure 8: Percentage of ILL beamtime requested by (red) and allocated to (blue) Italian proposal since 2008. Source: ILL.

10. Survey of Italian users of neutron facilities

10.1. Methodology and output of the survey

Through questionnaires, we consulted the Italian academic community (Universities, Italian Research Institutions and the Neutron Associations SISN and SoNS) (see Appendix 4) and separately, the community of industrial stakeholders of neutron science (see Appendix 5). This was done to receive independent advice, challenge and support, and to determine the needs and aspirations of the community. We believe that most, if not all, members of these communities had the opportunity to respond. The rate of return of these surveys has been comparable to that of similar reviews conducted in the UK and elsewhere.

We also consulted a range of experts from the international community of neutron users and providers, based at institutions and facilities in Europe and elsewhere, who were given the opportunity to provide early feedback on our review.

10.2. Analysis

10.2.1. Demography of the respondents

The respondents to the survey reflect a wide distribution of affiliations, with strong contingents from CNR and the 'traditional' neutron research centres in Italian universities (Figure 16 and Table 3). All the academic career stages are represented (Figure 15), but with a weighting towards senior roles (professors are the largest group, while PhD students are among the smallest groups). The vast majority of respondents (85%) are from Italy (Figure 17), with a small but significant contingent of 'expatriates', mostly based at international facilities and research centres with significant Italian participation. The majority of respondents are academic neutron users (Figure 18).

10.2.2. Research areas, expertise and techniques

The stated research fields of the respondents, as defined by the ERC classification, reflects the worldwide distribution of neutron users, who are predominantly from the Physical and Engineering sciences (Figure 19). The largest contingents are for Condensed Matter Physics (PE3) and Physical/Analytical Chemistry (PE4). The frequency of users among the respondents ranges from 'frequent' to 'occasional' (Figure 34). Most of the respondents consider themselves as either 'expert' or 'non-expert' users (Figure 35). Significantly, the fraction of respondents that define themselves as 'developers' varies widely depending on the facility. ISIS has the largest group of 'developers', while the ILL has the smallest. Less than 20% of respondents have been involved in facility access panels (Figure 49).

Figure 36 shows the percentage of respondents using each of the principal neutron techniques. These data are complementary to those in Figures 4 and 6 in defining the research interests of the Italian community. Elements that appear very significant are the popularity of techniques such as SANS and reflectometry with respect, for example, to diffraction and the relative lack of interest for magnetism, which has already been discussed in section 9.1.3.

10.2.3. Facilities use in the past 10 years

The breakdown of the use of different neutron facilities among the respondents is captured by Figures 20 and 22. The importance of ISIS and the ILL both in the past and, as we shall see, for the future is clearly reflected in these data.

Figures 23 26, and 29 display the year of first and most recent use of the ILL, ISIS and other facilities, respectively. These data are important in highlighting the fact that the respondents represent a cross section of the *active* neutron community, and therefore have fresh opinions based on recent experience. Although several respondents are clearly experienced, many are also relatively new neutron users.

Figures 24, 27 and 30 depict the frequency of use of neutron facilities in the past 10 years for the ILL, ISIS and other facilities, respectively.

Figures 37 and 38 display a breakdown to the use of individual instrument at the ILL and ISIS, respectively, while Table 5 lists a number of instruments at other facilities used by individual respondents.

10.2.4. Future use of existing facilities

Figures 25, 28 and 31 display the predicted use of the ILL, ISIS and other facilities in the next 10 years, with the breakdown by facility in Figure 20 and by ILL and ISIS instruments in Figure 37 and Figure 38, respectively. These data indicate very convincingly that the respondents consider their future neutron science as *strongly dependent on existing facilities*, especially ISIS and the ILL. Significantly, only sources that are closing down show a significantly 'decreased' use (Figure 20).

10.2.5. The Italian community and the ESS

The attitude of the respondents towards the ESS can be fairly described with the words 'interested' and 'uncertain'. Only a minority of respondents are confident that they will be ESS users in the next 10 years (Figure 21), while the same question without the 10-year time frame attracts a significant proportion of 'maybe' (Figure 33). Almost certainly, this large degree of uncertainty is related to the very small involvement in the ESS project (Figure 32). Although the respondents recognise that the ESS will be better in many areas with respect to existing sources (notably in flux/brilliance, Figure 41), and that existing sources need improvement to meet their science needs (Figure 40), the vast majority of them consider that ISIS and the ILL 'completely' or 'mostly' meet their requirements.

Figure 42 provides a breakdown on the future use of ESS instruments by the respondents, which indicates a good match between the research requirements of the respondents and the Italian engagement with ESS instrumentation.

10.2.6. Role of neutrons in science and society

The analysis of Figures 46, 47 and 48 provide and appreciation of the way the respondents view the contribution of their work to science, knowledge transfer and wider societal outcomes. The emerging picture is one of a community regarding itself as engaged in rather fundamental work, with an output that is predominantly focussed on generating basic knowledge rather than down-stream industrial or societal outputs. One indication of this is the fact that the respondents indicate 'Innovation' and 'Education of young people' as the main contribution of neutron science to the wider society. Overall, the respondents rate the contribution of neutron science to their research and that of the whole Italian and international community as 'extremely important' or 'absolutely essential'.

Figures 43, 44 and 45 depict the answer to questions that focussed more specifically on the respondents' scientific impact, careers and collaborations and their ability to train highly qualified research students. The respondents clearly believe that neutrons have greatly contributed to their understanding of their subject, their impact in their field of research and their opportunity for international collaborations, while the relatively low ranking of the opportunity for industrial collaboration reflects, once again, their self-perception as a fundamental research community. Overall, the respondents do not seem to regard their membership of the neutron community as a strong career asset. This may reflect the perceived standing of the neutron community within the wider Italian research community – a worrisome aspect that certainly deserves further investigation.

A large majority of the Italian users who responded to our survey state their belief that neutron facilities have helped them to make a significant contribution within their field, and to improve the quality of their research and their research productivity (Figure 42); in many cases, work at facilities has strengthened their capacity of attracting major industry collaborations, the skills of their research teams and their international reputation (Figures 43 and 44).

10.2.7. 'Strategic' questions

Figures 50, 51 and 52 depict the answers to questions designed to probe the willingness of the respondents to support particular elements of a future neutron strategy, whilst avoiding to be perceived as 'leading questions' with pre-defined answers. The respondents are clearly willing to engage with a range of complementary activities aimed at educating more effectively the next generation of neutron scientists. Also, a significant majority of them regards the lack of a national source as a detrimental factor that significantly hampers the progress of the community.

The question relating to Figure 52 was designed to probe the attitude of the respondents towards engagement with neutron instrumentation, and made specific reference to industrial collaborations, alluding to the 'in-kind' model that has become popular in international science collaborations. There seems to be no appetite for further engagement with the ESS – a puzzling outcome given that the 'in-kind' is the preferred ESS partnership model. By contrast, the respondents seem to believe that further collaborations with existing sources are the best way forward – once again, a very interesting outcome, particularly since negotiations for in-kind contributions to the ILL have historically proven difficult. There is a very significant interest to engage with the next-generation of compact sources, perhaps reflecting the hope that one of them could be built in Italy.

10.3. Survey of Italian industrial stakeholders

In parallel to the survey of the Italian neutron science community, we have conducted a survey of the main stakeholders within Italy's industrial research community. The answers to this industrial survey are summarised in Figures 53 – 60, and are analysed in detail in a letter by Sesto Viticoli, the vice-president of the Italian Association for Industrial Research (AIRI), which is reported in full in Appendix 8.

Since 1985, the ILL and ISIS facilities have established wide-ranging industrial links with several Italian companies involved in collaborative design and development of neutron instrumentation (see 9.3). These companies also benefited from being awarded contracts for the construction of such a highly technological beamlines, benefiting sales, reputation and productivity. Businesses have also benefited from long-term usage of these facilities to help solve industrial problems in areas ranging from consumer goods, automotive, oil and gas, aerospace, energy and pharmaceuticals (see Section 6). The strong engagement of Italy's industrial user base and the desire of a closer interaction between industry and academia in this strategic sector emerge clearly from our survey and Sesto Viticoli's analysis. Growing the use of neutron faculties by industry will require a *strategic programme* *of outreach* to inform and advise them of the opportunities and the available means of access. Increasingly close ties between sources, universities and industry, including staff exchanges, will help to achieve this.

11. Analysis of the Italian neutron capacity to 2033

11.1. Introduction and definitions

As we have seen in Section 10, the Italian neutron scattering community is ambitious when it comes to perform experiments beyond current capabilities and regards both access to the ESS and planning a domestic neutron source as important components of its future aspirations. Nevertheless, *maintaining sufficient neutron capacity*[4] *emerges as an absolutely vital element of any future strategy*: without sufficient access, key experiments cannot be performed, students cannot be trained, expertise is lost and, ultimately, the whole community will decline. Although new sources such as the ESS will enable science that was not previously possible elsewhere, it is very important to reiterate that many of the highest-impact neutron publications do not require the very highest brightness, because clever design of the instrumentation and of the experiments often compensates for the shortcoming of the source.

In this section, we therefore discuss prospects for the Italian capacity for neutron access, based on the most recent and reliable data. The starting point of this analysis must be an assessment of the overall neutron capacity for Europe – in essence an update of the data published in the ESFRI report published in 2016 [6]. The ESRFI report presented three scenarios: 'ESFRI Baseline', 'ESFRI Degraded Baseline' and 'ESFRI Enhanced Baseline' (see Figures 7, 10 and 11 in the ESFRI report). Significant delays in the ESS construction programme require a downward re-assessment of the neutron capacity provided by the ESS in the next 10 years, even with respect to the 'ESFRI Degraded Baseline' scenario. This lost capacity is, however, partly compensated by the realistic prospect of continuing to run the ILL well into the 2030's. In Figures 9 and 10 below, we present two revised scenarios in the same format of the ESFRI report: a 'Best Case' scenario (Figure 9), based on the current ESS construction programme, and a 'Degraded' scenario, (Figure 10) based on a more prudent assessment of the ESS instrument programme. The figures in the 'Degraded' scenario are being used in the UK business case to justify further funding of the ESS. Regardless of the set of figures one uses, the following conclusion seems inescapable;

The vast majority of the European neutron capacity for the next decade will be provided by existing sources, with the ESS providing approximately 10%-13% of the overall capacity.

[4] The concepts of neutron capacity and neutron capability are defined and discussed in Appendix 4.

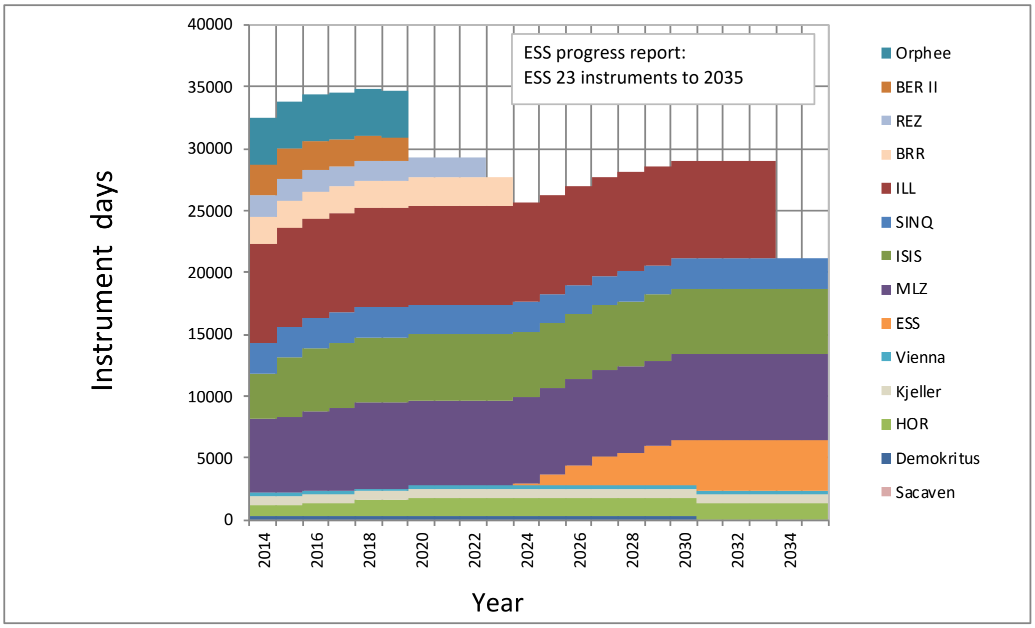

Figure 9: European neutron capacity between 2013 and 2035 – best case scenario, assuming that the ESS will build 35 instruments by 2031 and no further instruments thereafter. The unit of 'instrument day' corresponds to 1 day of beamtime on any of the available instruments. Sources: ESFRI report "Neutron scattering facilities in Europe" (published in 2016) and ESS. It is assumed that the ILL will operate at constant capacity until 2033, and that ISIS will continue to operate beyond this date.

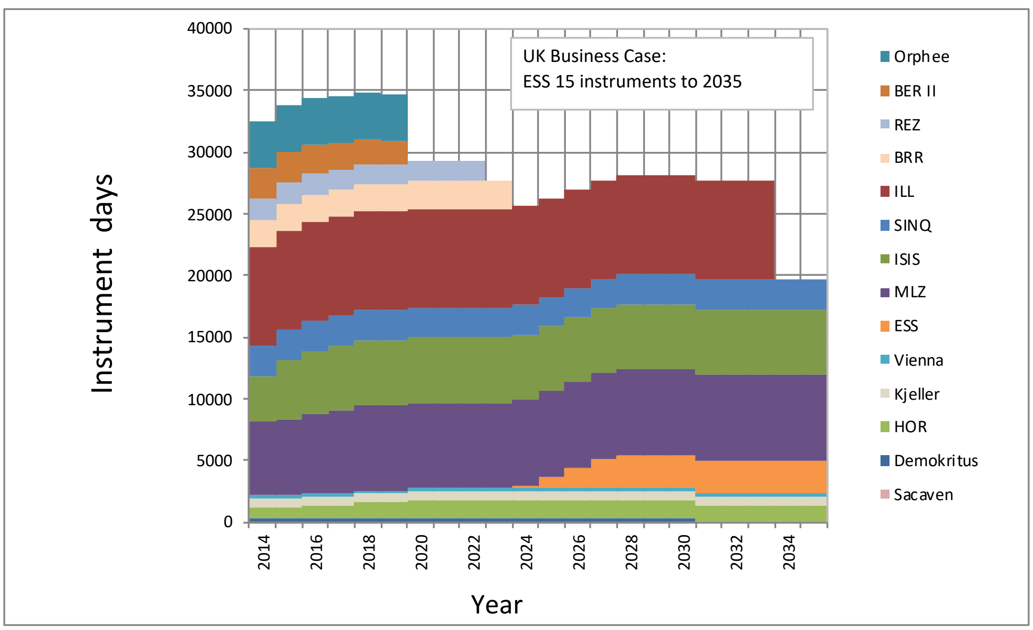

Figure 10: European neutron capacity between 2013 and 2035 – degraded scenario, assuming that the ESS will build 15 instruments by 2028 and no further instruments thereafter. The unit of 'instrument day' corresponds to 1 day of beamtime on any of the available instruments. Sources: ESFRI report "Neutron scattering facilities in Europe" (published in 2016) and ESS. It is assumed that the ILL will operate at constant capacity until 2033, and that ISIS will continue to operate beyond this date.

11.2. Fixed-cost scenarios

In Figure 11, we have gathered financial and neutron capacity data, comparing the *status quo* with a number of hypothetical fixed-cost scenarios having reduced neutron access for the Italian community. One key piece of information to produce the figure is the *cost per beam day* at each of the facilities, which we have calculated by dividing the operational cost of the facility (in 2018 Euros) by the total number of available beam days (from Figure 9). This is clearly an approximation, because Italy, through negotiations, might be able to obtain a better 'deal' than a straightforward sharing of the operation costs, but the history of previous engagement with international large-scale facilities indicates that the approximation is not too inaccurate.

The reference scenario (green lines, solid circles) is entirely hypothetical, and assumes that Italy continues to 'subscribe' to ISIS and the ILL at the current level, whilst *not* participating in the ESS. Since the current Italian neutron capacity (ISIS+ILL) is approximately 430 beam days/year, this would remain unchanged, at a cost (in 2018 €) of approximately €6.2M/year.

A contrasting scenario is presented by the purple line (solid diamonds) in Figure 11, which assumes that Italy participates at a 6% level to the transition-to-operation and operation of the ESS,

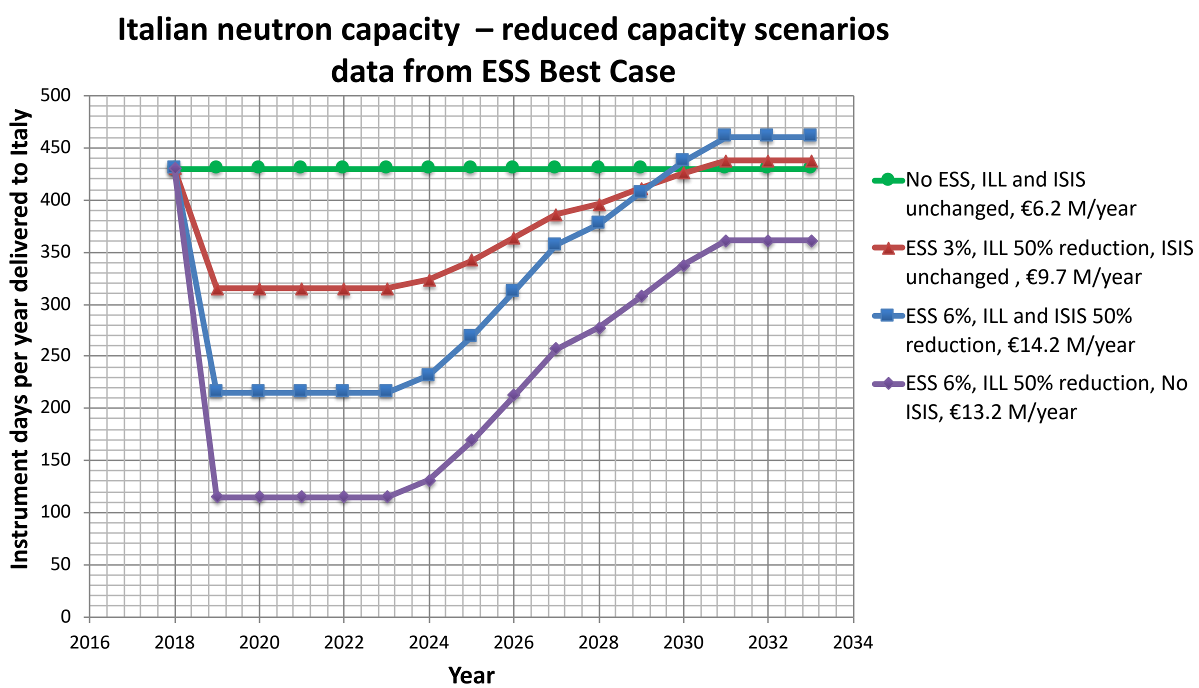

Figure 11: Italian neutron capacity for several fixed-cost, reduced capacity scenarios. **Green**: Italy does not contribute to the ESS and maintains the current level of access to ISIS and the ILL. Cost: €6.2M/year. **Red**: Italy contributes 3% to the ESS, reduces its contribution to ILL by 50% and maintains the current level of participation to ISIS. Cost: €9.7M/year. **Blue**: Italy contributes 6% to the ESS and reduces its contribution to ILL and ISIS by 50%. Cost: €14.2M/year. **Purple**: Italy contributes 6% to the ESS, reduces its contribution to ILL by 50% and pulls out of ISIS. Cost: €13.2M/year. These costs exclude the one-off capital contribution to the ESS construction costs, which is approximately €14.4M for a 6% contribution. The cost per instrument day at ISIS and the ILL was obtained by dividing the yearly operating budget (€55M and €100.6M, respectively) by the number of 'official' instrument days per year (5250 and 5600, respectively). The ESS capacity is based on the 'best case' scenario in Fig. 1. Sources: ISIS, ILL and ESS.

whilst cancelling its subscription to ISIS and reducing by 50% its participation to the ILL. The extent of the Italian legal commitment to future ESS activities is not known to this Committee, but a figure of 6% is generally assumed. Implementing this scenario would have an extreme impact on access: the Italian neutron capacity would be immediately reduced by approximately 75%, and would never revert to existing levels within the timeframe of our analysis. By contrast, the cost of providing this severely curtailed access would more than double with respect to the reference scenario, to €13.2M/year.

Two intermediate scenarios are presented by the blue line (solid squares) and red line (solid triangles). The blue line assumes 6% ESS participation and a 50% reduction of both ILL and ISIS subscriptions, while the red line assumes 3% ESS participation and a 50% reduction of the ILL subscriptions only. Both these intermediate scenarios are able to recover the present neutron capacity in the 2030's, but produce a significant capacity drop in the short term. The 'blue' scenario is the most expensive (€14.2M/year), while the 'red' scenario is relatively affordable (€9.7M/year) and is also the one with the least negative impact on neutron capacity.

One of the outcomes of our survey is that the *Italian neutron science community strongly relies on ISIS and the ILL*, and believes that the bulk of their scientific needs for neutron access will be provided by ISIS and the ILL. Consequently, we have considered and costed a number of scenarios in which access to these sources is maintained at the present level. In the absence of financial constraints, it would be desirable to set the Italian participation to the ESS operations at the same level of the construction phases (Figure 12). This 'scientifically optimal' scenario, however, would require an annual investment into neutron science that is almost trebled compared to the present

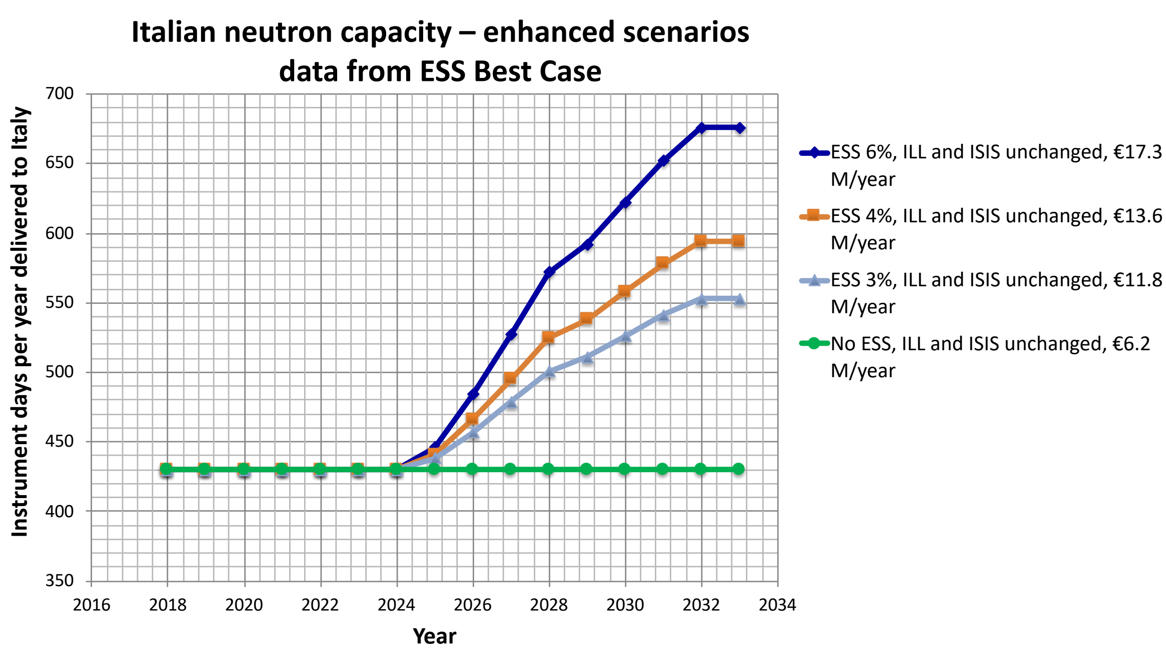

Figure 12: Italian neutron capacity for several fixed-cost, enhanced-capacity scenarios, all based on maintaining the current level of subscription to ISIS and the ILL. **Green**: Italy does not contribute to the ESS Cost: €6.2M/year. **Light blue**: Italy contributes 3% to the ESS. Cost: €11.8M/year. **Orange**: Italy contributes 4% to the ESS Cost: €13.6M/year. **Dark blue** Italy contributes 6% to the ESS Cost: €17.3M/year. The ESS capacity is based on the 'best case' scenario in Fig. 1. Sources: ISIS, ILL and ESS.

level. A number of alternative scenarios at intermediate costs are also presented. It is important to note that, in all these scenarios, the Italian neutron capacity would remain essentially unchanged until 2026 – a date that should be considered an optimistic lower bound for the ramp-up of the ESS user programme. Should the ESS deliver on schedule the kind of performances its users expect, there will be scope towards the end of the next decade to re-modulate the Italian contributions to the different sources, so that they are best matched to the requirement of the Italian neutron science community *at that time* (see next paragraph).

11.3. Fixed-capacity scenarios

In Figure 13, we have calculated the cost of maintaining the total Italian neutron capacity to the present value (430 days/year) in different ESS funding scenarios. The solid lines show the costs incurred by subscribing to the ESS from 2019 at 6% (blue line) or 3% (red line), whilst considering the full ESS subscription as part of the cost of providing neutron access. The downward trend of the two solid lines is easily explained by the fact that ESS will not produce any neutrons at least until

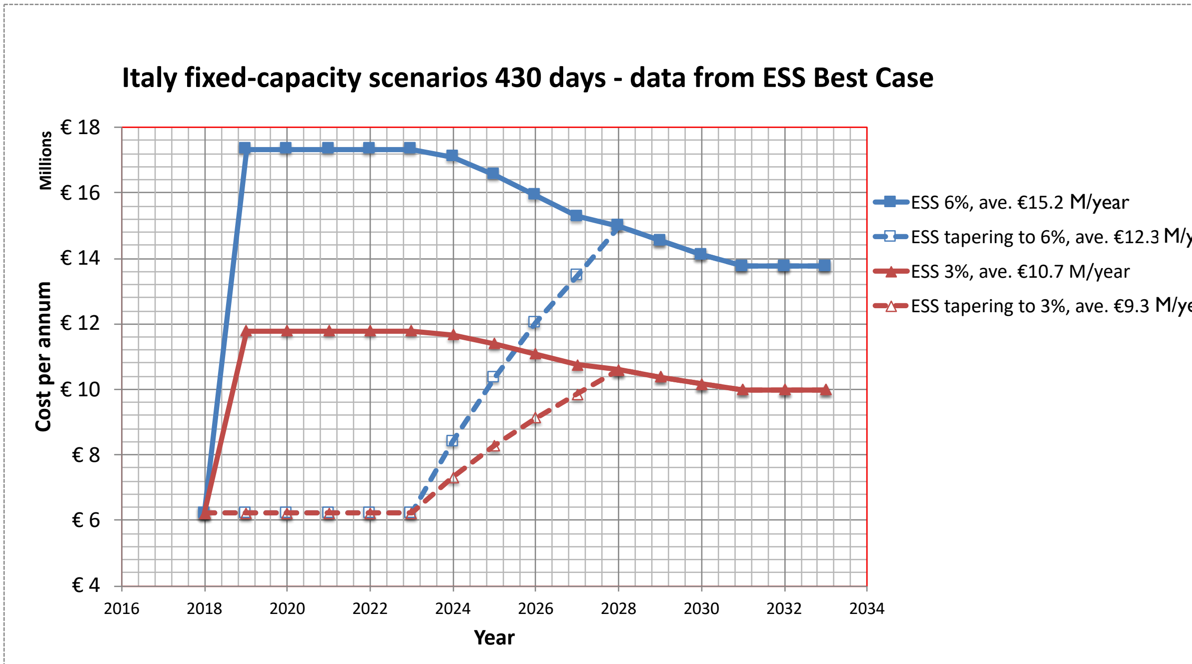

Figure 13: Cost for Italy required to maintain a constant neutron capacity (430 instrument days/year), whilst contributing to the ESS. ESS will not produce any neutrons until at least 2024, and all the capacity must be obtained from existing sources. The solid lines/solid symbols correspond to a contribution of 3% (red) or 6% (blue) to ESS, starting from 2019. As ESS starts producing neutrons, the capacity sought from other sources decreases, and so does the overall cost. The dashed lines/empty symbols correspond to 'tapering' the Italian contribution from 2024 reaching the same levels (3% or 6%) in 2028. These costs exclude the one-off capital contribution to the ESS construction costs, which is approximately €14.4M for a 6% contribution. The ESS capacity is based on the 'best case' scenario in Fig. 1. Sources: ISIS, ILL and ESS.

2023, so the cost of maintaining the present neutron capacity is the present cost plus the ESS subscription. From 2023 onwards, a small fraction of the overall neutron capacity will be provided by ESS, so that the ILL and ISS quotas (and their costs) will be reduced. The *average yearly cost* of these scenarios over the period 2019-2033 is €15.2M/year for ESS at 6% and €10.7M/year for ESS at 3%.

The dashed lines in Figure 13 present a different accounting approach to the same financial data, by *excluding* the cost of the ESS transition to operations from the computation of the neutron capacity cost. In other words, until the ESS starts to produce usable neutrons, the cost of the ESS subscription is considered as part of the *construction cost* (and therefore excluded from the computation of the neutron capacity cost), while for the subsequent 5 years (2024-2028) the cost is apportioned by linear interpolation between construction and operation. The rationale of this approach is that it reflects a more realistic assessment of the ESS progress towards operation. It should be emphasised that, unless a special exemption from contributing to the transition to operations is negotiated by Italy (a very unlikely outcome), the overall financial cost for Italy would remain the same for the dashed and solid lines of the same colour. Nevertheless, the nominal 'saving' to the cost of providing neutron access is very significant: the *average yearly cost* of these scenarios over the period 2019-2033 is €12.3M/year for ESS at 6% and €9.3M/year for ESS at 3%.

11.4. Discussion

Whilst not immediately providing an insight of what the Italian strategy for neutron access should be, the financial and projected neutron capacity data we have presented cast a very sharp light onto the true cost of providing *at the same time* the world-leading capability of ESS, which in many case will enable entirely new classes of experiments to be performed, *and* the overall neutron capacity required to ensure the health of the neutron community that is to benefit from these capabilities in the future. The inescapable conclusion is that the Italian participation in the ESS (and that of other countries as well) should be set to a level that is affordable *in addition to* (*rather than as a replacement of*) the existing neutron subscriptions to ISIS and the ILL – and approach that, on the European scale – is only possible by widening participation in the ESS.

12. A 10-year forward look: 2019-2033: recommendations for a future neutron strategy

In this section, we discuss what we consider to be the essential elements that any neutron strategy for the next decade and beyond *must* include. Clearly, these elements will need to be modulated and tensioned against each other and against other priorities for science and the country as a whole; in the next section, we will present two scenarios in which these elements are assigned different weights, depending on the constraints imposed by the funding environment.

12.1. Requirements for access to neutron beamtime

It is *absolutely vital* to sustain the health of the Italian neutron community well into the next decade, so that it is prepared for the new opportunity and challenges presented by the commissioning of the ESS. Specifically, this means that *the neutron community must remain productive* and, ideally, increase its productivity and scientific impact; *it must be able to train the next generation of neutron scientists; it must continue to engage with Italy's industrial base,* and, ideally, become even more relevant for the wider societal challenges. This is only possible if the Italian neutron science community has adequate access to neutron beamtime, and this can only be provided by a combination of ISIS and the ILL, well into the next decade. Indeed, the vast majority of the respondents to the survey believes that bulk of their neutron access will be provided by these two facilities.

> *Maintaining the current level of access to ISIS and the ILL (as a minimum requirement), and ideally increasing the subscription level to match Italy's real usage, must be the cornerstone and absolute first priority of any prudent neutron strategy for the next decade.*

12.2. Collaborations in the development of new neutron sources

The ILL can remain highly competitive well beyond 2030, and it is highly desirable that it continues to run well past this date. It seems clear that this facility will at some point come to the end of its extraordinary life. An upgraded ISIS may develop into a second, high brilliance source for Europe, but plans for this upgrade are only at the drawing stages. The inescapable conclusion is that, for many years beyond 2030, the ESS will represent the future of neutron science in Europe, and will provide the bulk of the required neutron capacity.

> *It is imperative for Italy to remain coupled to the development of the ESS, and to influence its policies and instrumentation portfolio so they are most relevant to its needs.*

This can only happen if Italy's engagement is commensurate with its role as a major scientific powerhouse.

Meanwhile, neutron scientists and accelerator specialists are working together in the attempt to overcome current limitations of accelerator-based neutron technologies. They have produced a wealth of new ideas, including designs for so-called 'compact' neutron sources. Many respondents to our survey have expressed a keen interest in these sources, which may represent an interesting avenue for a future national capability. Although these schemes have the potential of reducing the size (and cost) associated with the accelerator/target element of the source, it must be born in mind the rest of the facility cannot be 'compacted' in the same way. *The Italian neutron community* *requires a fully-fledged user facility*, and this will continue to represent a significant investment for the foreseeable future.

Italy should continue to be involved in the technical design and development of 'alternative' neutron sources, including those driven by compact accelerators. The Italian neutron science community should be attentive to these developments, whilst maintaining a realistic outlook on their potential.

12.3. Collaboration in neutron instrumentation

For the past three decades, Italian scientists have collaborated intensely in the field of neutron instrumentation with both ISIS and the ILL. Their scientific and technical contribution has been highly valued by the management of these facilities, who have recognised the high level of creativity and innovation brought by these collaborations. In some cases (e.g., CHIPIR at ISIS), Italian scientists have come up with entirely new ideas for instrumentation that did not previously exist. These programmes had extremely positive repercussions on the engagement of Italy's industrial base with neutron science.

Although Italy has collaborated with the ILL in the past, in the last few years the bulk of Italy's neutron instrumentation activity has been in partnership with ISIS. This has been in part due to the fact that STFC has demonstrated greater flexibility to accommodate an in-kind contribution than the ILL associates. Most recently, this partnership as led a fruitful cooperation on the development of the Italian and British in-kind contributions to the ESS.

It is important to emphasise that Italy cannot be completely independent in the development of neutron instrumentation, for the obvious reason that it lacks a national source. Therefore, *providing an element of neutron instrumentation as in-kind contribution to the ESS is only possible if Italy continues to engage collaboratively with existing sources, and most particularly with ISIS*. The *conditio sine qua non* for this to happen is the renewal of the existing CNR-ISIS agreement.

Italy must continue to collaborate with existing neutron facilities in the field of neutron instrumentation. If possible, the successful model of in-kind contributions to ISIS should also be extended to the ILL.

Such an agreement with the ILL would have significant scientific and technical benefits for both sides, as well as a positive impact on Italy's industrial engagement with neutron science.

12.4. Industrial requirements

In order to achieve a more innovative economic portfolio for Italy, industries and companies must capitalise on their strengths in research and innovation and expand their engagement in areas such as smart and clean energy technologies (e.g., energy storage, demand-responsive grid technologies); robotics and artificial intelligence (including connected and autonomous vehicles and drones); leading edge healthcare and medicine; manufacturing processes and materials of the future, including new joining technologies and cultural heritage; biotechnology and synthetic biology quantum technologies, and transformative digital technologies, including advanced modelling.

It is clear from the examples presented in Sections 5 and 6 that neutron techniques are extremely relevant for industry's science, providing unique and powerful insights into an extraordinary breadth of science disciplines and applications in all these sectors. For example, in the field of smart and clean energy technologies, neutrons will enable us to follow the critical changes that take place within operating energy storage devices non-destructively, by establishing the relationship between the structure and properties of alternative cathode materials, including lithium manganese oxide, lithium iron phosphate and lithium nickel manganese cobalt oxide. In healthcare and medicine, amongst other things, neutron can determine the solution structure of multicomponent biological systems as well as determining the interaction of drugs with biomolecules in solution and the nature of materials suitable for implants. In manufacturing processes and materials, neutron scattering provides unique insights into the structure and dynamics of materials as a function of temperature and pressure, and yields important information for materials development and integration into devices and products that are important to the health, digital, manufacturing and energy sectors.

In Italy, there is a committed group of industrialists who have engaged enthusiastically with the opportunities presented by neutron science. However, among the wider industrial community, there is little awareness of the opportunities and capabilities provided by neutron facilities, and of the means to access them. In general, research with neutrons is considered 'too expensive', and in this respect there is hardly any awareness of the benefits of collaborations between industry and Academia.

Italy must implement an aggressive programme of outreach to strengthen the ties between neutron sources, universities and industry. Exchanging staff is an excellent way to inform and advise industries of the opportunities and the available means of access. In parallel, new access modes will need to be developed together with our partners at the ILL, ISIS and the ESS, to ensure that academic and industrial users can effectively exploit neutron techniques to address high priority science and technology challenges.

12.5. Skills and training

As we already mentioned, training the next generation of neutron scientists, engineers and technical staff is a vital necessity for Italy. At present, this training is provided by a combination of doctoral and post-doctoral programmes delivered within user groups at universities and national laboratories, experimental campaigns at user facilities, secondment of technical staff and a series of very successful neutron schools. In this respect, the Italian community has been extremely pro-active, and has also benefitted from for the engagement of a strong contingent of Italian neutron 'expatriates', many of whom are experts in fields, such as magnetism, that are under-represented in Italy. Indeed, a current limitation of Italy's research system is the relative lack of opportunities for talented early-career researchers who are not associated with Italian groups.

Italy must nurture its talent base and continue to strengthen its training provisions with a variety of targeted programmes. A strategic initiative to recruit and the best and the brightest in neutron science, regardless of nationality, could be a game changer, enabling Italy to match or exceed the impact of its closest competitors.

12.6. Funding scenarios

In this section, we develop in some detail two scenarios for future funding of the Italian neutron programme, based on the analysis presented in Section 11. The financial element of this analysis is, by necessity, only an estimate, since the exact cost of each option will largely depend on the outcome of negotiation between the MIUR and CNR on one side and the facilities on the other. We have nevertheless included our figures as 'nominal costs' in the discussion, since they provide both an order of magnitude and a useful comparison between these and other possible scenarios.

12.6.1. Common elements to both scenarios

On the basis of the discussion above, which reflect the essential requirements of the Italian community, the scenarios we consider have the following common elements:

- Access to ISIS and the ILL at least at the current level.
- Participation to ESS at a significant level, although not necessarily at the same level as Italy's contribution to the construction programme (this is included in the 'scientifically optimal' scenario).
- Continuation of the instrumentation development programme in partnership with STFC and, if possible through negotiation, extension of the *in-kind* funding model to the ILL, as explained above
- Re-assessment of Italy's neutron capacity requirements in the middle of the next decade, and re-modulation of the agreements on this basis.

12.6.2. Scientifically optimal scenario

The 'scientifically optimal' funding scenario is based on the (somewhat unrealistic) premise that sufficient funding will be available to match *all* the scientific and technical ambitions of Italy's neutron community. Consistent with this would be to implement at the highest level the 'enhanced capacity' option presented in Figure 12. This would entail *maintaining the current level of subscription to ISIS and the ILL, and contributing 6% to the cost of the ESS transition to operation and, later, ESS operation*. Scientifically, the 6% contribution to ESS could be justified because it is likely to provide, by 2033, approximately the same neutron capacity as the ILL, hence preparing the community for a possible closure of the ILL in the 2030's. Italy should also be prepared to negotiate with ISIS and ILL a subscription cost that is commensurate with its actual usage, although it would be desirable that a significant fraction of this cost could be provided *in kind*.

Figure 12 shows a significant enhancement of Italy's neutron capacity from 2026, due to the build-up in ESS capacity. This is, of course, entirely conditional on ESS delivering instruments according to its current project plan, and on these instruments performing according to expectation, including necessary provisions for data analysis, sample environment, etc. A review of Italy's requirements, to take place around 2025, will assess the actual need for extra capacity as well as the capacity prospects at ESS *at that time*, and may well conclude that the appropriate course of action would be to 'fall back' to a constant-capacity scenario, such as the solid blue line in Figure 13. In any case:

> *The nominal cost of implementing the 'scientifically optimal' scenario, in which Italy continues to contribute to ISIS and the ILL at the current level for the next 6 years at least and 'subscribes' to 6% of ESS, is initially €17.5M/year, and could be gradually reduced, starting from 2026, to an average of €15.2M/year for the period 2019-2033.*

i.e., almost three times the current cost of the ISIS and ILL subscriptions combined.

12.6.3. Constrained scenario

The 'constrained' scenario assumes that the total cost of Italy's contribution to all neutron facilities is constrained by tensioning against other scientific and national priorities. We consider that *the minimum level of participation to ESS's operation is 3%*, and we have assumed this as the most pessimistic figure, and we have also assumed that the ILL and ISIS subscriptions will be renegotiated periodically to maintain constant capacity (solid red line in Figure 13). With these assumptions:

The nominal cost of implementing the 'maximally constrained' scenario, in which Italy continues to contribute to ISIS and the ILL at the current level for the next 6 years at least and 'subscribes' to 3% of ESS, is initially €11.8M/year, and would be gradually reduced, starting from 2026, to an average of €10.7M/year for the period 2019-2033.

Although sub-optimal from the scientific and technical point of view, we believe that this 'constrained' scenario would continue to meet the fundamental requirement for Italy's access to the best world-class neutron facilities in the world.

13. Conclusions and outlook

Neutrons are and will remain a key requirement for Italian researchers in academia, national institutions and industry. They are an essential component to realise an end-to-end materials research and development sector, from materials discovery through materials and component scale-up to high-volume manufacturing and system and service integration. Competitive economies are increasingly banking on the ability of academic and industrial teams to rapidly carry out characterisation studies during the design and discovery phases, including *in situ* and *in operando* studies of realistic devices. This national capability is equally critical in the biosciences and soft matter disciplines as in the physical sciences and engineering areas, as illustrated by the range of case study and examples we presented in this report (see Sections 5 and 6).

Neutron sources are high-cost infrastructures: providing access to existing facilities, investing in the construction of new ones and funding the science programmes that use them all will continue to be a challenge. Over the next ten years, there will be a significant change in the European neutron landscape. In the context of developing the best access plan for Italy, it is worth summarising here some of the key dates for decisions and milestones:

- 2019 – The BERR and Orpheus reactors are expected to close
- 2021 – Deadline for a decision on agreeing on a new protocol for ILL operations beyond 2023
- 2023 – ILL current protocol ends
- 2023 – Planned date for first instruments to begin user operations at ESS
- 2028 – Planned date for full suite of instruments to come on line at ESS and the full accelerator power is reached

From the early days of neutron scattering, Italy has developed a tradition of innovation and leadership in this sector. This covers a range of fields ranging from scientific and technical developments of the methodology, all the way to scientific achievements, through innovative access policies. Of particular note has been the impact of the Italian community in developing advanced neutron instrumentation and agreeing and planning instrumentation suites both at the ILL and ISIS (see details at Section 9.3). Italian scientists and engineers have taken responsibility for specifying, designing, constructing and ultimately operating specific instruments, particularly those of greater interest for the Italian community. Moreover, Italian researchers have regularly succeeded in securing, through competitive review by facility access panels, a significantly greater share of the available beamtime than the time formally allocated to them in the bilateral agreements signed with both facilities.

This review concluded that Italy's continuing investment in *the current level of access* to both ILL and ISIS is *vital* to ensure that Italian users can continue to address important challenges for science and industry, and is also a *strict prerequisite* to achieve technical and scientific readiness for the ESS in the middle of the next decade.

Further on, a strategic approach to delivering the optimal neutron capacity and capability mix will be needed to ensure that Italy's role in these areas of science and technology can be maintained and strengthened for the foreseeable future. In particular, Italy role as a leading manufacturing economy demands innovative approaches and funding arrangements, to broaden the access to neutron techniques and secure new partnerships and collaborations between industry, national laboratory and Academia.

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Appendices

APPENDIX 1: THE BIRTH AND DEVELOPLMENT OF NEUTRON SCIENCE IN ITALY AND IN EUROPE: A HISTORICAL SNAPSHOT

Significant breakthroughs and new insights in many science areas have been achieved using neutron and muon techniques. The organization of matter at the atomic level and the forces that hold atoms together determining their dynamics are the fundamental issues that physicists, chemists, and material scientists address using neutron (and muon) sources.

The ability of neutrons to reveal the structure of matter and distinguish between isotopes has made them a prime tool for research fields ranging from condensed matter physics through to soft matter biology. Muons provide a complementary probe to neutrons, particularly in the areas of magnetism, superconductivity and charge transport. This diversity of applications and the cost of the facilities needed to enable neutron and muon-based research mean that it is appropriate to review and reassess the provision made to support this research.

Neutron scattering is a vital part of many areas of science. Many of the global challenges that lie on the horizon, from clean water to green energy, from an increasingly interconnected world to ensuring an innovative manufacturing base, will require the insights that future neutron experiments can bring. Neutron scattering will continue to be a key element to the success of Italy's future industrial strategy in such areas.

Figure 14: The famous "Goldfish fountain" in Via Panisperna. Following Chadwick's discovery of neutrons in Cambridge, Fermi opens up in Via Panisperna a new era of applications with neutrons (Figure XX).

The birth of neutron science can be traced back to 1934, when Enrico Fermi and his collaborators started to investigate the phenomena induced by neutron irradiation in a variety of materials. Fermi experiments were conducted at the Institute of Physics of the University of Rome, funded by Pietro Blaserna in 1880 and located in Via Panisperna. Various substances were irradiated by neutrons emitted by a polonium-beryllium source and the induced radioactivity was examined using a Geiger-Müller counter. After several attempts, Fermi and collaborators observed a small but significant amount of beta activity in aluminium and in calcium fluoride. The discovery was announced on the 25th of March 1934 in a paper published in *La Ricerca Scientifica*, "*Radioattività indotta da bombardamento di neutroni*" (Radioactivity induced by neutron bombardment) [4]. Other experiments followed, showing that a block of paraffin inserted between the neutron source and the irradiated sample had a positive effect on the induced radioactivity. In the afternoon of the 22nd of October 1934, the experiment was repeated in the garden fountain of the Institute (Figure 14). The neutron source and the sample were immersed in water to test the effect of a large quantity of hydrogenous substance, different from paraffin. The results confirmed the hypothesis formulated by Fermi that slowing down the neutrons by elastic collisions against the protons present in hydrogenous substances resulted in an increase of their probability to be absorbed by the nuclei of the bombarded substance. Later in the evening Fermi wrote for *La Ricerca Scientifica* the announcement of their new discovery: *Influence of hydrogenous substances on the radioactivity produced by neutrons* [5] (Figure 14).

In 1946 the Centro Informazioni Studi Esperienze (CISE) (G. Bolla, G. Salvini, C. Salvetti, M. Silvestri) was established in Milan with the scope of developing applied nuclear research and designing an Italian nuclear power reactor.

In 1952 Alcide De Gasperi established the *Comitato Nazionale per le Ricerche Nucleari* (CNRN) within the Consiglio Nazionale delle Ricerche (CNR). The Committee had the scope of promoting research and applications of nuclear energy. Francesco Giordani was the first president of the CNRN.

In 1955, one year after Fermi's death, the Italian government decided to install a CP-5 type nuclear research reactor in Ispra, on the shore of Lake Maggiore. The USD-3M facility was purchased from the "American Car and Foundry" and the installation started under the direction of Carlo Salvetti.

In 1957, in the occasion of the Signatures of the Treaties of Rome a Nuclear Joint Research Centre is established in the framework of EURATOM.

In 1959, the Ispra-1 reactor goes critical with a 5 MWt power production. On the same year, CNRN acquires a juridical status and become CNEN. Emilio Colombo, then Minister for Industry in the Italian Government, is nominated as first CNEN President.

In 1960, The National Nuclear Energy Centre is created at Casaccia, near Rome. A TRIGA-RC1 Research Reactor is built with 0.1 MWt, later upgraded to 1 MWt. TRIGA is a class of small nuclear reactors using UZrH fuel, with U enriched to 20%. The design team for TRIGA included Edward Teller and was led by Freeman Dyson.

In 1963, the Babcock & Wilcox Co. 5 MWt pool Research Reactor "Galilei" becomes critical at the Centro Applicazione Militari per l'Energia Nucleare (CAMEN) in S. Piero a Grado (Pisa).

In 1957, Edoardo Amaldi, then vice-president of CNRN, realizes the importance of exploiting the potential of neutron scattering techniques being developed at Argonne, Brookhaven, Oak Ridge, Chalk River, and Harwell for the exploration of condensed matter. Wishing to import these techniques in Italy, Amaldi asked three young researchers, Giuseppe Caglioti, Antonio Paoletti, and Francesco Paolo Ricci, to design and build a crystal neutron spectrometer. The design optimization study produces a series of papers on luminosity and resolution of crystal spectrometers that were going to acquire an unexpected importance. G. Caglioti, was sent to Chalk River, to work with Bert Brockhouse, A. Paoletti to Brookhaven to work with Bob Nathans, and F. P. Ricci to MIT in Boston to work with Cliff Shull on neutron scattering and experimental methodologies. In the following years Paoletti and Ricci moved to Casaccia and Caglioti to Ispra, and the neutron scattering activity in Italy started and rapidly expanded.

In 1968, an International Conference on "Current Problems in Neutron Scattering" held in Casaccia recognized the primary role of Italy's neutron science.

From 1969, more research groups in neutron scattering developed at Centro Studi Nucleari E. Fermi at the Politecnico di MIlano, at SORIN in Saluggia, and at CAMEN in S. Piero a Grado, whereas materials properties and radiation damage started to be studied by Small Angle Neutron Scattering. At CAMEN, FIAT scientists started the first industrial applications of SANS.

In 1965, the French Republic and the Federal Republic of Germany approve a project to construct the ILL Research Reactor in Grenoble. Its construction follows that of the HFBR Research Reactor in Brookhaven, which first goes critical in 1965. The ILL high-flux reactor starts delivering neutrons for science in 1972. In 1973 UK joins the ILL consortium.

In the early 1980's, C. Bucci, F. Menzinger and F.P. Ricci, promoted a new investment in the ISIS pulsed neutron and muon spallation source, under development in the Oxfordshire at Rutherford Appleton Laboratory, to CNR President Quagliarello. ISIS Pulsed neutron and muon source produced the first beam in 1984 and was formally opened in 1985. In 1985, the president of CNR Luigi Rossi Bernardi signed the first bilateral Agreement with CCLRC [1].

In 1985, Bucci and his team play a key role in developing muon spectroscopy capabilities at ISIS.

On November 4th 1988, Luigi Rossi Bernardi, inaugurates the PRISMA spectrometer at ISIS, the first neutron beamline built within the CNR-SERC agreement by a team of Italian and British researchers. Many other neutron and muons instrument built in Italy within the CNR agreements with CCLRC and STFC and installed at ISIS will follow in the years to come: PRISMA II-IV, TOSCA I-II, INES, EMU, DIZITAL, NIMROD, SLOWMU, CHIPIR, IMAT, VESUVIO, e.VERDI.

In 1990, a LETI's 2D Position Sensitive Detector installed at CAMEN is moved from PISA to ILL and installed on the IN4 neutron beamline, representing the first Italian research collaboration with ILL [1].

APPENDIX 2: SCIENCE WITH NEUTRONS

A2.1 Characteristics of the neutrons and muon probes

Neutrons are charge-free particles that since their discovery (by Chadwick [2]) and applications (by Fermi [3-4]) are used in numerous scientific and technological/industrial fields thanks to their ability to "see" in a unique way where "atoms are" and how "they move" [5]. When beams of neutrons are used to probe small samples of materials they have the power to reveal what cannot be seen using other types of radiation. Neutrons appear to behave either as particles or as waves or as microscopic magnetic dipoles. It is these specific properties which enable them to yield information which is often impossible to obtain using other techniques: they have the ability to deeply penetrate matter, interact with nuclei and – unlike x-ray – can distinguish and image light elements such as hydrogen; they have a spin, or magnetic moment, so they are also sensitive to magnetic sources in materials and thus can provide images of magnetic structure.

Muons have a mass of 105.7 MeV/c^2, about 200 times the mass of an electron, thus can be thought of as a much heavier version of the electron. The interactions of muons with matter are very similar to those of the electrons. Muons can be created by colliding a fraction of the proton beam generated from a spallation neutron source with a graphite target, producing pions, which then decay rapidly into muons. In the majority of cases, studies of materials make use of positive muons. When implanted into materials, positive muons can be thought of as acting like "light protons" (same charge as the proton, and about 1/9 of their mass). In the same way that a proton can pick up one electron to form a hydrogen atom, implanted muons can also capture an electron to form 'muonium'. The latter behaves chemically just like a hydrogen atom, with similar ionization potential and radius. Thus, one can use muonium to study what isolated hydrogen atoms do inside materials.

A2.2 Neutron (and muon) user facilities

Progress in neutron science is the result of developments in neutron user facility technologies, advanced in instrumentation, ancillary equipment and material synthesis and engineering.

Neutron user facilities are typically high- or medium-flux facilities (reactors with thermal power > 15 MW, or spallation sources with beam power >100 kW), multiple cold-neutron sources, guides and between 10 and 35 state-of-the-art beam instruments. There is also typically a very extensive suite of equipment to allow in-beam experiments at high and low temperatures, high pressures, intense magnetic fields, significant uniaxial stress, high electric fields, gas dosing with a wide range of gases, humidity control and so on. While most facilities support some fee-for-service commercial work, the main method of access is for non-proprietary research evaluated competitively by peer review.

Reactors and Spallation Sources, or more precisely continuous sources and pulsed sources, are seen as *complementary*. Many of the key methods are equally well pursued at either, but reactors tend to be better in narrow dynamic range experiments, in which one does not need the highest wavelength resolution, while pulsed sources are strongest for high-resolution experiments with very wide dynamic range. Often the initial survey experiments are better done at spallation sources, with detailed follow up at a reactor, especially for single crystals or when polarised neutrons are needed. Having said this, other factors often turn out to be more important, for instance the quality and interests of the facility staff, or the nature and reliability of the sample environments that are available.

A2.2.1 Steady-state reactor sources

Steady-state thermal reactors have been the mainstay source for neutron scattering since the 1940's. Typically, the neutrons are produced by fission of Uranium-235, in the form of an enriched-uranium high-density fuel. Most reactors designed to produce intense beams of neutrons are cooled with light or heavy water, and moderated using heavy water. All modern reactors include one or more cold neutron sources (essentially a bottle of liquid hydrogen or liquid deuterium at around 20 K, close to the core) and some also include a hot neutron source (a block of graphite heated to 2000 °C). All modern research reactors make heavy use of neutron guides to carry neutrons, with low loss, to the experimental areas. The leading example of a research reactor for neutron beams is the High-Flux Reactor at the Institut Laue-Langevin, in Grenoble, France, with other high-performance well-instrumented reactors in Germany, the USA, Australia, Japan and South Korea.

A2.2.2 Pulsed reactors

Thermal reactors can also be pulsed, though this is relatively unusual. The prime example is the IBR-2 pulsed reactor in Dubna, Russia, in which a pair of flywheels rotates blocks of reflector material next to the core, in such a way as to provide a very intense pulse of neutrons. In principle, the performance can be similar to that of long-pulse spallation sources (see A 2.2.5 below), as the time-pulse structure, moderation times and peak fluxes are similar. In addition, some relatively low flux TRIGA reactors have been run in pulsed modes, in the past. The advantage of pulsing any source is that one can get a higher flux in the peak of the pulse, but distribute the heat load over the whole time, including when the source is not producing neutrons.

A2.2.3 Steady-state spallation sources

Spallation is a process in which fragments of material are ejected from a body due to impact or stress. Nuclear spallation is one of the processes by which a particle accelerator may be used to produce a beam of neutrons. Typically, a 1-GeV beam of protons is fired onto a heavy-metal target. It is roughly ten times as efficient (per unit of heat generated in the target) as fission. One factor in choosing a spallation source, rather than a reactor, is to reduce the regulatory burden and to have less problematic waste streams.

If the accelerator operates continuously, for instance using a cyclotron, the source is continuous, and it supplies beams very similar to those from reactors. This method has been implemented at the SINQ source in Switzerland.

A2.2.4 Short-pulse spallation sources

An accelerator-based spallation source that produces pulses of the order of microseconds in length is called a "*short-pulse spallation source*". Typically a ring structure is used, either a rapid-cycling synchrotron or a LINAC together with full-energy injection of H^- ions into a storage or accumulator ring. The proton pulse length is characteristic of the circumference of the ring. This method is particularly well-suited to high-resolution experiments, in which a wide dynamic range of neutron wavelengths or energies is valuable. The leading example of this type of source has been the ISIS spallation source in the UK, and more intense ones are now operating in the USA and Japan.

A2.2.5 Long-pulse spallation sources

These are neutron sources that make use of a linear accelerator able to deliver a high power, high-energy proton beam. The absence of a storage ring makes the system simpler than the one used in a short-pulse spallation source. This typically give pulses of length in the millisecond range, which combined with appropriate moderators are useful for experiments that do not require high wavelength or energy resolution, for instance small-angle neutron scattering measurements. This type of source is known as a "*long-pulse spallation source*", and the first one to be built will be the European Spallation Source in Lund, Sweden.

A2.3 Alternative neutron sources

In this section, we describe an array of other methods for lower flux sources that are useful for training, technique and instrumentation development, in-field or portable applications, and which can be useful for some of the simpler measurements using the least demanding methods (from a flux view point): typically, neutron activation analysis, neutron radiography, some of the less demanding irradiation protocols, and so on.

A2.3.1 Pulsed neutron generators

Sources of this kind emit mono-energetic neutrons in repetitive bursts (pulses) at a pre-set frequency. In the simplest pulsed neutron generators, deuterium (D) and tritium (T) ions are accelerated into a thin layer of titanium hydride loaded with the same isotopes. The D-T collisions give rise to nuclear fusion reactions releasing a helium nucleus and a neutron with energy of about 14.1 MeV. Each burst is typically 10^{-5} seconds long and may contain as many as 10^6 to 10^7 neutrons, with pulse frequencies ranging from 1 to 150 Hz. D-D collisions produce 2.5 MeV neutrons with a yield 50 to 100 times lower than D-T fusion reactions. The ion accelerator generally consists of several cylindrical electrodes with an acceleration voltage of 100-500 kV. The radioactive tritium gas is held in a sealed vacuum enclosure containing the ion source, a metal hydride reservoir, the beam focusing optics, and the accelerator target. The size of the cylindrical accelerator assembly of a commercial pulsed neutron generator is typically 10 cm diameter and 50 cm height, weighting 10-20 kg.

Higher neutron intensities, up to 10^{12} neutrons per pulse, with a pulse width down to 10^{-7} s, can be obtained in dense plasma focus generators. In these devices, an electrical current flows through an ionized gas of deuterium and tritium. The associated system of Lorentz forces rapidly compresses (pinches) the plasma, producing instabilities and breaks up that are accompanied by intense neutron bursts. Being compact and transportable, pulsed neutron generators are considered for in-field applications in several domains, from medicine to security and non-destructive materials analysis.

A2.3.2 Radioisotope neutron sources

Alpha neutron sources. The most common type of radioisotope neutron sources is obtained by finely mixing a high-activity alpha-emitter (such as radium-226, americium-241 or plutonium-238) and a low atomic mass nucleus, usually beryllium-9. The absorption of the alpha particle by Be-9 leads to the formation of carbon-12 and the emission of one neutron and a photon. Am-Be sources provide a yield of about 6×10^4 neutrons/s per GBq of activity, with average neutron energy of 4.2 MeV and maximum energy of 11 MeV.

Spontaneous fission neutron sources. Actinide and trans-actinides even-even isotopes can undergo radioactive decay by spontaneous fission. In this process the nucleus splits into two fragment nuclei and several neutrons (2-4) that are released within 10^{-14} s of fissioning. Some further neutrons are released on a much longer timescale and are associated with the decay chain of the primary fission products. Plutonium-238, californium-252, and curium-244 are examples of radionuclides exhibiting spontaneous fission, and the latter two are used for the fabrication of portable neutron sources. Cf-252, for example, has a half-life of 2.645 years and a neutron yield of 2.3 - 2.4 x 10^{12} n s^{-1} g^{-1}. The neutron energy spectrum of a Cf-252 source (usually a californium oxide or californium-palladium alloy doubly encapsulated in stainless steel) is similar to the one of a nuclear reactor, with an average energy of 2 MeV.

Gamma neutron sources. Almost mono-energetic neutrons can be produced from beryllium-9 and deuterium by photonuclear reactions induced by high-energy gamma-rays. Available sources consist in a cylinder of reactor-irradiated antimony-124 of 2-3 cm diameter, surrounded by a thin layer of Be-9 or deuterium. In that case, the yield of neutrons with 240 keV energy can be as high as 0.6×10^4 neutrons/s per GBq.

Radioisotope neutron sources find applications in reactor start up, density and moisture gauges, well logging, activation analysis, gemstone colorization, neutron radiography, and detector calibration.

A2.3.1 Accelerator-based neutron sources.

Quasi-monoenergetic neutrons can be produced by accelerating light positive ions like protons or deuterons with Van de Graaff or Tandem accelerators and firing them into low Z targets. For instance, 2.5 MeV neutrons can be obtained by bombarding a deuterium-loaded metal hydride target with accelerated deuterium ions. Neutrons with energy from 0.01 to 2 MeV can be obtained using protons and Li-7 targets, whereas neutrons with energy from 0.5 to 6 MeV can be obtained bombarding tritium with protons. Higher energies between 13.4 to 23 MeV can be covered by firing deuterium on tritium-loaded targets. The MONNET neutron source operated in Geel (Belgium) by the Joint Research Centre (JRC), the European Commission's in-house science service, is an example of such a neutron source.

A different example of accelerator-based neutron source is given by facilities making use of the bremsstrahlung radiation that high-energy electrons emit when stopped by a heavy element target, made for instance by tungsten or uranium. Neutrons originate from the photonuclear (gamma, n) reaction in beryllium or by the photo-induced fission of uranium.

An example of such a facility, especially designed and built for high-energy-resolution cross section measurements, is the JRC neutron source GELINA, in Geel. This source provides neutrons in bunches of less than 1 ns duration, at repetition rates up to 800 Hz, in the energy range between 1 meV and 20 MeV. The main components of the facility are a linear electron accelerator delivering a pulsed electron beam, a post-acceleration relativistic-energy compression magnet system, and a rotary mercury-cooled uranium target. The energy of the electrons in a pulse leaving the accelerator varies linearly from 140 MeV at the start of the pulse to 70 MeV at its end. The peak current at the exit of the compression magnet is of about 120 A, corresponding to 10 kW of full beam power delivered to the rotating U-Mo target. Heat dissipation is provided by liquid mercury, mainly to avoid neutron moderation. Neutrons are produced by (gamma, n) reactions and, to a lesser extent by gamma-induced fission. The target delivers an average neutron intensity of 3.4×10^{13} neutrons/s. Two light-water moderators are placed above and below the target to increase the number of neutrons in the energy range below 100 keV.

APPENDIX 3: STRATEGIC REVIEW TERMS OF REFERENCE

A3.1 Terms of reference of the review panel

- Examine the key science challenges that require long-term access to neutron facilities based on inputs from the Italian Research Councils, the Italian science community and via relevant advisory panels and user groups, industrial stakeholders, and relevant facility directors.
- Identify the requirements to address the key science challenges
- Identify means for meeting the Italian's neutron facility access requirements
- Recommend a ten-year strategy for Italian access to neutron facilities, including underpinning technology, skills and community development; and a 15-20- year vision for Italian science requirements for neutrons and the facilities needed
- Estimate potential capital and operating costs to implement the strategy, and potential technology and instrumentation R&D costs. This should include an optimum strategy and options under financial constraint

APPENDIX 4: ANALYSIS OF THE SURVEY OF ITALIAN USERS OF NEUTRON FACILITIES

A4.1 Survey of the Italian users of neutron facilities

Question 1.

Email address

Your name

Your surname

Your post / job title .... Figure 15

Your research group / centre .... Table 3

Your school / department / industry / association .... Table 4

Your organisation........ Figure 16

Question 2.

Where are you based .... Figure 17

Question 3.

How do you describe yourself? .... Figure 18

Question 4.

Your research field .... Figure 19

Question 5.

Which of the following neutron facilities have you used since 2010 or plan to use in next 10 years .... Figure 20

Do you plan to use ESS in the next 10 years? .... Figure 21

Are you / Will you be an user of (ILL/ISIS/Other) .... Figure 22

Question 6.

In which year did you first make use of the ILL facility?........ Figure 23

In which year did you most recently use the ILL facility? .... Figure 23

How many times during this period have you used the ILL facility .... Figure 24

Assuming ILL continues to operate for the next 10 years, your planned use of ILL will .... Figure 25

Question 7.

In which year did you first make use of the ISIS facility?........ Figure 26

Question 8.

Question 9.

Question 10.

Question 11.

Question 12.

Question 13.

Question 14.

Question 15.

Question 16.

Looking forward over the next 10 years, do you feel that neutron instruments at ILL and ISIS will meet your needs? .... Figure 39

If you have not answered "completely" to the question above, please specify which improvements over existing sources you will require to meet your scientific objectives .... Figure 40

Question 17.

Looking forward over the next 10 years, which of the following capabilities do you expect to be better or worse at the ESS with respect to the ILL and ISIS? .... Figure 41

Question 18.

Which beamlines or instruments do you expect to use at the ILL in the next 10 years? .... Figure 37

Which beamlines or instruments do you expect to use at ISIS in the next 10 years? .... Figure 38

Which beamlines or instruments do you expect to use at the ESS in the next 10 years? .... Figure 42

Question 19.

To what extent has your use of neutron science contributed to the following scientific advances? .... Figure 43

Question 20.

To what extent has your use of neutron science contributed to the following scientific achievements? .... Figure 44

Question 21.

To what extent has your use of neutron science impacted positively on the development of your research experience in the following ways? .... Figure 45

Question 22.

How important has your use of neutron science been for the development of the following knowledge transfer outputs (where applicable)? .... Figure 46

A4.2 Analytical figures and tables

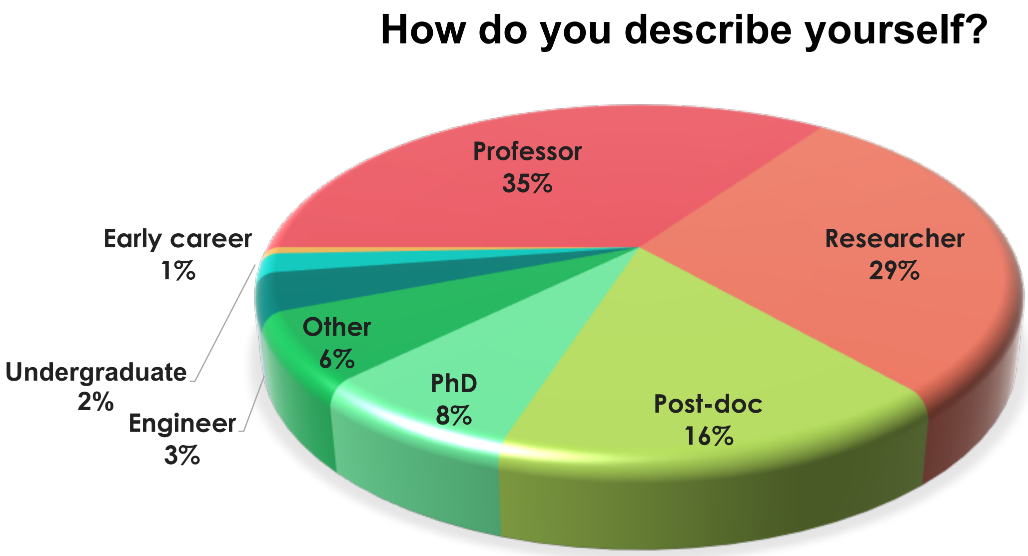


Figure 15: Career stages of the respondents to the survey, expressed as a percentage of the total number of responses.

Table 3: Your research group / centre

Applied Physics	Materials Chemistry
Bari	Messina University
Biophysics	Micro and Nano Systems
BioSoftMatter Lab	Microelectronics Group
Center for Research Computing	University of Modena
Centro NAST	Mineralogy
CERN	Mineralogy and Crystallography
Chief Technical Office	MLZ User Office
Chimica Fisica delle Macromolecole	Molecular Biophysics
CHOSE (chose.uniroma2.it)	Molecular Magnetism group
CIRCe Centre	Molecular Spectroscopy Group
Complex Systems	Musa Group
Crystallography Group	Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"
CSES-Limadou JEM-EUSO	n_TOF
CSGI	Nanolab @ Dept. of Energy, Milan Polytechnic
Department of Earth, Environmental and Physical sciences	Nanoporous Materials
design of high reliability digital systems for space and automotive applicat.	Nanosoft
Dipartimenti di Chimica	Neutrons & Gamma/ JET
Dipartimenti di Fisica	Neutron and gamma-ray group
Dipartimento di Scienza dei Materiali	NIS Center
Disordered Matter	NMR and Medical physics laboratory
e_Libans/ ANET/ CMS	No group or centre
Elettra Sincrotrone	Nuclear instrumentation
ENEA Frascati	OG-Grenoble
ENEA, Bologna	Paduano group
ESRF	CNR
Università di Roma Tor Vergata	Parma
European Spallation Source	PARMA, PArma Research on MAgnetism
Excitations Group	Personal
Exp. Phys. INFN	Pharmaceutical technology
University of Ferrara, Italy	PhD in Materials for health, Energy, Environment
Fisica sperimentale delle interazioni fondamentali	PhysiX
FRascati FNG-ENEA	Plasma
Guglielmo Lanzani's group	Plasma and Neutron Group
High Pressure Laboratory	Plasma and neutron physics
HSERLab - ALTEA	Plasma physics and spectroscopy
IFP neutron and gamma	Plasma research
INFN	Politecnico di Milano
INFN, Department of Ferrara, Italy	Polymer physics laboratory
Inorganic Materials	powder diffraction/PDF on nanomaterials
Institut Laue-Langevin - Seydel	Quantum Materials Group
Institute for Complex Systems, Rome	R&D
Istituto di Fisica del Plasma	Radioactivity Lab Milano Bicocca
IPCF-CNR	Università degli Studi di Milano
ISC-CNR	Sezione di Genova
ISIS facility, STFC, UK	CNR
ISIS- crystallography	Solid State Group
ISIS MSG	Spectroscopy
ISMAC CNR Genova	SPIN-SuPerconducting and other INnovative materials&devices institute
ISS Molecular Spectroscopy Science Group	Structural Biophysics
Istituto di Fisica del Plasma "P. Caldirola"	SupraBioNanoLab (https://www.suprabionano.eu/)
Laboratori Nazionali di Frascati	Synchrotron Radiation group
Laboratorio Biofisica Molecolare	Synthesis and characterisation of materials
LABORATORIO SPES	T.E.E.S. srl
Laboratory Experimental Neuropathology	Thermodynamics
Laboratory of computational science and modeling	Università di Milano Bicocca
Laboratory of Physical Chemistry	Università degli Studi di Milano
Large Scale Structures	Università di Lecce
Liquids Group	Università di Torino
ILL	University of Florence
Lycril lab , of the CNR nanotech institute, and Univ. of Calabria	University of Messina
University of Ancona	University of Bologna and INFN
MAGFUN	University of Palermo
Magnetic materials group	WiZard group
Magnetic resonance group	XtalChemGroup @ Unimi-Dipchim
Material synthesis by physical techniques	University of Trieste

Table 4: Your school / department / industry / association

Bari	DSCTM
Catalysis	DSFTM
Center for Nanoscience and Technology	Electronic engineering
Centro NAST	Electronics
Chemistry	Elettra
Chemistry Department	ENEA FSN-FUSPHY-SAD
CHIMICA FISICA	ESRF
Crystallography group	Fisica
Dep. of Physics	Physics and Chemistry
Department of Chemical Science	FSN
Department of Chemical Sciences and Technologies	FUSTEC-FSN-TEN
Department of Chemistry	IFP
Department of Chemistry "Ugo Schiff"	IMEM
Department of Chemistry, Materials and Chemical engineering	Independent University
Department of Life and Environmental Sciences	INFN
Department of Materials Science	INFN, sezione di Trieste
Department of Mathematical, Physical and Computer Sciences	Information Engineering
department of medical biotechnologies and translational medicine	Institute for Complex Systems (ISC)
Department of Physical Sciences and Technologies of Matter	Institute of Materials
Department of Physics	Institute di Fisica del Plasma
Department of Physics and Astronomy	Instrument Design Division Electrical
Department of Physics, Sapienza University, Rome	IOM
Department Systems Medicine	ISIS
Dept Earth sciences	ISM
Dept. Biotechnology and Biosciences	ISMAC CNR Genova
Dept. Chemistry Ugo Schiff	Istituto di Fisica del Plasma, CNR
Dept. Electronic Engineering	Laboratori Nazionali del Sud
Dept. Fisica e Geologia	MIFT Department
DEPT. OF CHEMICAL SCIENCE AND TECHNOLOGIES	MINAS Lab
Dept. of Energy	MLZ in Garching, Germany
Dept. of Energy, Politecnico di Milano	Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"
Dept. of Molecular Sciences and Nanosystems	Niels Bohr Institute
Dept. of Physics and Chemistry	No school, department, industry or association
Dip. di Ingegneria Elettronica	Phys. Dept. Univ. Torino/INFN Sec.Torino
Dip.to MIFT Scienze Matematiche Informatiche, Scienze Fisiche Scienze della Terra	Physics
Dipartimento di Biotecnologie Mediche e Medicina Traslazionale	Physics Department
Dipartimento di Chimica	Physics Department "G. Occhialini"
Dipartimento di Fisica	Plasma Physics Institute (IFP-CNR) Milan Italy
Dipartimento di Fisica e Scienze della Terra	Roma Tor Vergata
Dipartimento di Geoscienze	Rutherford Appleton Laboratory
Dipartimento di Scienza dei Materiali	School of Pharmacy
Dipartimento di Scienze	Sezione di Genova
Dipartimento di Scienze Chimiche	Spectroscopy
Dipartimento di scienze della vita e dell'ambiente	STEBICEF Department
Dipartimento di scienze fisiche e tecnologie della materia	STFC
Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra	T.E.E.S. srl
Dipartimento di Scienze Matematiche, Fisiche e Informatiche	Thales Alenia Space Italia
Dipartimento Ingegneria, ICT e Tecnologie per Energia e Trasporti	Università di Roma Tor Vergata
Dipartimento Scienze della Terra	Università della Calabria
Dipartimento Scienze fisiche e tecnologie della materia	Université Grenoble Alpes
University of Pisa	University of Siena

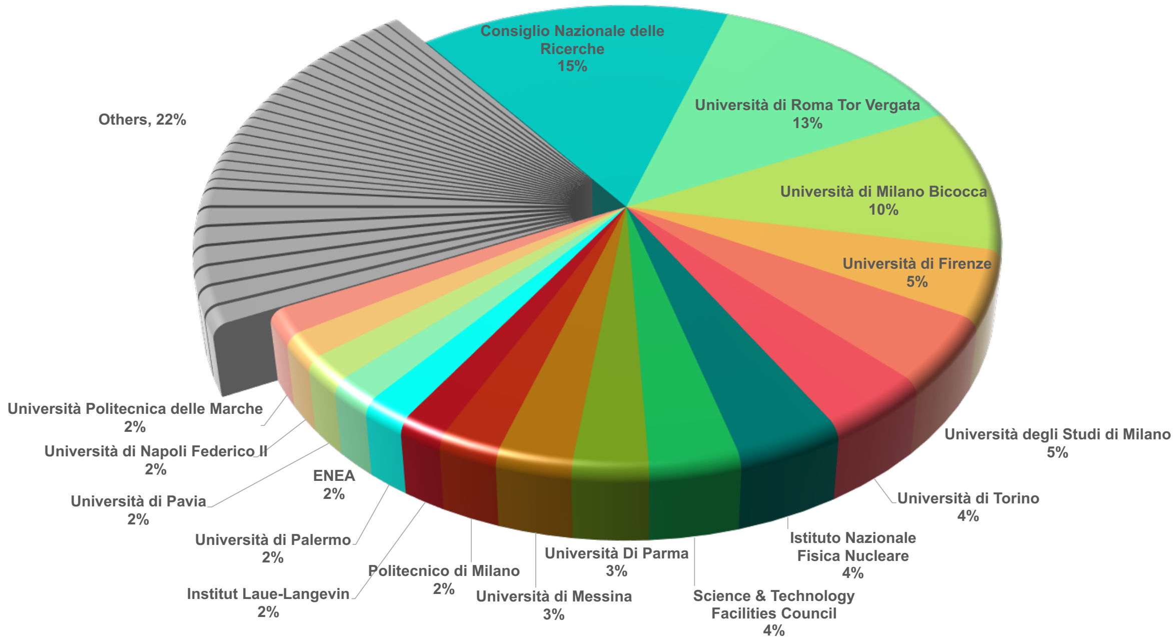


Figure 16: Affiliations of the respondents to the survey.

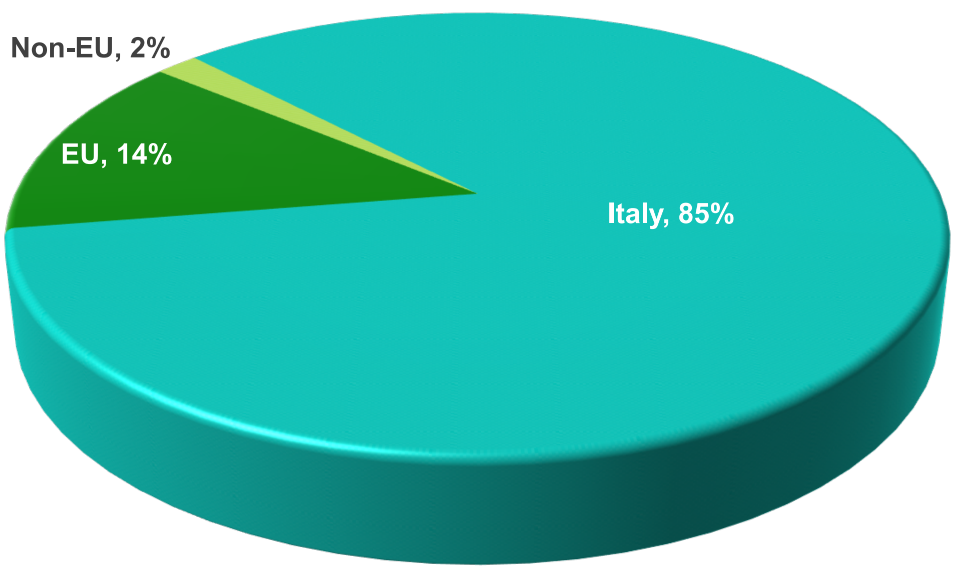


Figure 17. National base of the respondents to the survey, expressed as a percentage of the total responses

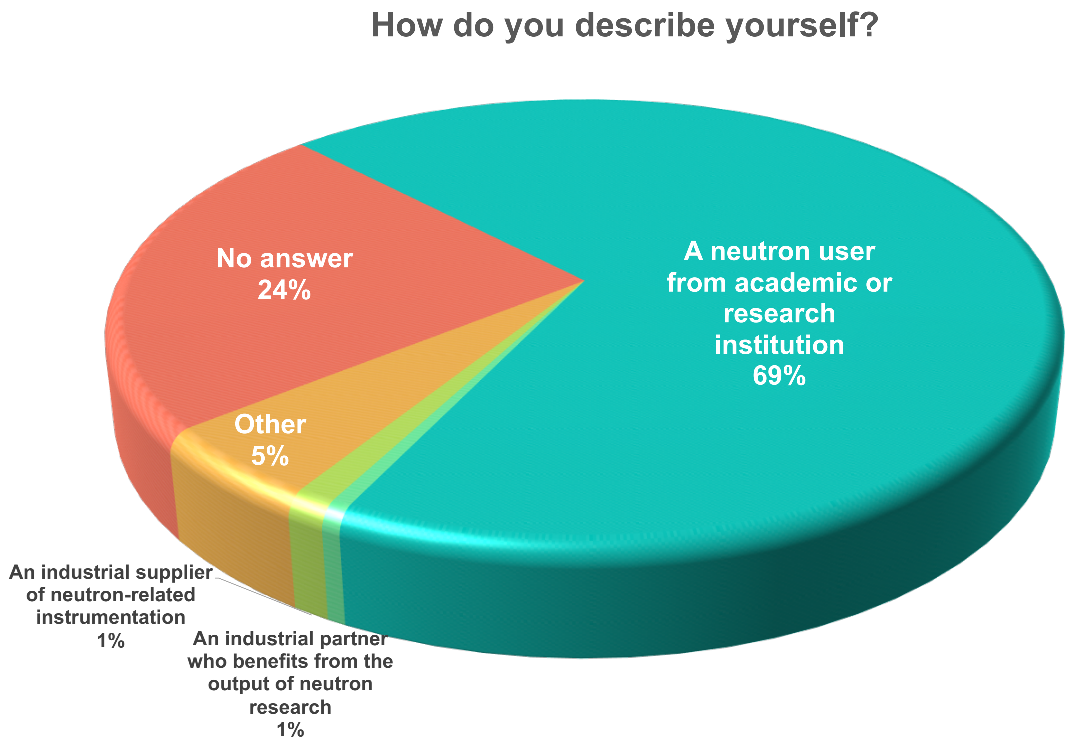


Figure 18. Engagement with neutrons of the respondents, expressed as a percentage of the total responses.

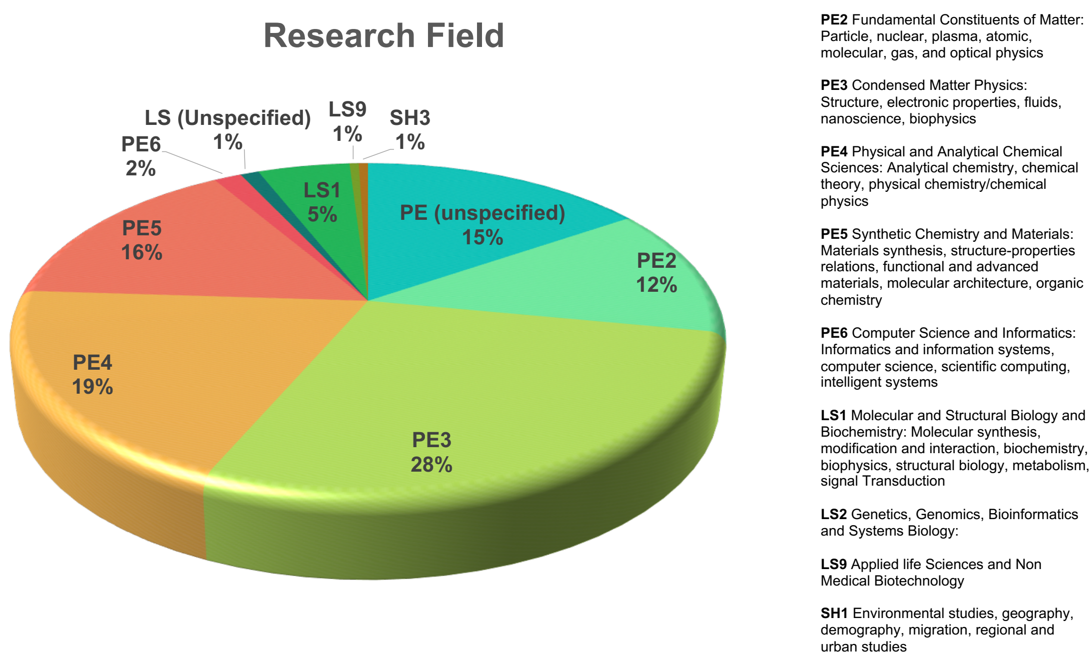


Figure 19. Research fields of the respondents, expressed as a percentage of the total responses.

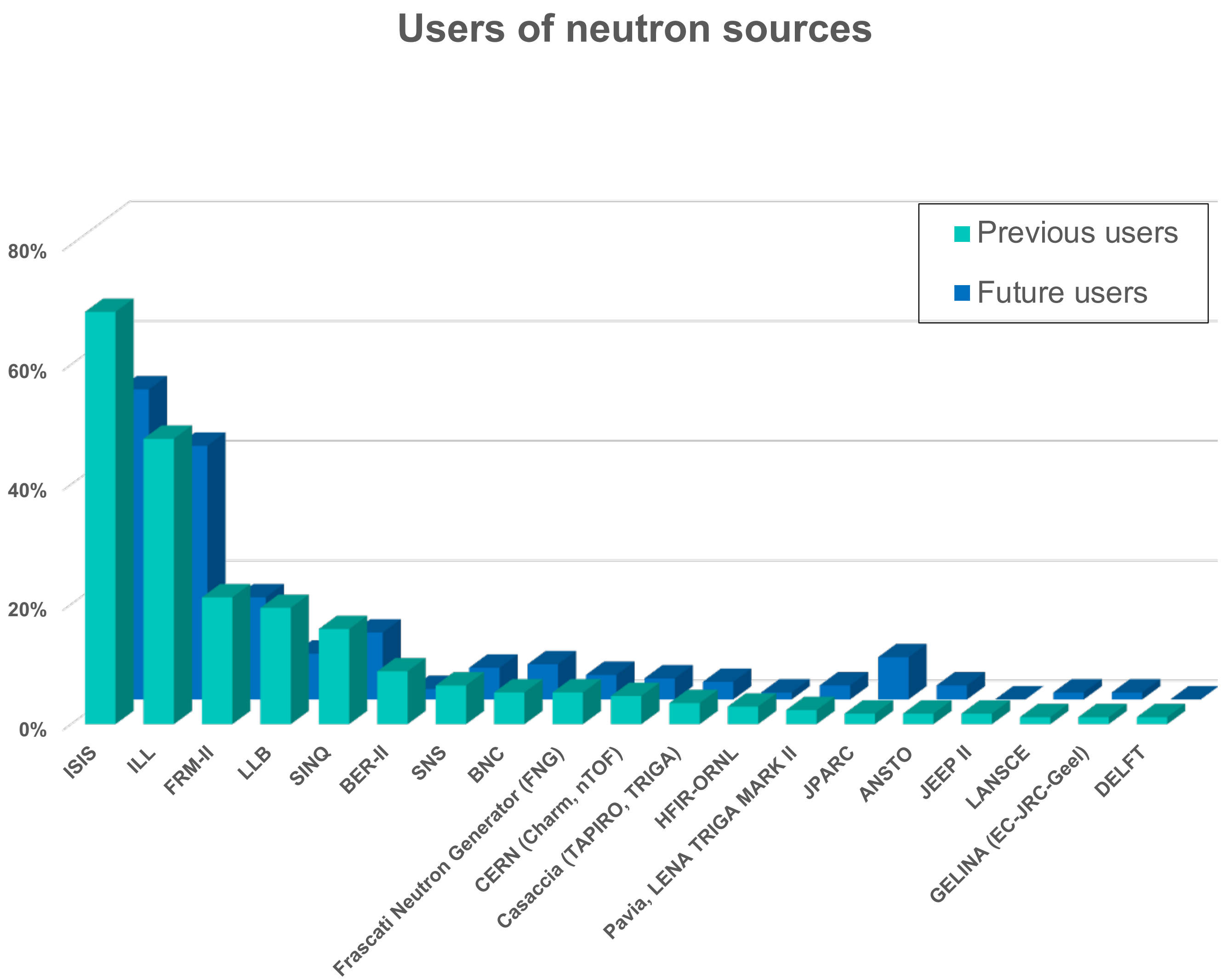


Figure 20: Fraction of respondents who have used/plan to use individual national or international neutron sources (Excluding ESS), expressed as a percentage of the total responses. Only sources with more than two previous users are included. Other sources used by the respondents are (previous users/future users): TRIUMPH (1/3), e_Libanans (1/1), JET (1/1), LNL (1/1), MUSE@J-PARC (1/1), NPL Teddington (1/1), PTB, Braunschweig (1/1), SMS@PSI (1/1), REZ(1/0), Indiana(1/0), ISSP TOKAI (1/0), Dido & Pluto reactors (1/0), DIGRA (1/0) CSNS (0/2), Vienna (0/1), Unspecified (2,1).

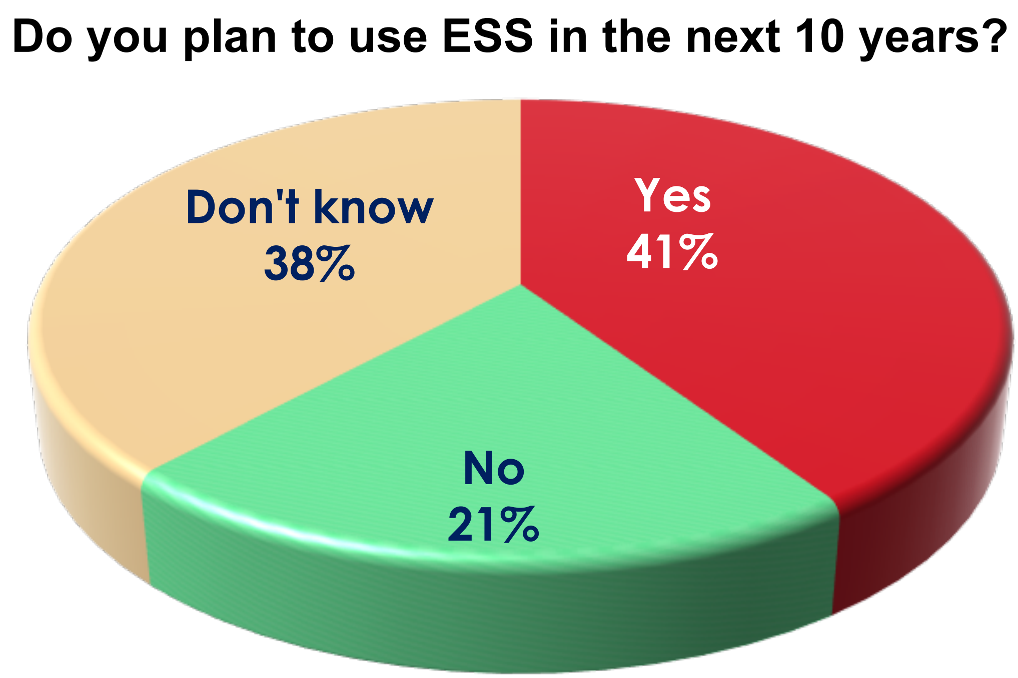


Figure 21: Fraction of the respondents who plan to use the ESS, expressed as a percentage of the total responses (compare with A.9b, which asks the same question on a broader timescale).

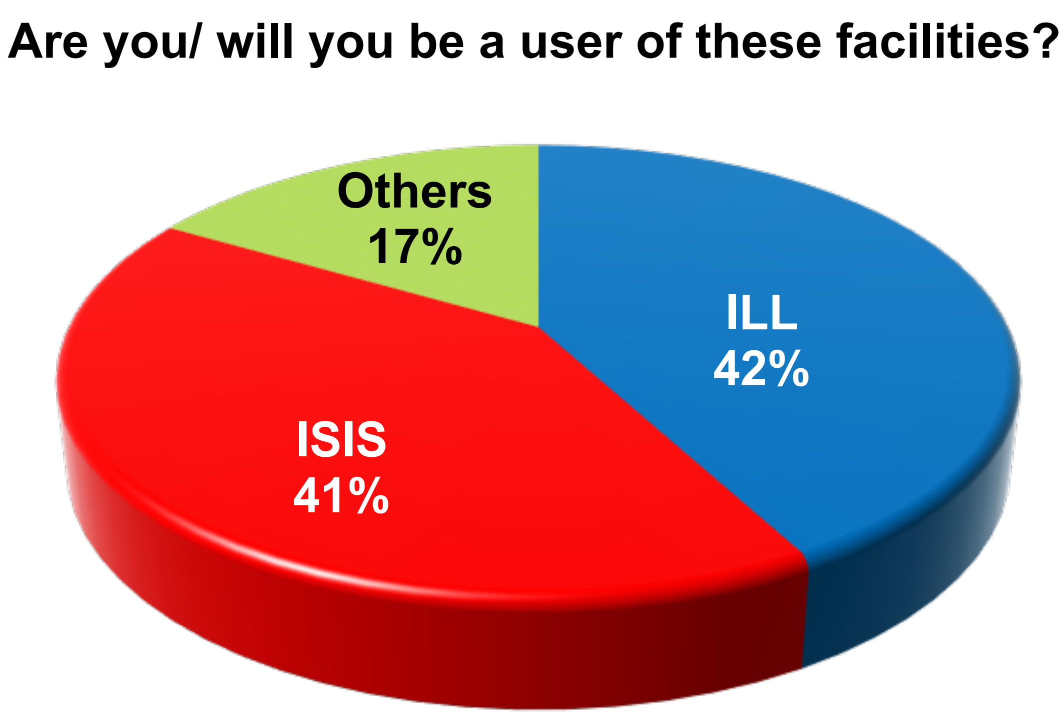


Figure 22. Fraction of the respondents who plan to use facilities other than ESS, expressed as a percentage of the total responses.

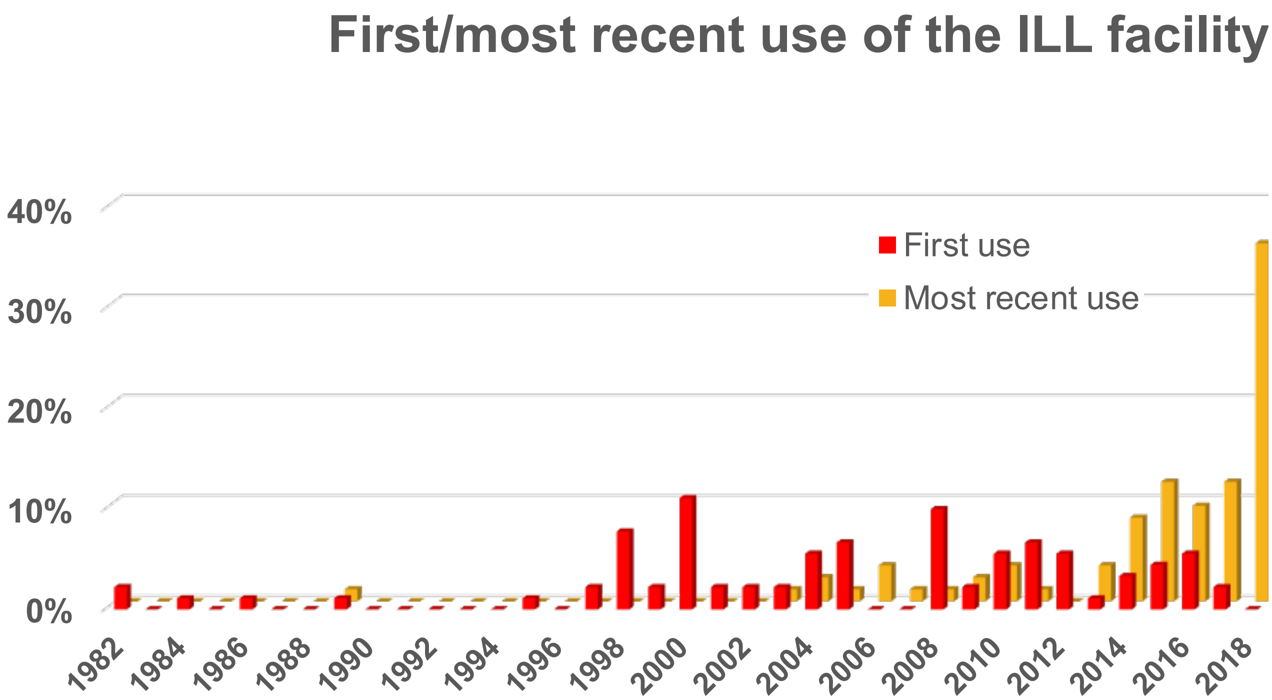


Figure 23: First/more recent usage of the ILL by year, expressed as a percentage of the total number of ILL users among the respondents.

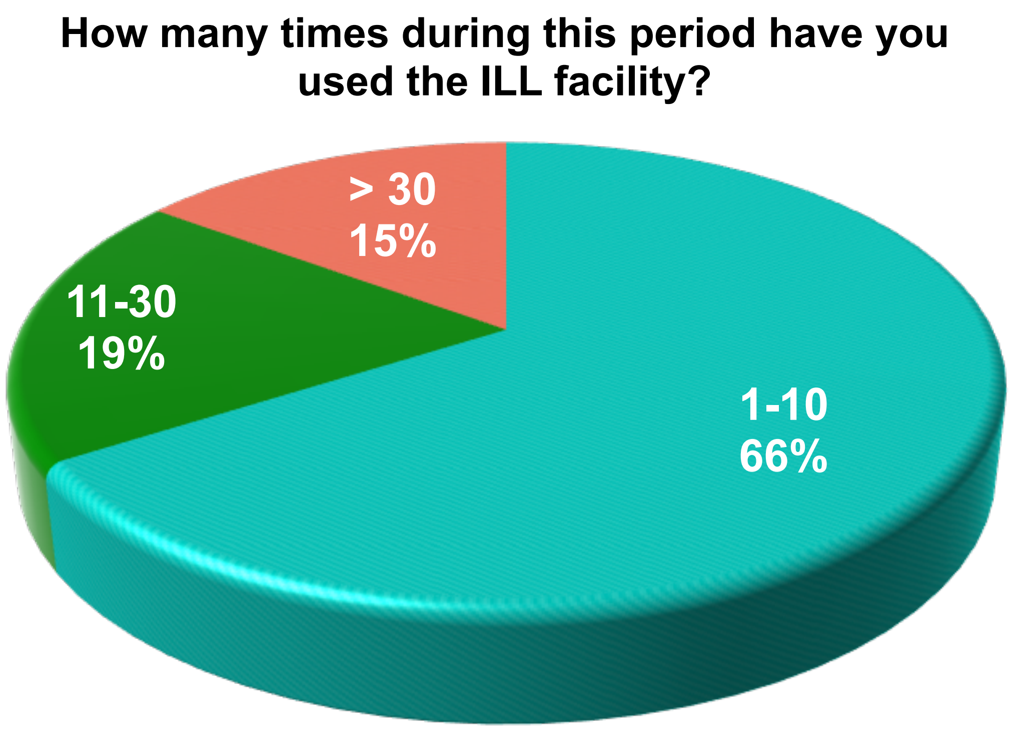


Figure 24: Frequency of use of the ILL, expressed as a percentage of ILL users among the respondents.

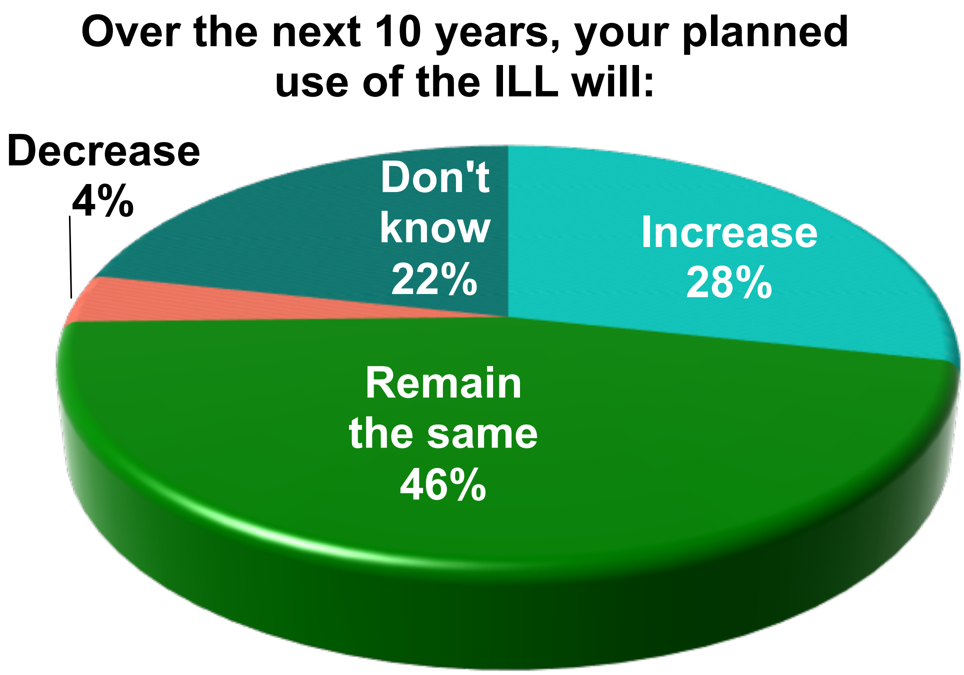


Figure 25: Predicted use of the ILL in the next 10 years, expressed as a percentage of ILL users among the respondents.

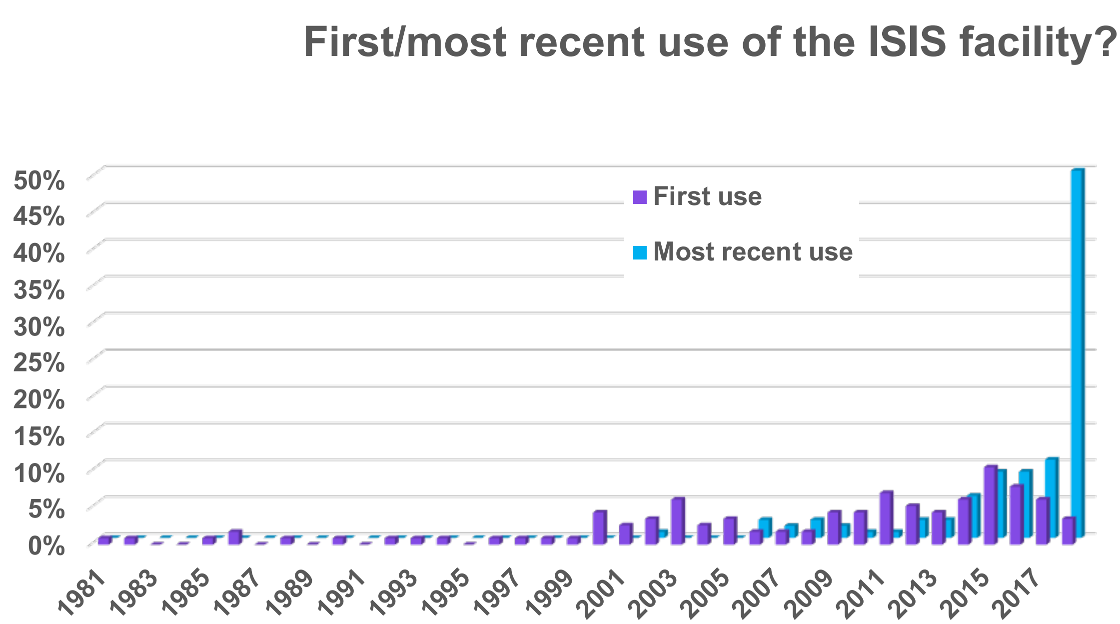


Figure 26: First/more recent usage of ISIS by year, expressed as a percentage of the total number of ISIS users among the respondents.

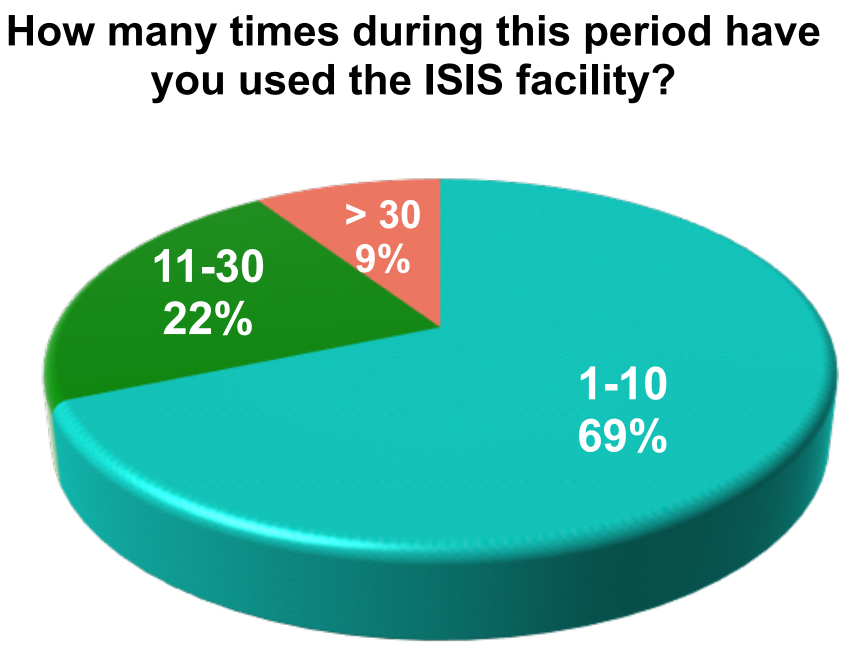


Figure 27: Frequency of use of ISIS, expressed as a percentage of ISIS users among the respondents.

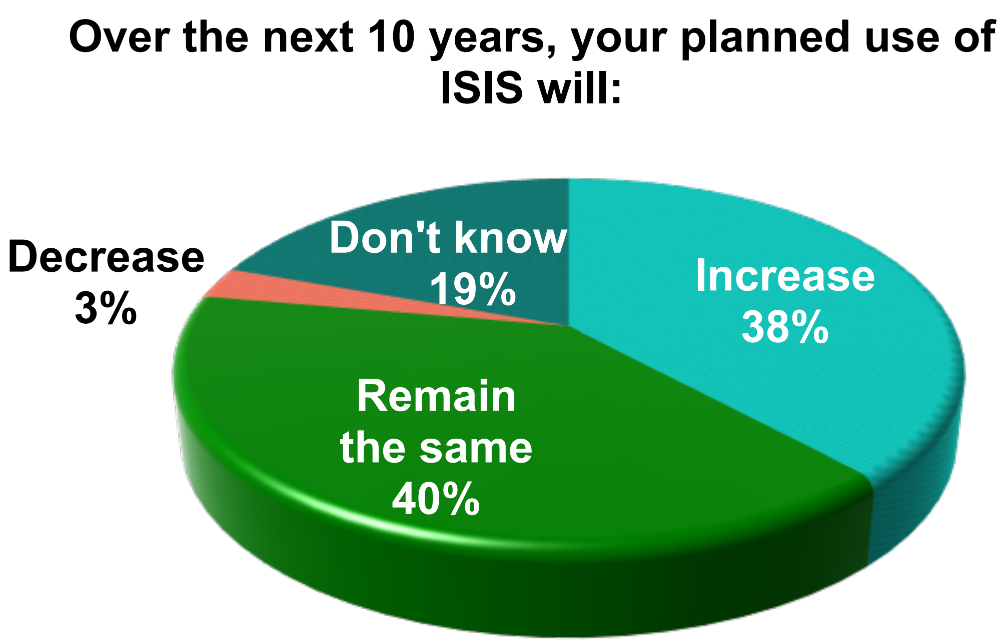


Figure 28: Predicted use of ISIS in the next 10 years, expressed as a percentage of ISIS users among the respondents.

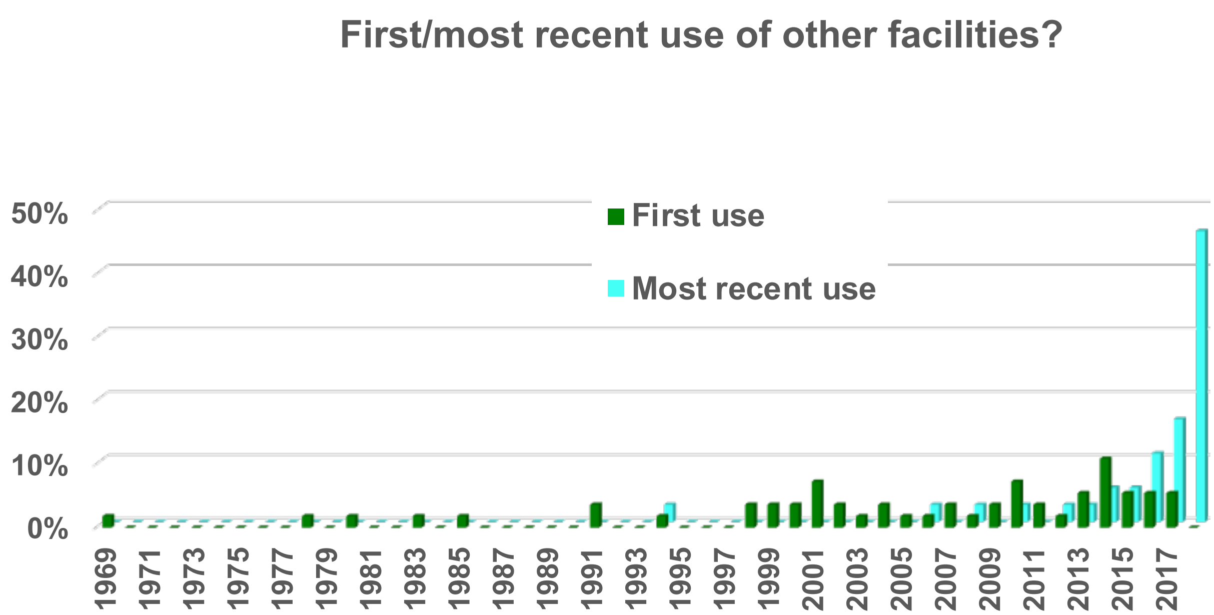


Figure 29: First/more recent usage of other neutron facilities by year, expressed as a percentage of the total number of other facilities users among the respondents.

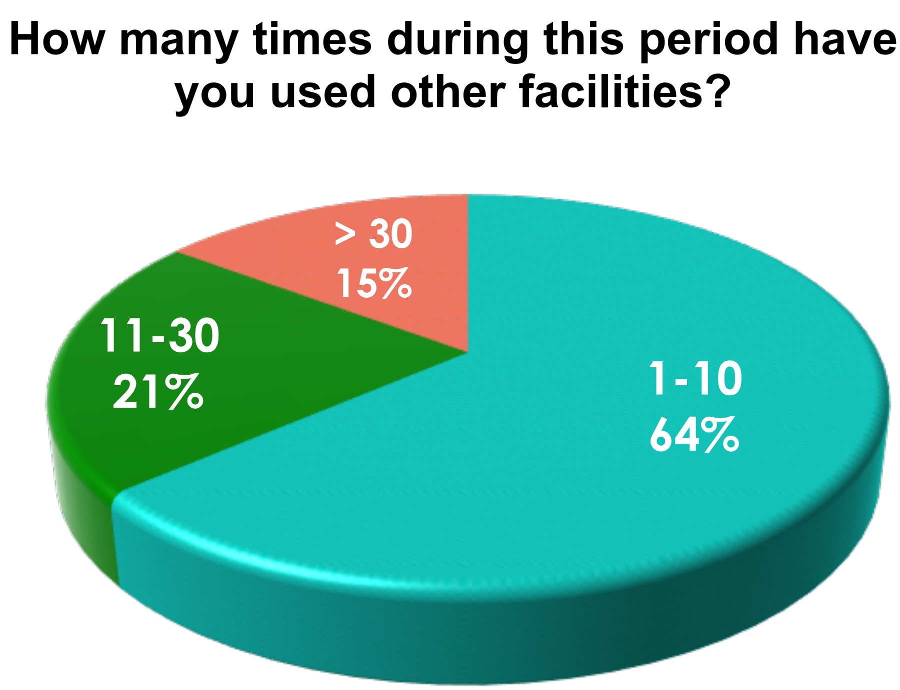


Figure 30: Frequency of use of other neutron facilities, expressed as a percentage of other facilities users among the respondents.

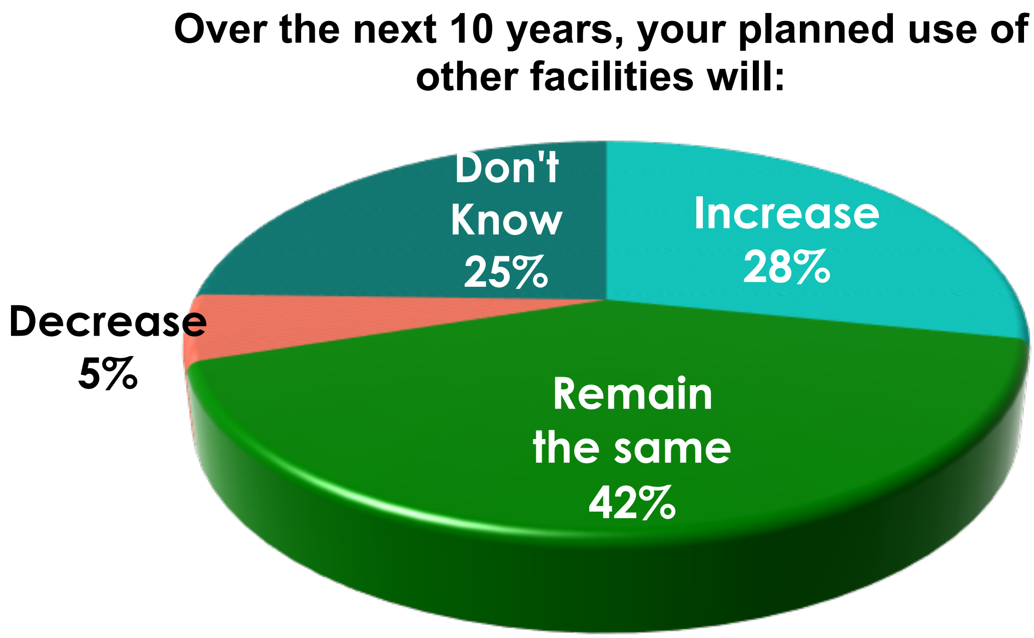


Figure 31: Predicted use of other facilities the next 10 years, expressed as a percentage of users of other facilities among the respondents.

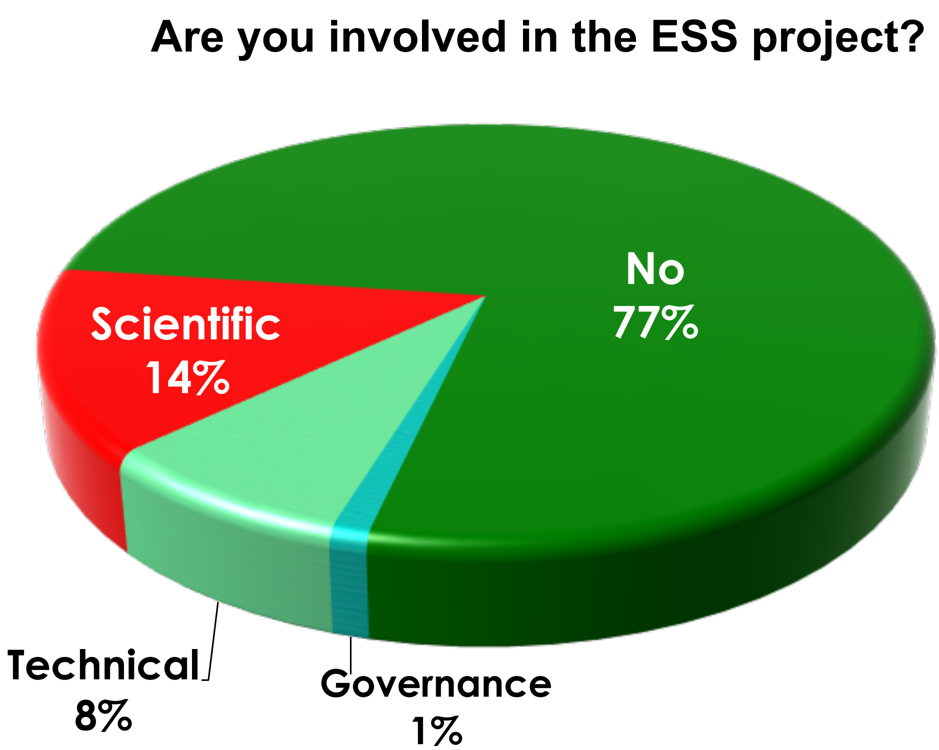


Figure 32: Involvement of the respondents in the ESS project, expressed as a percentage of respondents.

Do you plan to become a user of ESS?

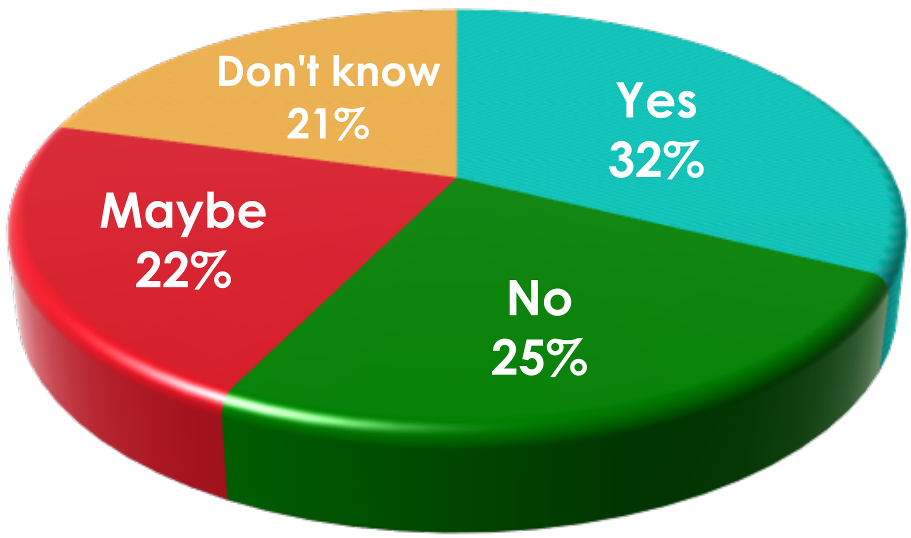


Figure 33: Percentage of respondents who plan to become users of ESS (compare with A.5b, which focusses on the next 10 years).

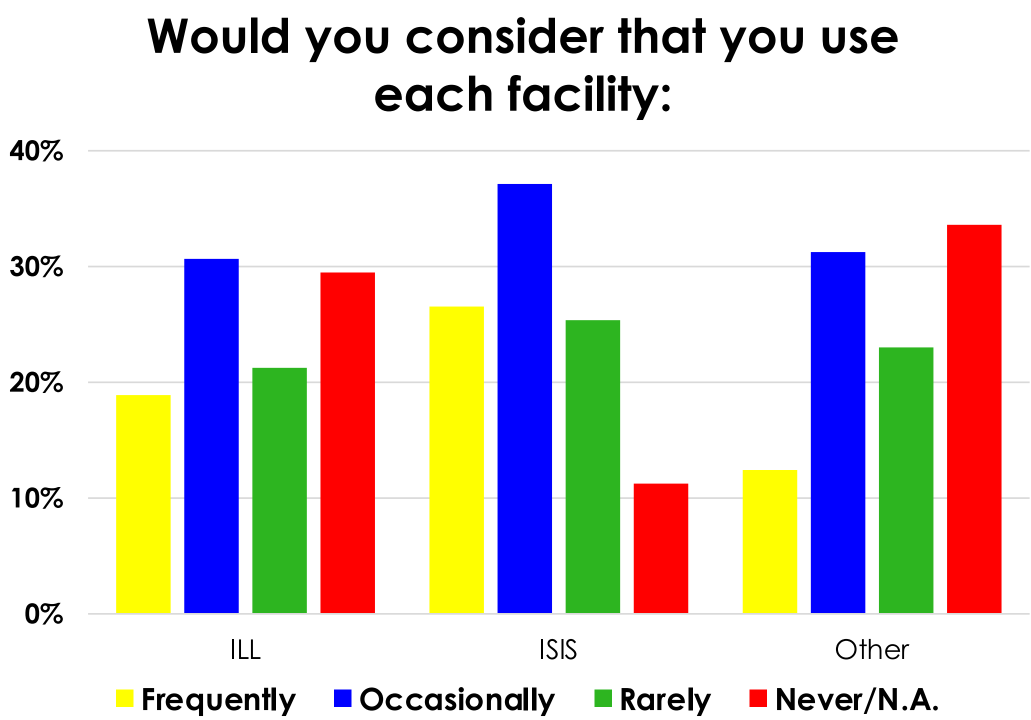


Figure 34: Frequency of use of ISIS, ILL and other facilities, expressed as a percentage of the total number of respondents to the questionnaire.

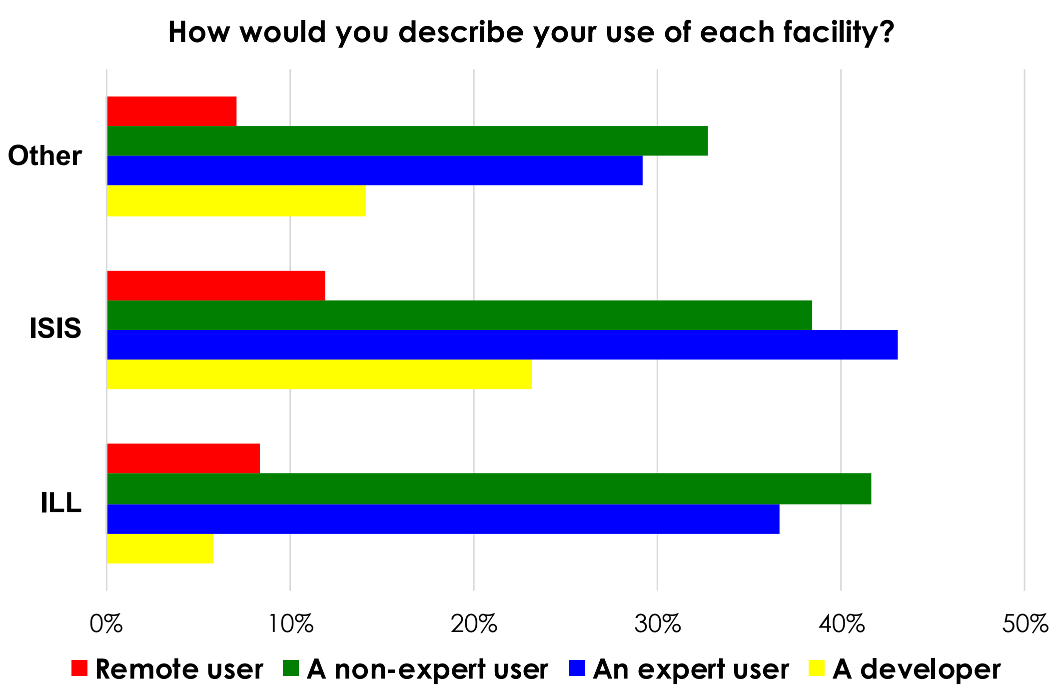


Figure 35: Type of use of ISIS, ILL and other facilities, expressed as a percentage of the total number of users of that facility.

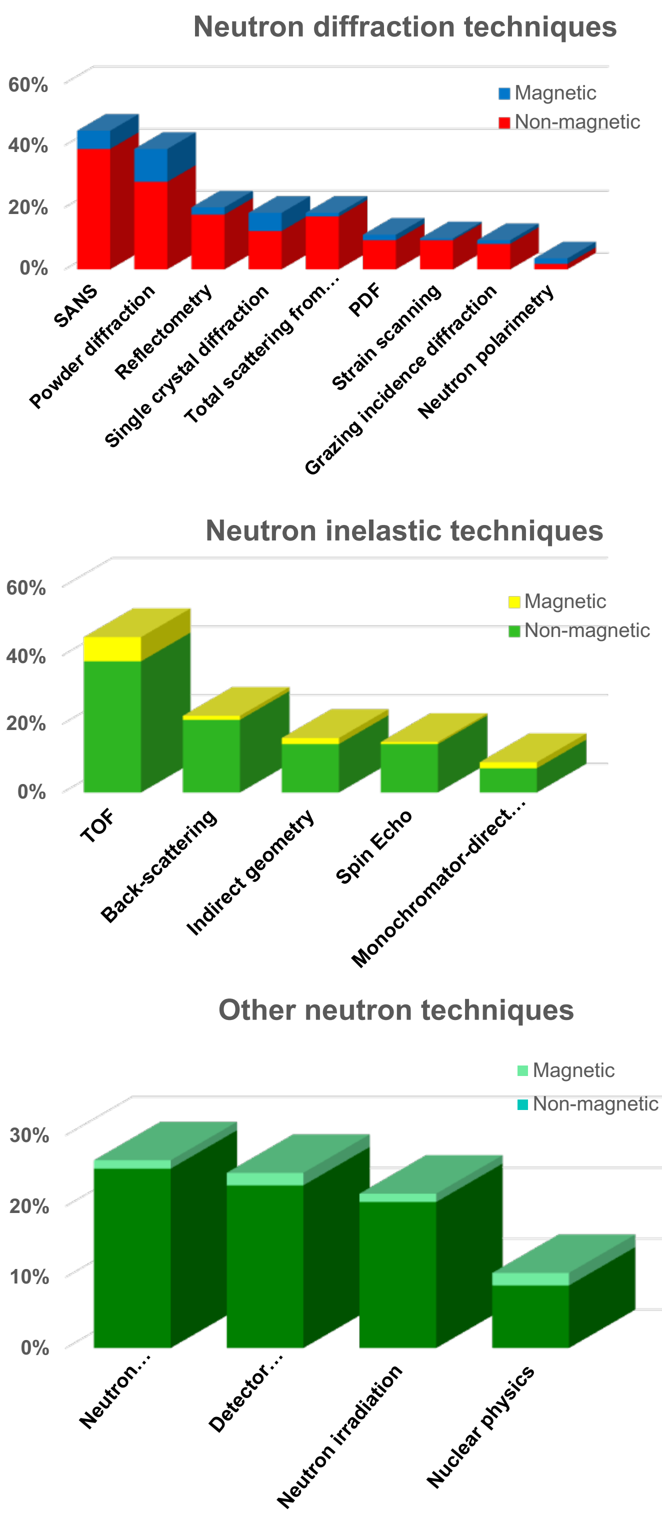


Figure 36: Usage of different neutron techniques, expressed as a percentage of the total number of respondents to the questionnaire.

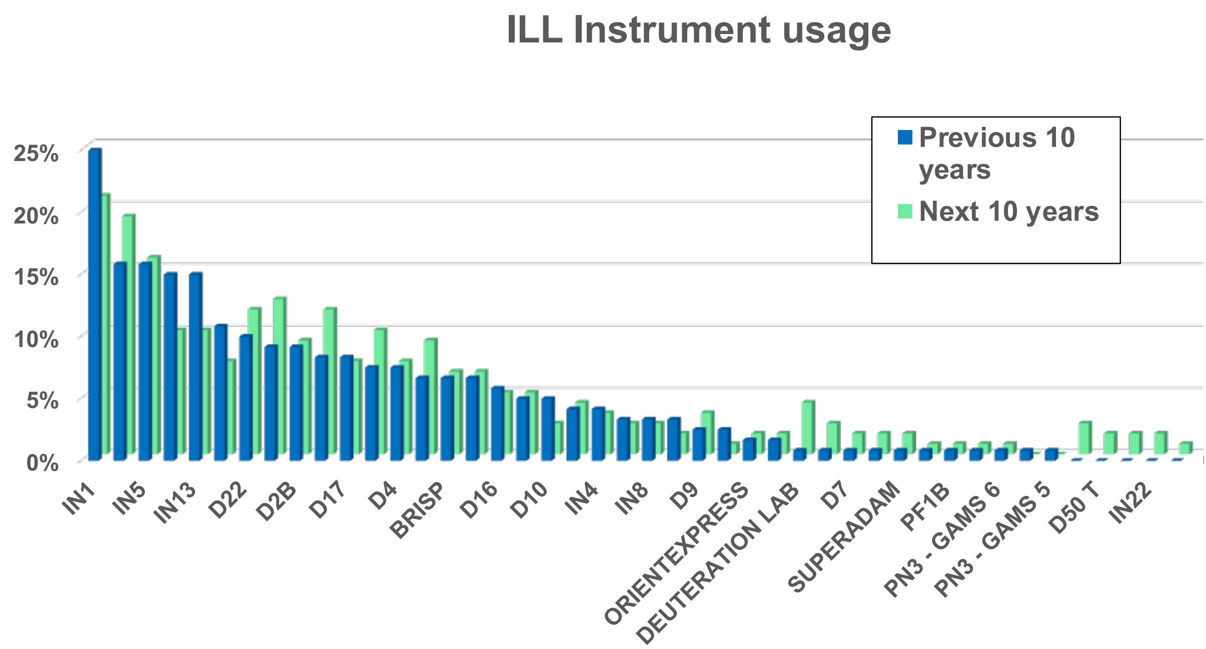


Figure 37: Past and future ILL instrument usage, expressed as a percentage of the total users of ILL.

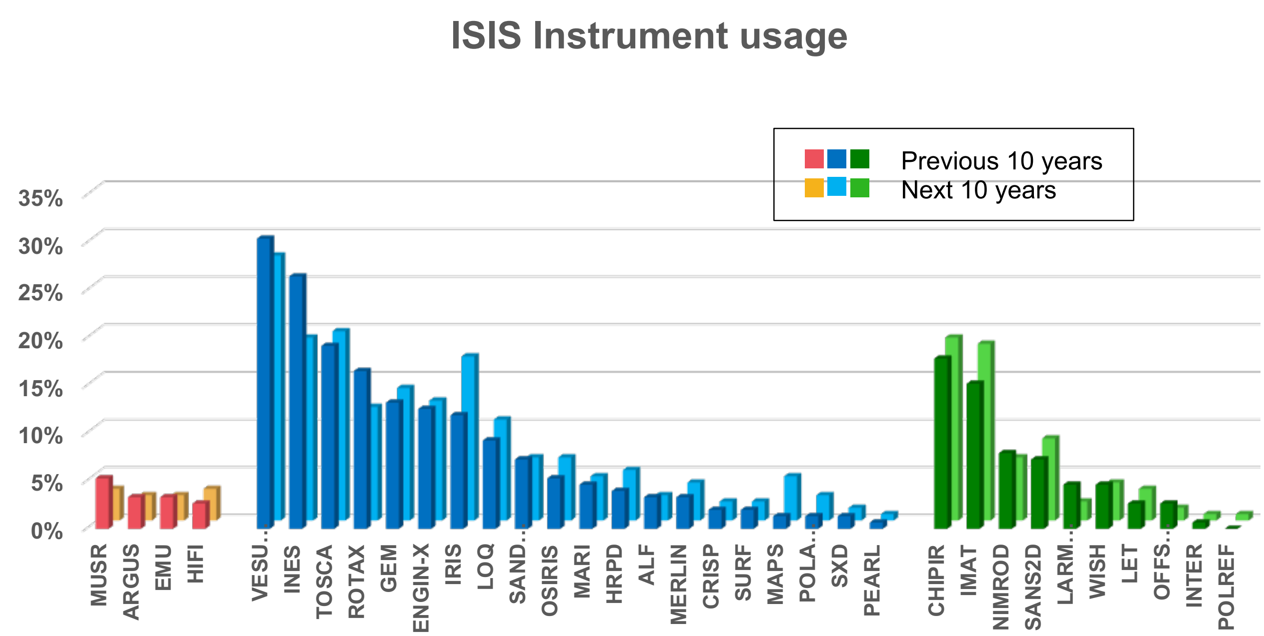
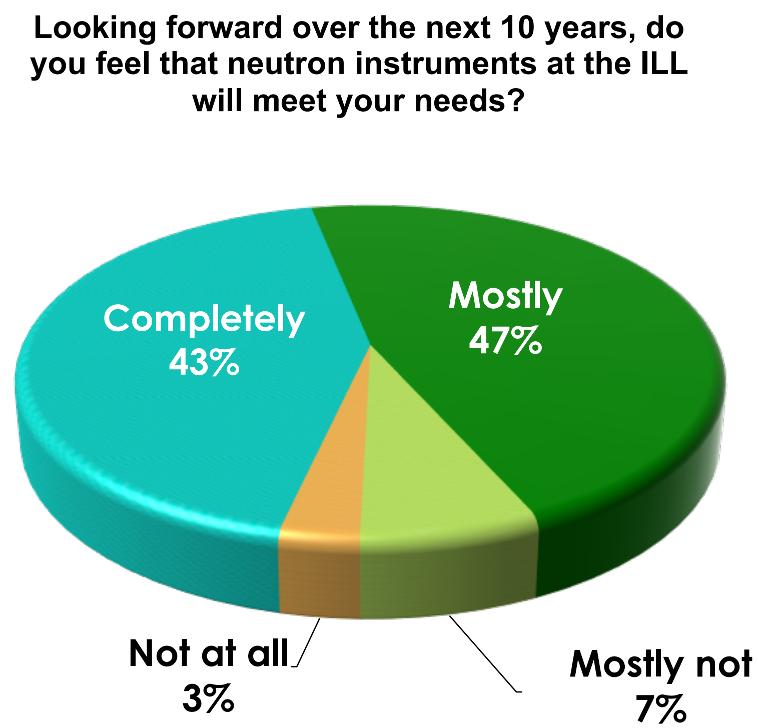


Figure 38: Past and future ISIS instrument usage, expressed as a percentage of the total users of ISIS.

Table 5: Use of beamlines or instruments at other facilities since 2010.

FRM-II TOF-TOF
200 m flight path (EAR1) and 20 m (EAR2) at n_TOF; scintillator detectors, gas detectors (fission chambers and parallel plate avalanche counters), solid state detectors,
CERN, n_TOF facility
D4 at BER II and BESSY at LLB
ENEA Frascati Neutron Generator - Monochromatic neutrons from DD and DT fusion TRIGA reactor LENA-University of Pavia - thermal neutrons in graphite moderator TAPIRO reactor, ENEA Casaccia - in-core fast neutrons Monochromatic neutron beams, PTB - neutrons beams of different energies from p+T and p+7Li reactions
FNG (Frascati)
MLZ: KWSII
muon beamlines at SINQ/PSI: GPS LEM DOLLY GPD HAL
n_TOF at CERN/EAR1 and EAR2, fission, capture and (n,cp) detection systems
n_TOF/EAR1, n_TOF/EAR2
n_TOF: EAR1 and EAR 2, GELINA: Capture 25, 60 mt Transmission 25 mt
NEUTRA at PSI
nToF, Charm @ CERN and FNG @ ENEA Frascati
SNS/SEQUOIA
V12 (Ber II); PAXE (LLB); TPA (LLB)



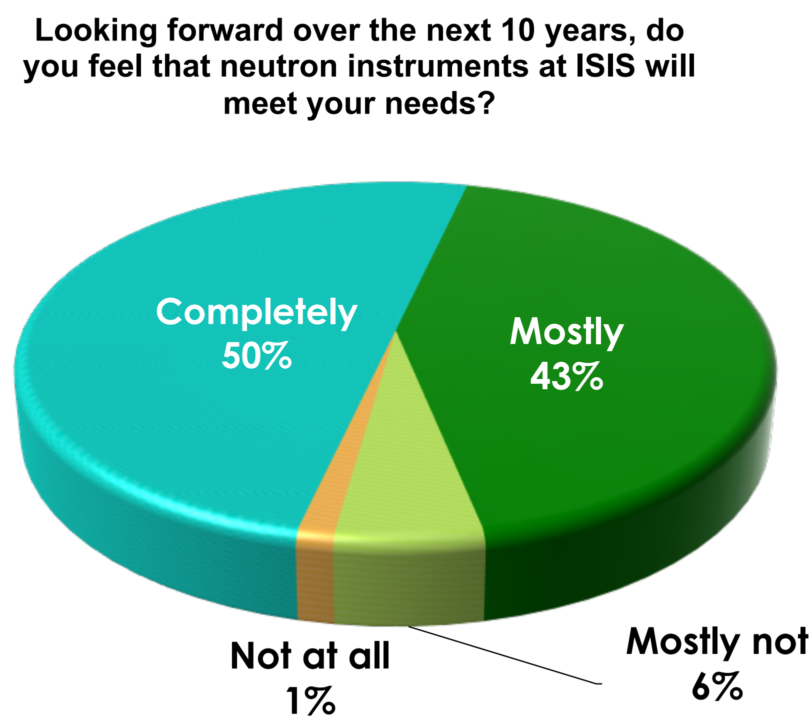


Figure 39: Match between ILL and ISIS instrumentation current instrumentation and future needs, expressed as a percentage of ILL and ISIS users.

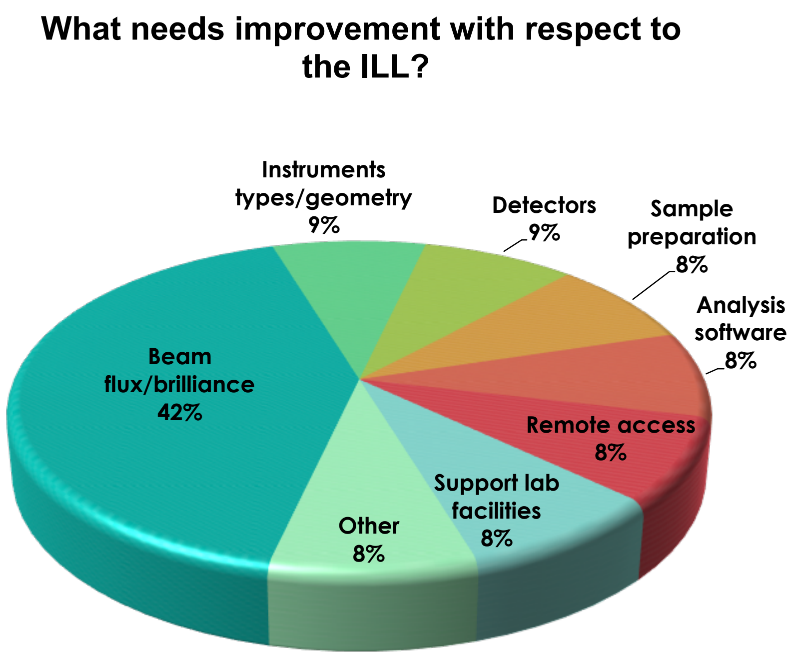


Figure 40: Improvements required with respect to the ILL and ISIS, expressed as a percentage of those who declared not to be completely satisfied with those facilities.

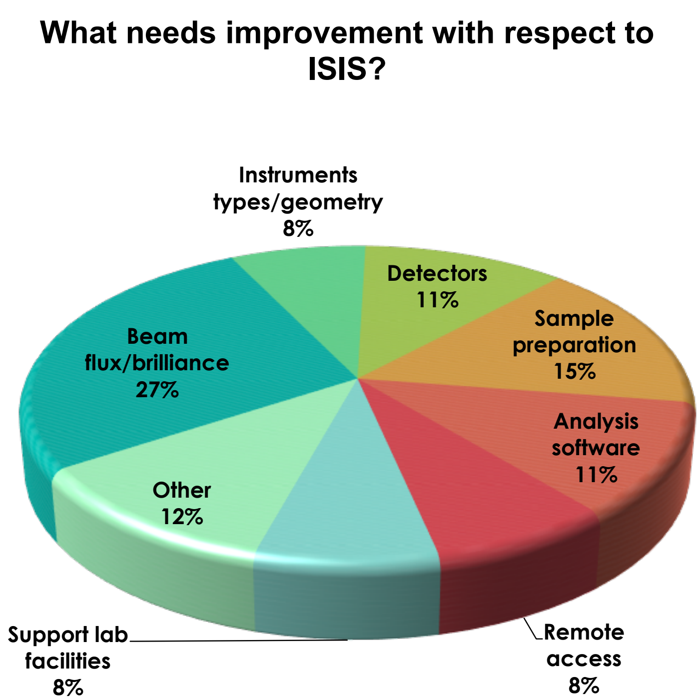


Figure 41: improved/degraded capabilities at ESS with respect to ISIS and the ILL, expressed as a percentage of the total number of respondents to the survey.

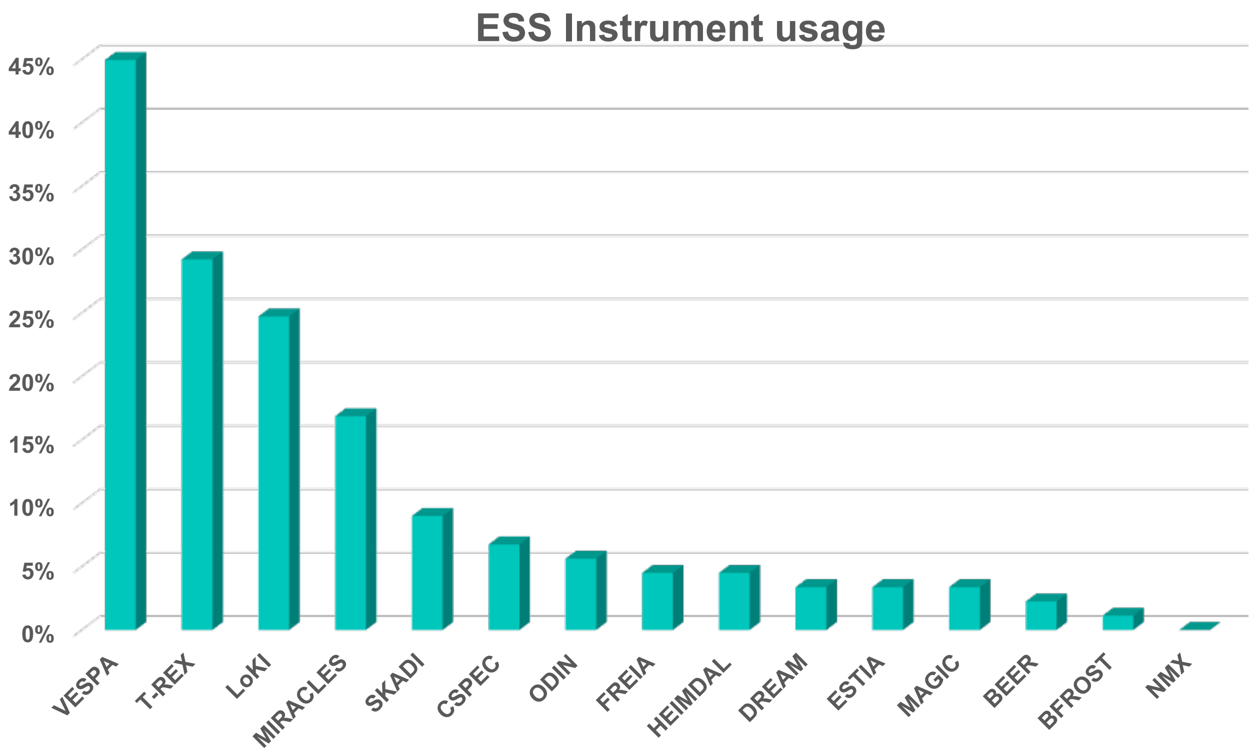


Figure 42: Future ESS instrument usage, expressed as a percentage of the perspective ESS users (Question 9, 'Yes' + 'Maybe'.)

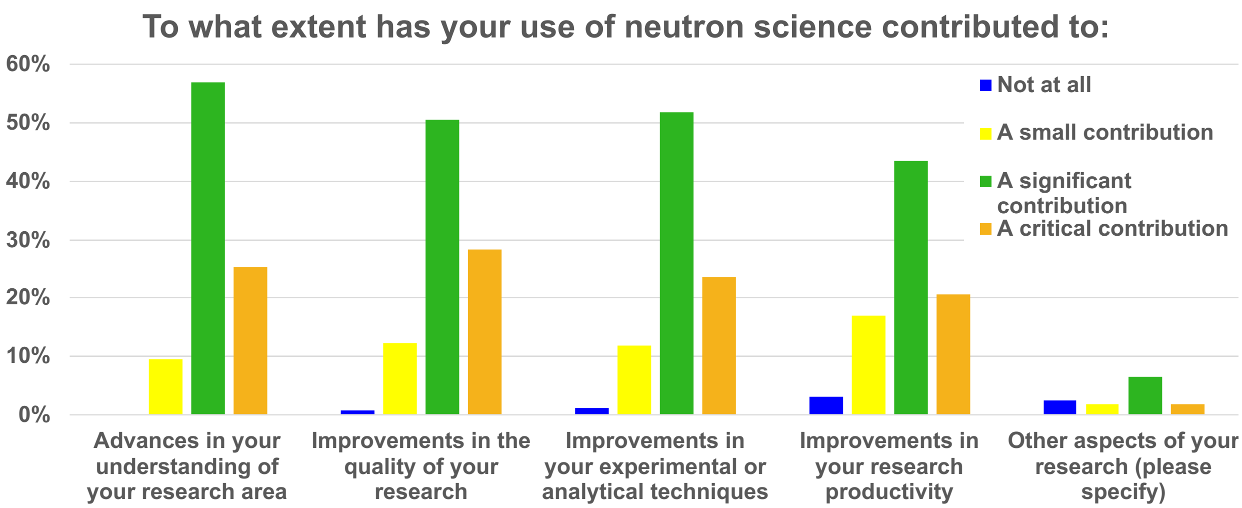


Figure 43: Contribution of neutrons to specific scientific advances, expressed as a percentage of the total number of respondents to the questionnaire.

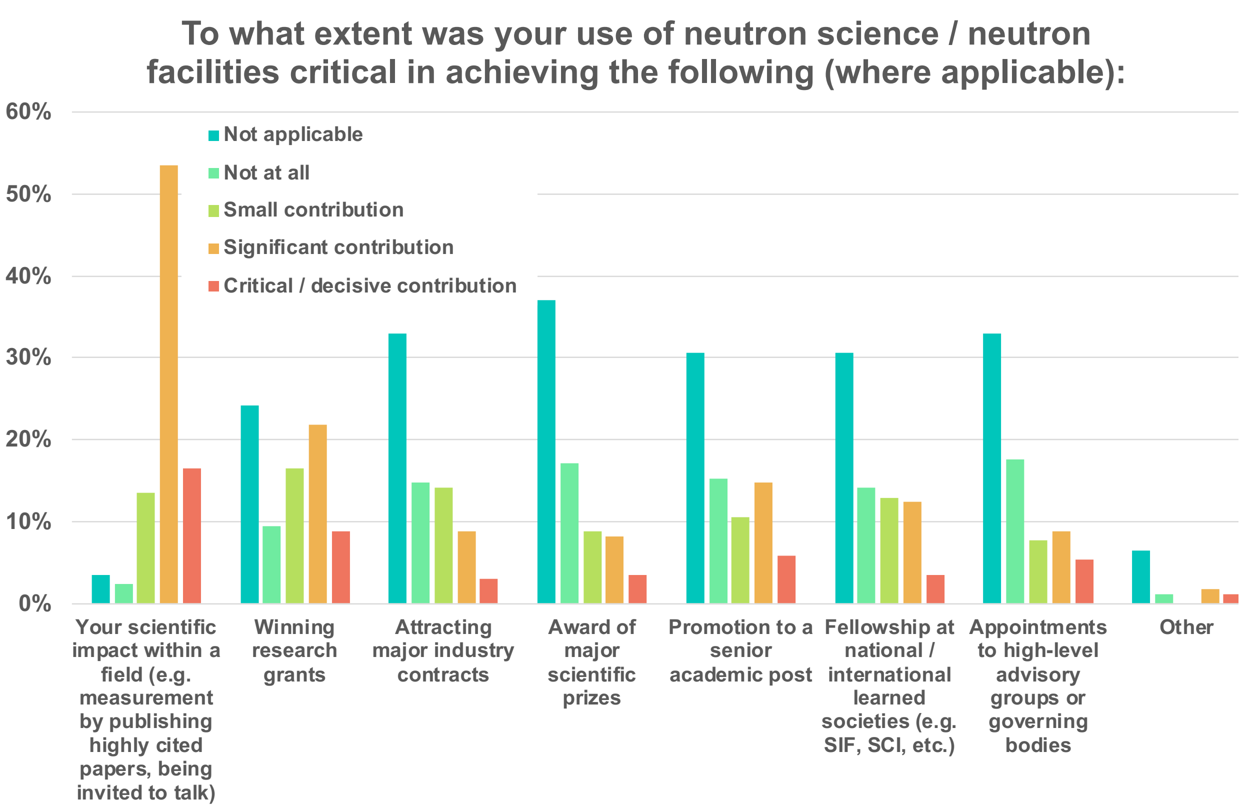


Figure 44: Contribution of neutrons to specific scientific achievements, expressed as a percentage of the total number of respondents to the questionnaire.

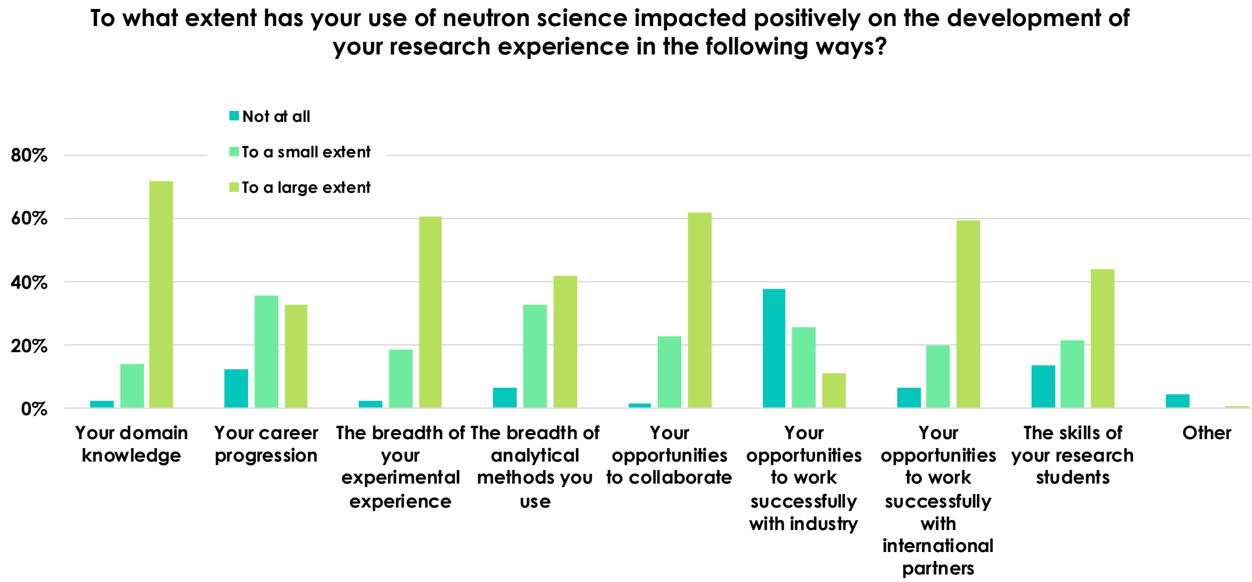


Figure 45: Contribution of neutron science on the knowledge, skills and opportunities of the respondents, expressed as a percentage of the total number of respondents to the questionnaire.

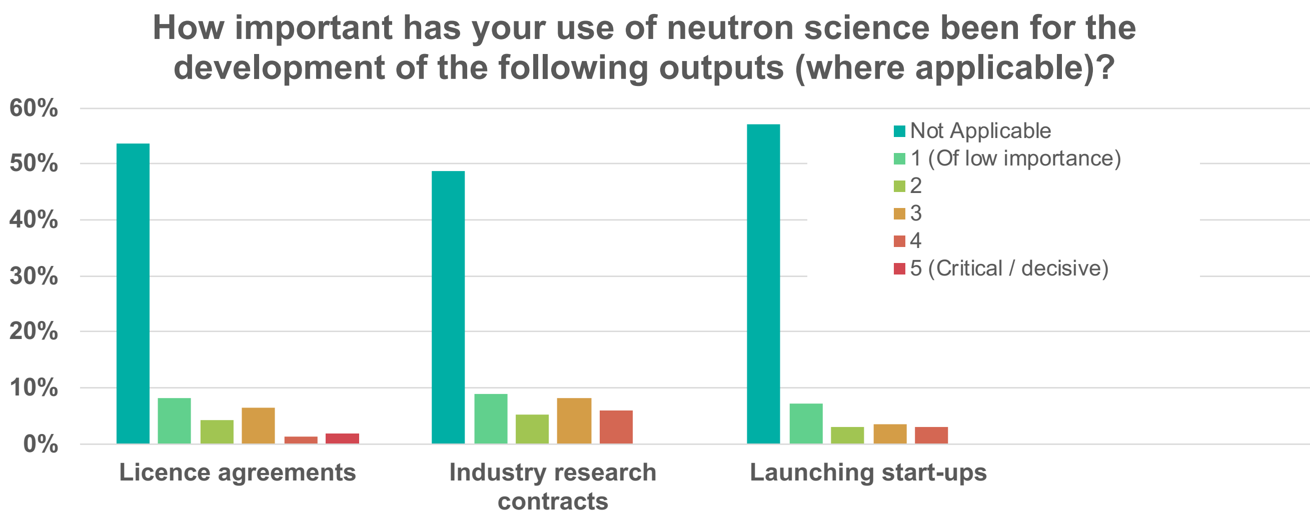


Figure 46: Contribution of neutron science to specific knowledge transfer objectives, expressed as a percentage of the total number of respondents to the questionnaire.

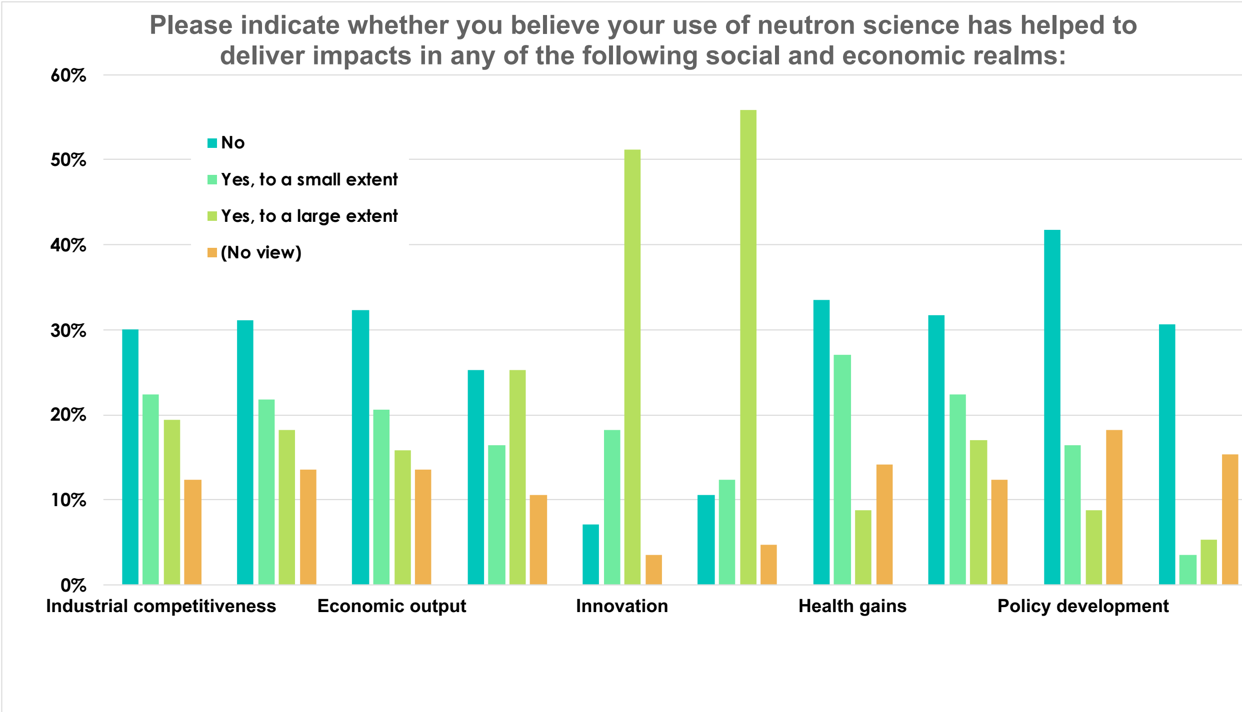


Figure 47: Contribution of neutron science to specific outcomes in the wider society, expressed as a percentage of the total number of respondents to the questionnaire.

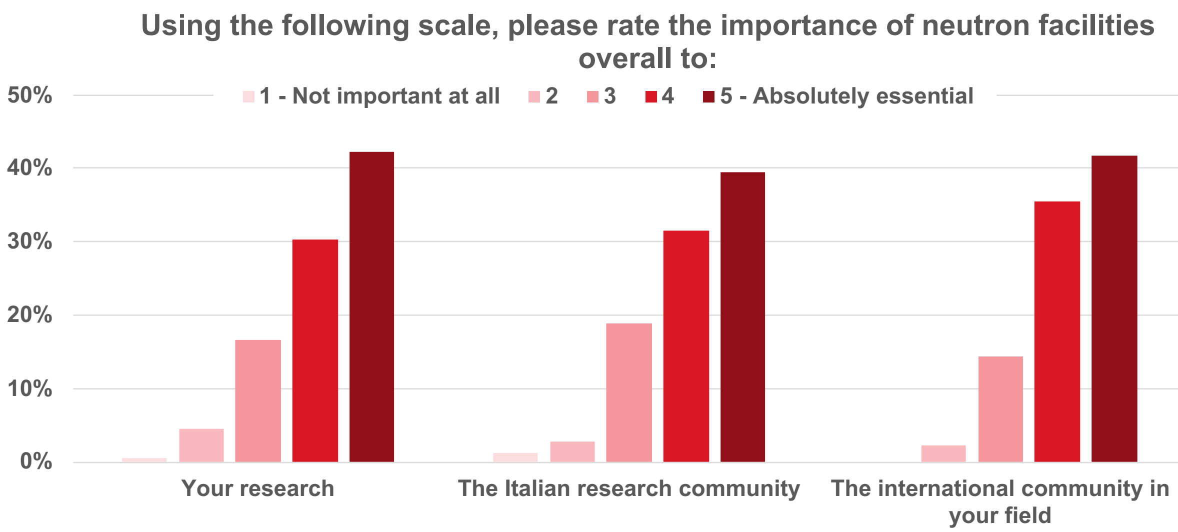


Figure 48: Overall importance of neutron science for individual, scientific and societal outcomes, expressed as a percentage of the total number of respondents to the questionnaire.

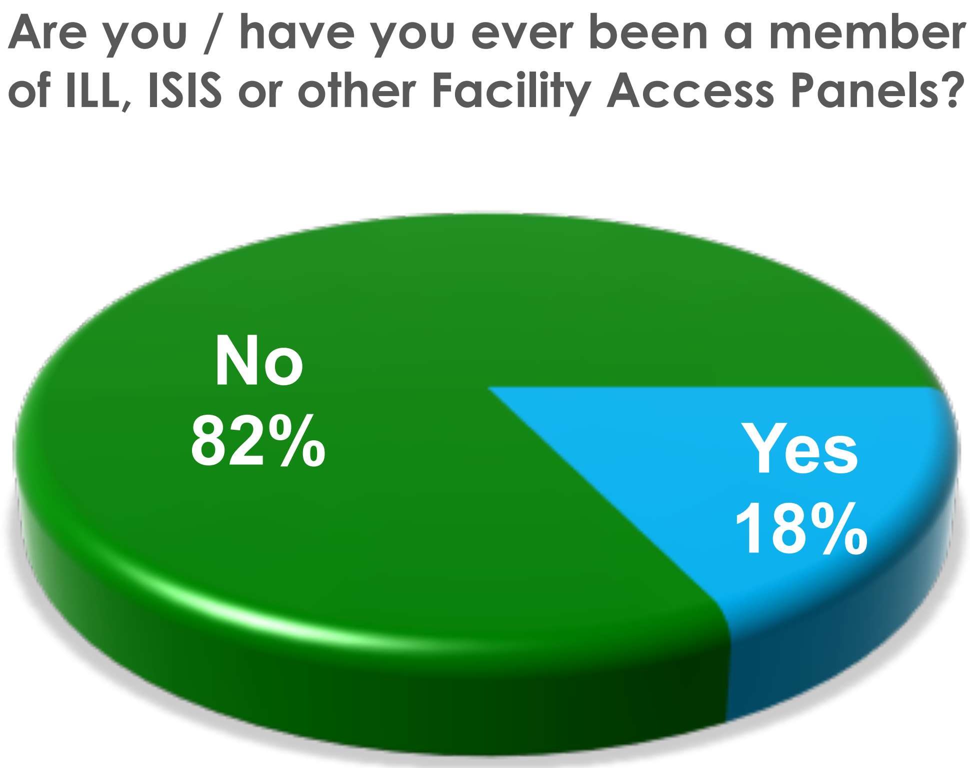


Figure 49: Percentage of respondents who have been members of facility access panels.

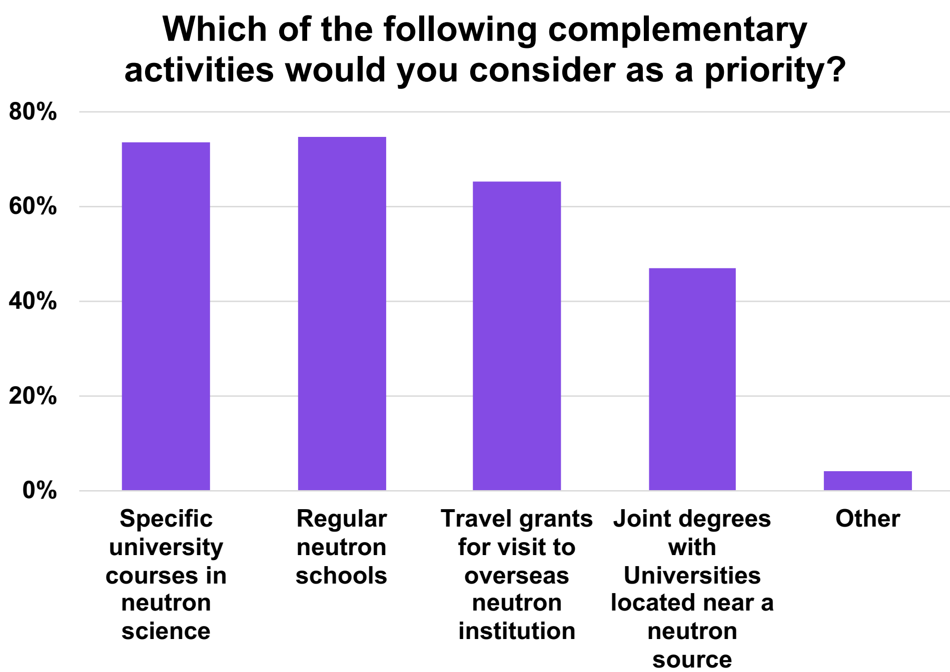


Figure 50: Importance of specific activities towards strengthening the Italian neutron community, expressed as a percentage of the number of respondents to the questionnaire.

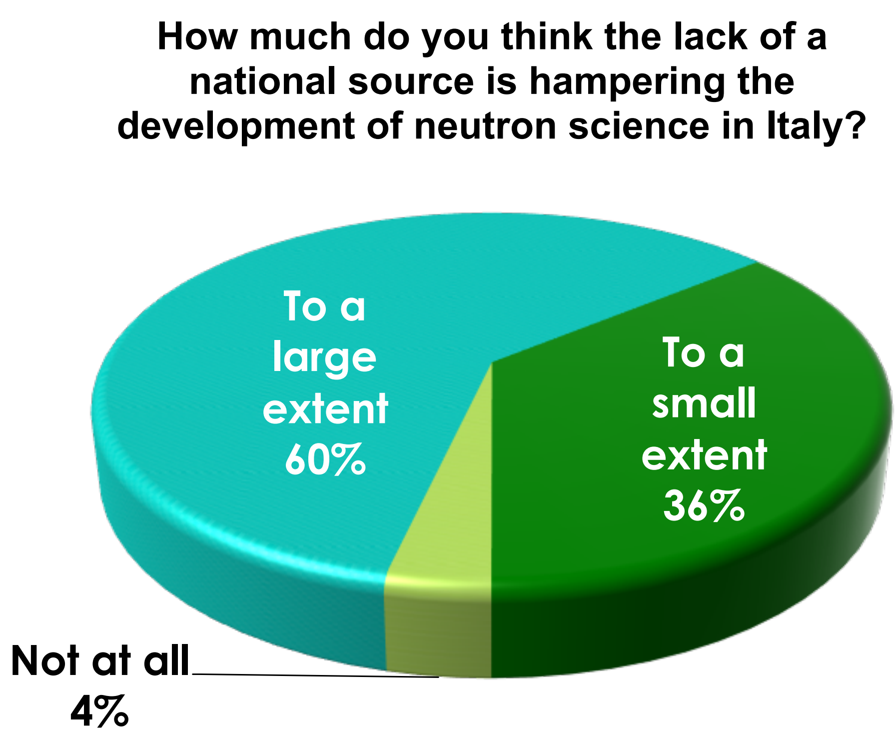


Figure 51: Effect of the lack of a national source on hampering the development of neutron science in Italy, expressed as a percentage of the number of respondents to this question.

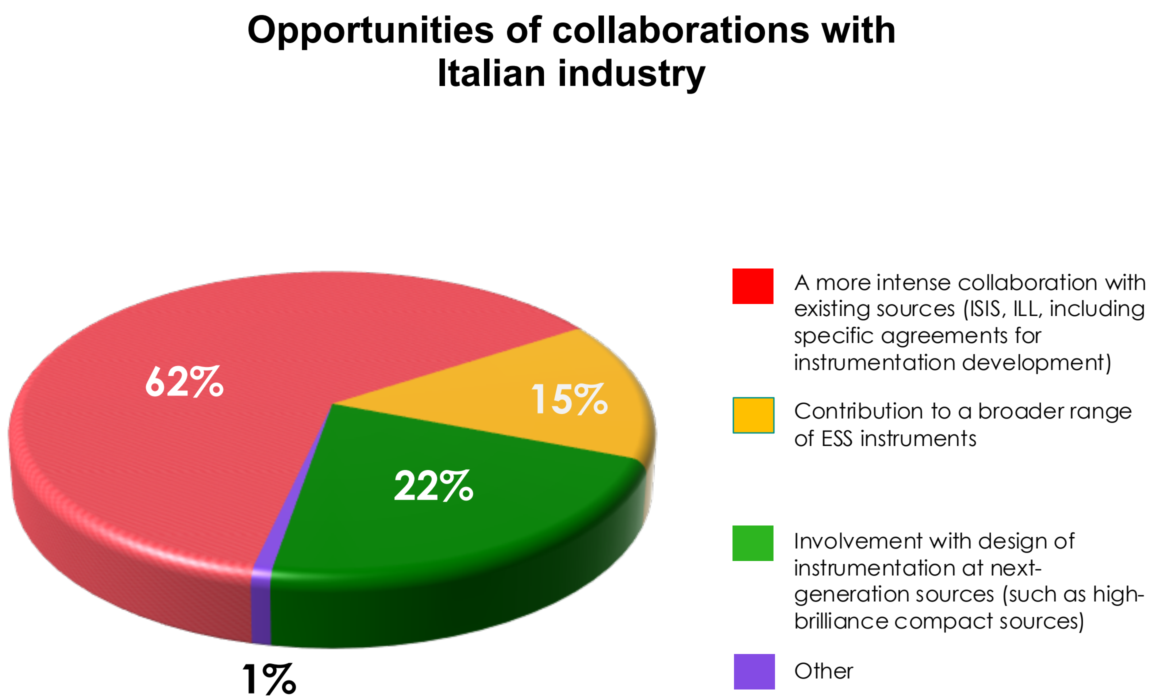


Figure 52: Opportunity created by different types of engagement towards fostering collaborations with Italian industry, expressed as a percentage of the number of respondents to this question.

APPENDIX 5: INDUSTRIAL SURVEY

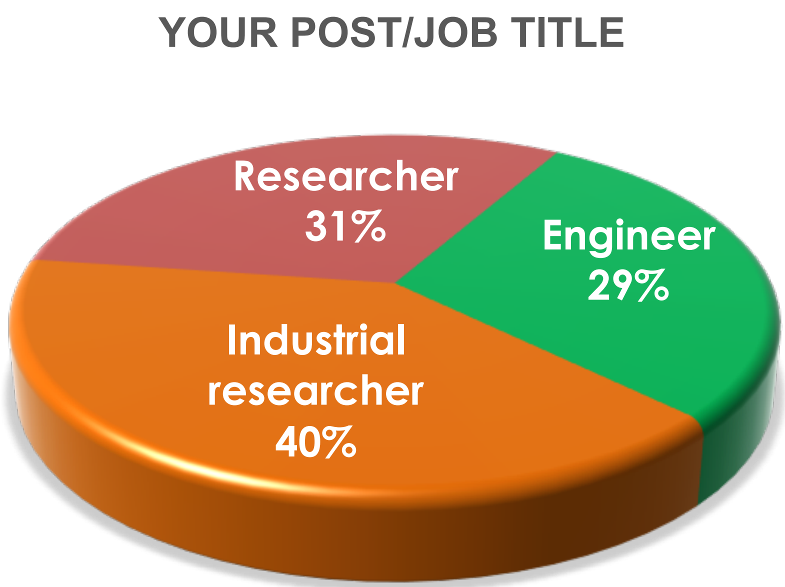


Figure 53: Career stages of the respondents to the industrial survey, expressed as a percentage of the total number of responses

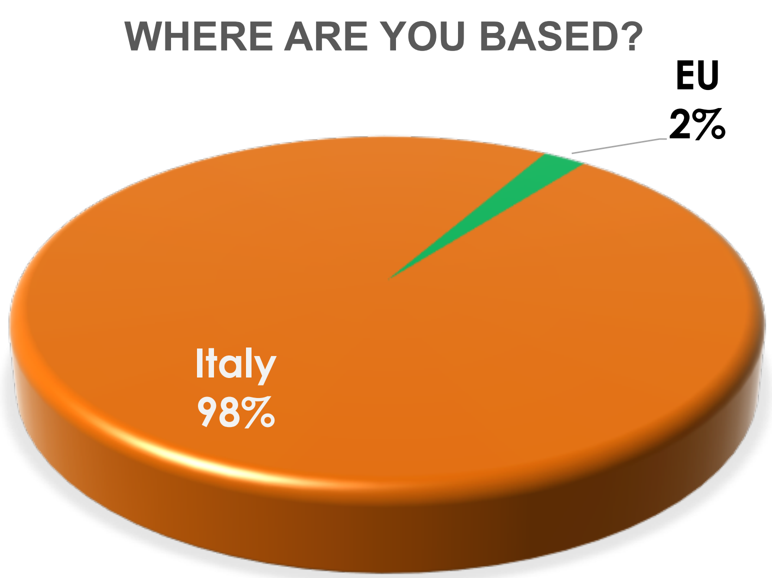


Figure 54: National base of the respondents to the industrial survey, expressed as a percentage of the total responses

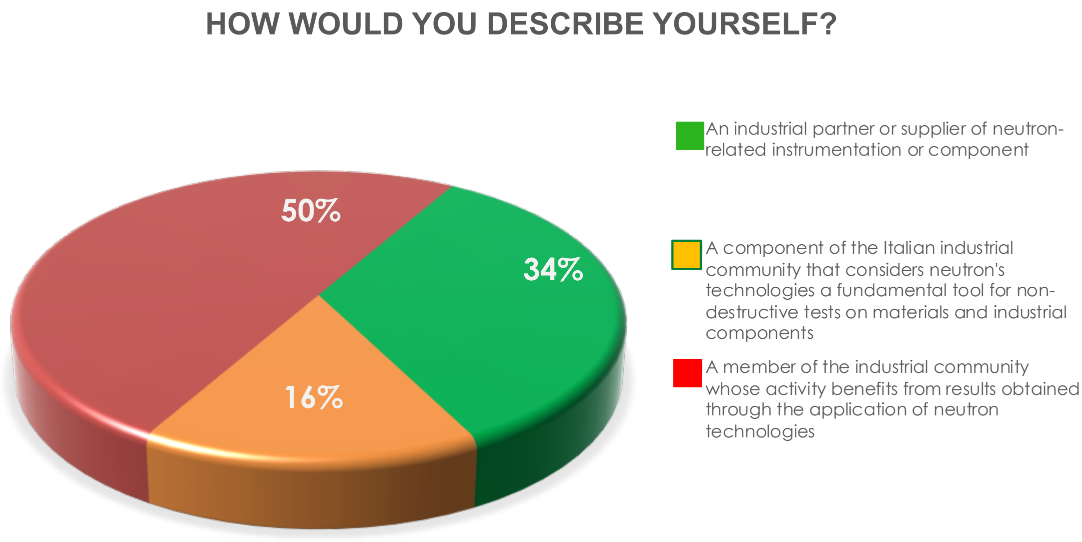


Figure 55: Engagement with neutrons of the respondents, expressed as a percentage of the total responses.

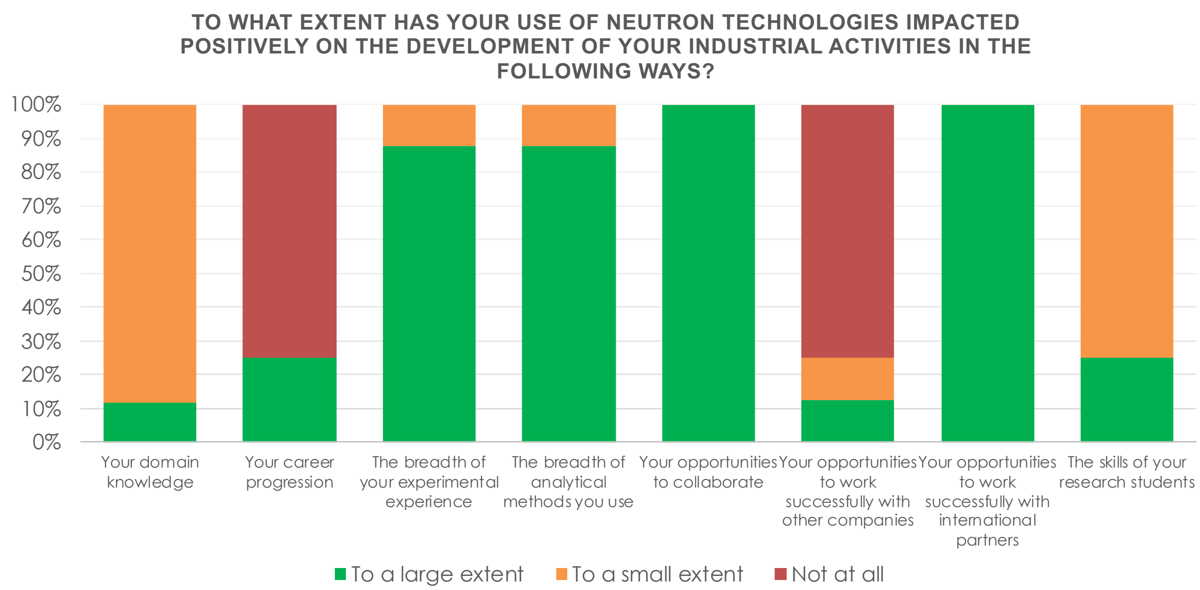


Figure 56: Contribution of neutron science on the knowledge, skills and opportunities of the respondents, expressed as a percentage of the total number of respondents to the questionnaire.

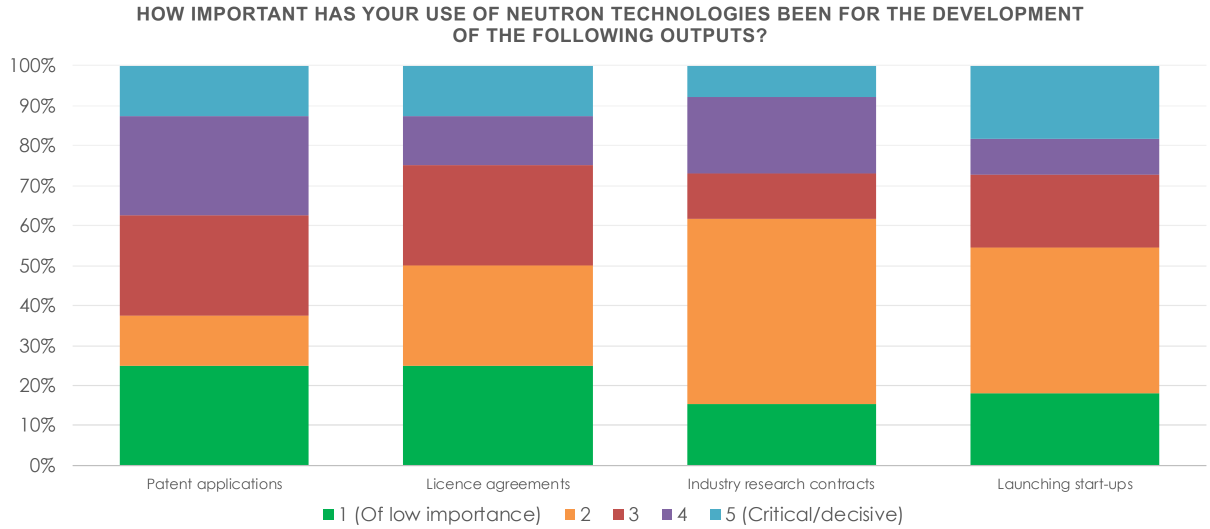


Figure 57: Contribution of neutron science for the development of specific knowledge transfer outputs., expressed as a percentage of the total number of respondents to the questionnaire

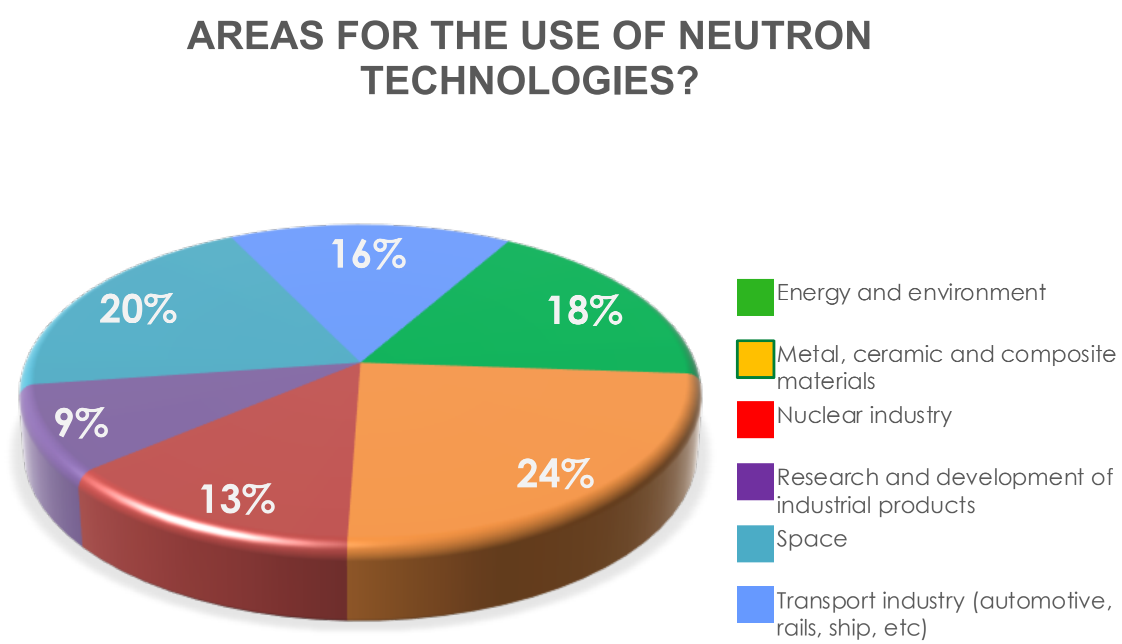


Figure 58: Overall importance of neutron technologies for specific areas of societal outcomes, expressed as a percentage of the total number of respondents to the questionnaire.

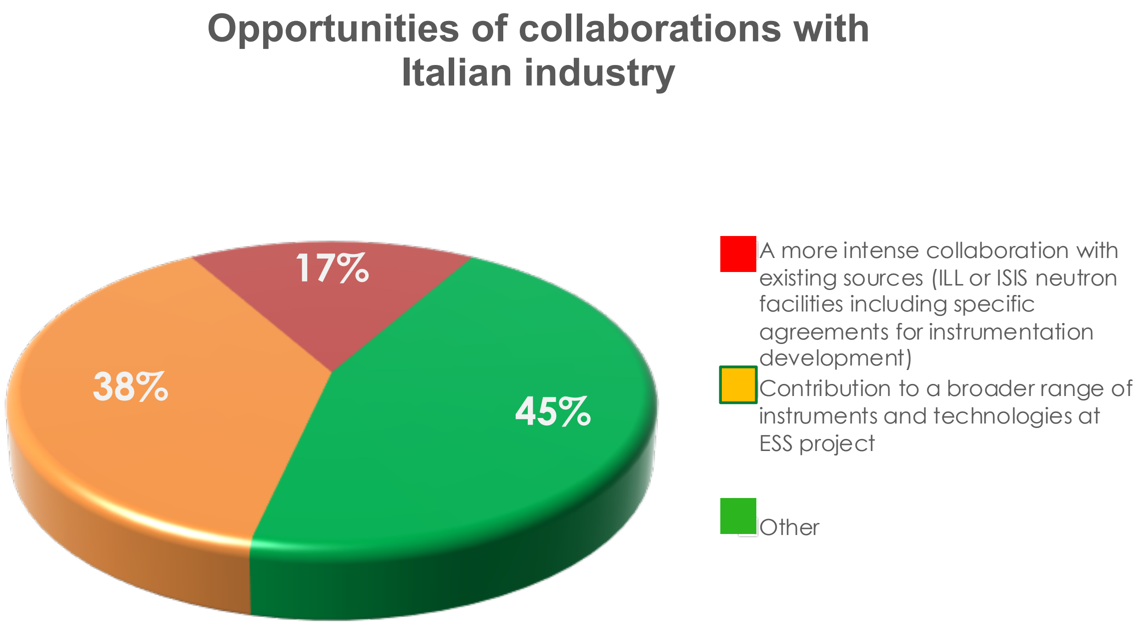


Figure 59: Opportunities of collaboration of Italian industries with existing sources (ILL) and the future source ESS, expressed as a percentage of the number of respondents to the questionnaire.

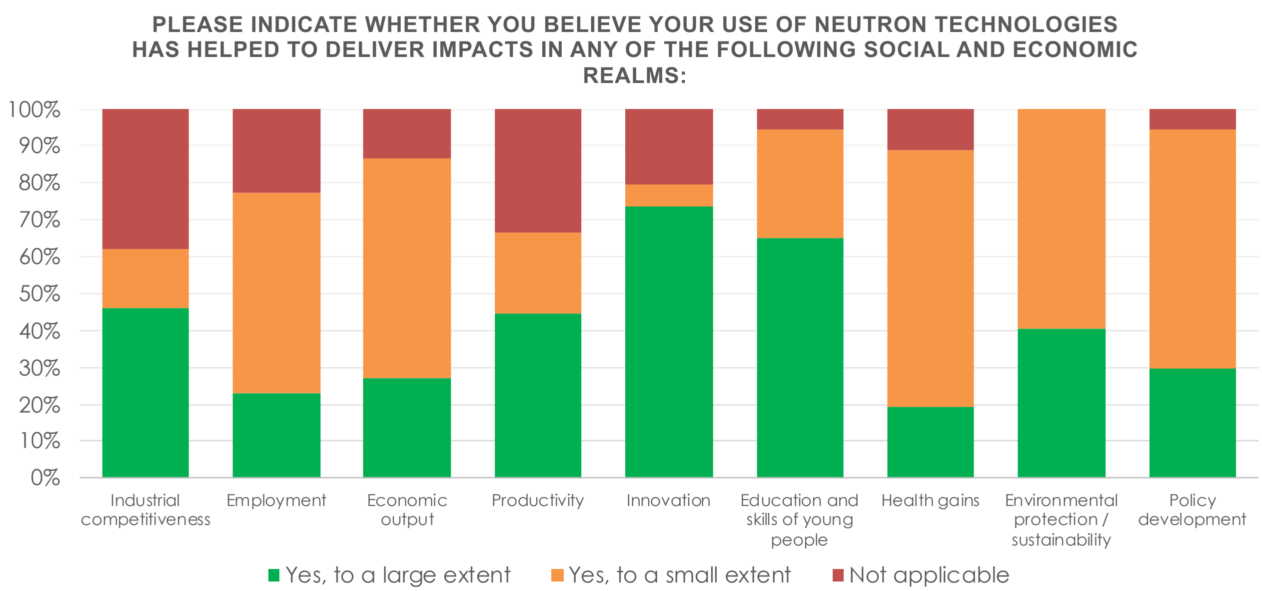


Figure 60: Contribution of the neutron technologies to specific knowledge transfer objectives, expressed as a percentage of the total number of respondents to the questionnaire.

APPENDIX 6: CAPACITY AND CAPABILITY

Neutron capacity is universally defined as the total number of beam days, on any instrument and on any source (without scaling factors), available for experiments proposed by Principal Investigators (PIs) with a given national affiliation. A beam day is defined as a day of beamtime on a single instrument. The availability is calculated based on official agreements between a national institution acting as a funding body (e.g., CNR for Italy) and the relevant neutron facilities. In reality, neutron access is not fixed, because the theoretical capacity is generally over- or under- exploited, depending on success rates in beamtime applications. True access will never be zero, because the very top-tier experiments are usually accepted regardless of PI nationalities. *Neutron capacity* is often contrasted with *neutron capability*, which measures access to the very top-tier instrumentation. Unlike the case of neutron capacity, there is no universally accepted definition of neutron capability. Although one might imagine, for example, defining a quantitative measure of capability by scaling the neutron capacity with the brilliance of the source, this metric is generally not employed in international reviews.

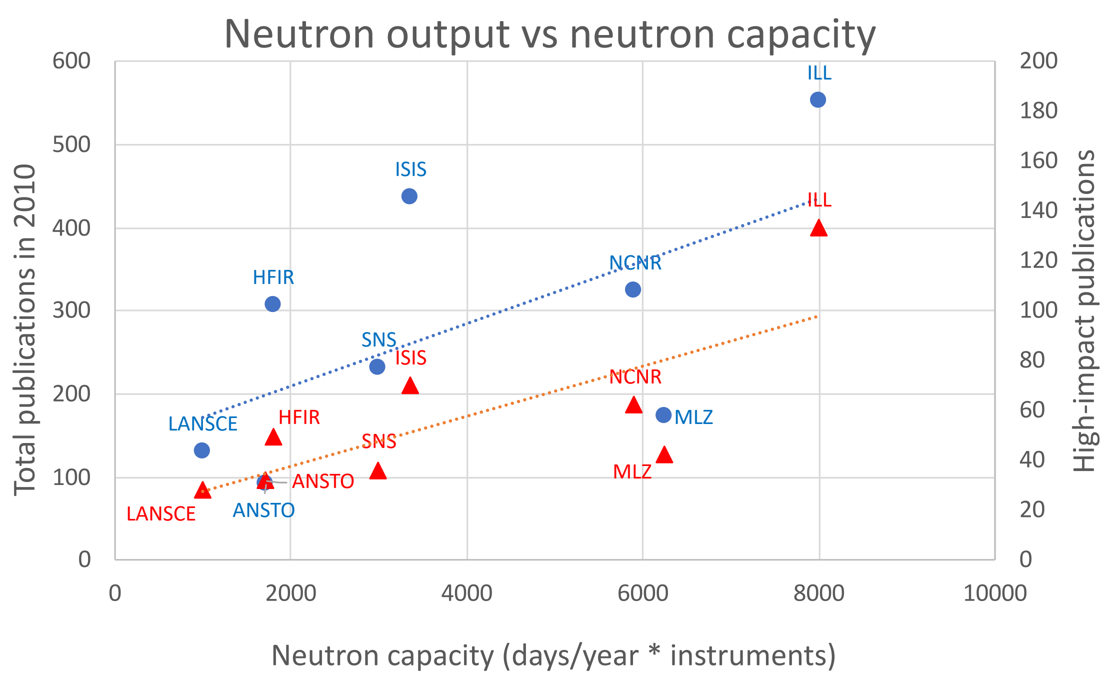


Figure 61: Output of total publications (blue circles) and high-impact publications (red triangles) versus the neutron capacities of different sources around the world. The line are best fits through the points (data source: "An assessment of the NIST Centre for Neutron Research – 2013", National Academy Press, ISBN-13: 978-0-309-29608-3).

Figure 61 shows the output of total publications (blue circles) and high-impact publications (red triangles), plotted against the neutron capacities of different sources around the world. The data (from a 2013 NIST report) are representative of a transition phase in which the SNS – then a relatively new source – was ramping up towards full capacity, and could be taken as a guide for the European scenario in the next decade. It is very clear that capacity and output scale in an approximately linear way, while the deviations from linearity *do not* correlate with the source brilliance. Data for the SNS, then the most intense neutron source in the world, are below the trend line for both total and high-profile publications, while both ISIS and the ILL are significantly above. This is entirely explicable, if one understands that source brilliance (which for each technique scales well with flux on sample) is only one of the factors contributing to publication output. Other important factors are source reliability, adequate software and sample environment, experience of the users and the instrument scientists etc., all these additional factors providing and advantage to well-established facilities with a long experience of running a user programme.

APPENDIX 7: BIBLIOMETRIC SEARCH METHODOLOGY

Establishing the output of the neutron science community (as defined in this report) through a direct bibliographic search is problematic, because the keyword "neutron" is not sufficiently specific, being shared by other communities such as high-energy physics, nuclear physics, astronomy, occupational health etc. Yet, achieving a high degree of specificity is critical for the search to be meaningful. We have adopted the following iterative approach:

- We have employed the Web of Science (WoS) scientific citation indexing service, originally produced by the Institute for Scientific Information (ISI), later maintained by Clarivate Analytics.
- We have limited our search to journal articles and excluded review articles, which tend to skew the citation metrics.
- We have retrieved all papers containing the keyword "neutron" in the title, abstract and keywords (TS search key in WOS), whilst excluding all papers in non-pertinent WOS categories (e.g., Astronomy & Astrophysics) or containing non-pertinent keywords (e.g., "magic number"). This first search yielded 40,776 papers in the period 2008-2018.
- We have selected the subset of papers that have at least one author with an Italian address.
- We have further classified these papers using keywords that are pertinent to neutron science (e.g., all the papers containing the keywords "spin echo" or "spin-echo" were grouped together). The number of papers that did not belong to any of these groups was found to be small, but we had a high proportion of misattributions. These were eliminated by an iterative process, in which new keywords were identified and applied. This process produced a list with >97% specificity.
- The same protocol was applied to identify the output of other national communities.

For the most part, the papers in our list are either the direct result of neutron experiments performed at user facilities or discuss such experiments, attributing to them sufficient importance to deserve a keyword or a mention in the abstract. This would be the case, for example, for theory papers or for papers discussing other experiments performed with other techniques, which can only be interpreted with the help of previous neutron data. We believe that all these papers, taken collectively, are a fair representation of the output of neutron science. Moreover, this methodology enabled us to compare the output of different national community in a quantitative way.

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A Vice President

Relevance of Neutron Technologies for the Italian Industries

Italian industrial community considers analysis with neutrons important for non-destructive tests of industrial materials and components, given that through the use of neutron technique it is possible to obtain information on the structure or on processes inside the object investigated by means of transmission. This technique provides complementary or even completely original information, since the interaction of neutrons with the material presents fundamental differences with respect to other types of radiation.

The neutron tests are particularly relevant in the following industrial applications:

- automotive industry: study of the flow of fluids and lubrication in combustion engines, and control of the gas charge in the airbags;
- metal, ceramic and composite materials: distribution in alloys and structure information regarding inclusions, cracks, porosity and density, in metallurgical components, high-tech ceramic materials and composite structures;
- chemical and petrochemical industry, concerning mechanical components, structures and two-phase processes (visualization of the two phases);
- the construction industry for concrete samples, including the type with normal reinforcements and those with plastic coverings: water permeability, concrete aging, steel behavior in reinforced concrete; turbine construction, aircraft and helicopter maintenance: study of corrosion, humidity, adhesion defects in turbine blades, aluminum components, composite and honeycomb structures;

- ❖ nuclear industry: safety and testing in combustible elements, command rods, etc.
- ❖ research and development of industrial products: for example, tests on freon-like materials, oil flows in engines and components, study of the flow of fluids in refrigeration and compression systems; diffusion of hydrogen in metals, thermodynamic properties of two-phase systems.

Results from the Survey indicate that industrial community consider the neutron technique of particular importance in the following industrial applications:

- **Transport industry** (automotive, rails, ship, etc.) **16%**: maintenance of aircraft and helicopters: study of corrosion, humidity, adhesion defects in turbine blades, aluminum components, composite and honeycomb structures; study of fluid flow and lubrication in combustion engines, and control of gas charge in airbags;
- **Metal, ceramic and composite materials**, **24%**: distribution in alloys and information on the structure of matrices with particular regard to inclusions, fissures, porosity and density, in metallurgical components, high-tech ceramic materials and composite structures;
- Chemical and petrochemical industry
- Construction industry for concrete samples
- Turbine construction, aircraft and helicopter maintenance
- **Nuclear industry 13%:** safety and testing in fuel elements, control rods, etc.
- **Research and development of industrial products, 9%**: for example, tests on freon-like materials, oil flows in engines and components, study of the flow of fluids in refrigeration and compression systems;
- **Space, security and SEE in electronic devices, 20%**
- **Energy and environment, 18%**
- Other

Issues

Despite the undoubted advantages, the use of neutron techniques normally encounters a series of difficulties substantially linked to the insufficient presence in the industrial community of adequate skills. This problem could be overcome through a close relationship and strategic planning with the Public Research system, which in fact possesses sufficient and adequate professional experience. This connection would also facilitate access to the Research Infrastructure.

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